Dear Colleague,

The 6th International Workshop on Compound-Nuclear Reactions and Related Topics (CNR*18), will be held in Berkeley, California, USA, during the week of September 24-28, 2018. The web site is: https://indico.bnl.gov/e/CNR2018

The CNR* workshop series brings together experts in nuclear theory, experiment, data evaluations, and applications, and fosters interactions between these groups.

Abstracts: The (extended) abstract submission of June 20 has passed. Post-deadline submissions received by September 4 will be considered for the poster session.

Program: The workshop will run Monday morning through Friday afternoon. A welcome reception will take place Monday evening, a poster session and conference banquet are planned for Wednesday, and an excursion to Muir Woods will be offered for Thursday afternoon. A tentative schedule with speakers has been posted on the conference web site.

Registration: The registration fee is $400 regular/$200 reduced and includes the reception, lunches, coffee breaks, and proceedings. Some funds are available to support students and postdocs (upon request! Priority will be given to presenters who can demonstrate a need for support.). Please register and sign up for functions (reception, dinner, excursion) by September 4; we cannot guarantee availability after that date.
ABOUT CNR*  

The CNR* series was initiated in 2007 with a meeting near Yosemite National Park. It has since moved to Bordeaux (2009), Prague (2011), Sao Paulo (2013), and Tokyo (2015). The workshop series brings together experts in nuclear theory, experiment, data evaluations, and applications, and fosters interactions between these groups.

Topics  

- nuclear reaction mechanisms  
- optical model  
- direct reactions and the compound nucleus  
- pre-equilibrium reactions  
- fusion  
- fission  
- cross section measurements (direct and indirect methods)  
- Hauser-Feshbach theory (limits and extensions)  
- compound-nuclear decays, particle and gamma emission  
- level densities and strength functions  
- nuclear structure for compound-nuclear reactions  
- nuclear astrophysics  
- nuclear energy and other applications  

The workshop will consist primarily of plenary talks, which include overviews, invited and contributed presentations, a poster session, and opportunities for discussions.

Additional information and updates will be posted on the CNR*18 web site: https://indico.bnl.gov/e/CNR2018.

Supporting organizations  

Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and the National Nuclear Science and Security Consortium (NSSC).  
Website provided by Brookhaven National Laboratory (BNL).
International Advisory Committee

G. Bertsch (INT), C. Brune (Ohio U), R. Capote (IAEA), B. Carlson (ITA), S. Chiba (Tokyo Tech), M. Dupuis (CEA, DAM, DIF), A. Hayes (LANL), K. Jones (UTK), B. Jurado (CENBG), T. Kawano (LANL), P. Koehler (LANL), A. Koning (IAEA), M. Krticka (Charles U), G. Perdikakis (CMU), R. Reifarth (GU Frankfurt), M. Wiescher (Notre Dame), and V. Zelevinsky (MSU/NSCL).

CNR*18 Organizing Committee

J.E. Escher (LLNL), L.A. Bernstein (LBNL), Y. Alhassid (Yale), D. Brown (BNL), C. Fröhlich (NCSU), P. Talou (LANL), and W. Younes (LLNL).

MEETING AND VENUE

The meeting will be held at Lawrence Berkeley National Laboratory, located in the hills above Berkeley, California, USA.

Berkeley is conveniently accessible from San Francisco International Airport (SFO), Oakland International Airport (OAK), and San Jose International Airport (SJC) via public transport, private shuttles, ride-sharing services, and rental cars.

Lodging has been reserved in the downtown Berkeley area and on the LBNL site. Shuttles connect downtown Berkeley to LBNL.

Working lunches

We have scheduled generous 2-hour lunch breaks in order to allow for more in-depth discussions of the workshop topics. We will provide box lunches and spaces for group discussions. Every day, workshop participants can select a topic they are interested in and have lunch with other participants in a designated discussion space. We will offer several topics each day and rotate themes throughout the week. We will also provide opportunities for workshop participants to propose their own topic of interest. If you would like to propose a topic, please notify the organizers.

Meeting Site

All on-campus events will be held in Building 54 (the Cafeteria and Perseverance Hall) and Building 66 (the meeting itself). The Lawrence Berkeley Laboratory site map is shown in Figure 1.

Orange and Blue Shuttles

Lawrence Berkeley National Laboratory operates two shuttle busses to and from downtown Berkeley and through the lab. The bus routes are shown in Figure 2.

Directions from the meeting accommodations:

- From the downtown Berkeley Inn: Board the Orange Shuttle at Shattuck and Addison and deboard at B66 - MAP: https://goo.gl/maps/kkGW5DBBrts
- From the Faculty Club: Board the Orange Shuttle at Gailey and the East Gate and deboard at B66 - MAP: https://goo.gl/maps/TUTGNCWZbJR2
- From the Women’s Faculty Club: Board the Orange Shuttle at and the East Gate and deboard at B66 - MAP: https://goo.gl/maps/88jFymv18792
- From the Guest House: Board the Blue shuttle at the B70 shuttle stop and deboard at B66 or Board the Blue shuttle at the B54 shuttle stop and transfer to uphill Blue shuttle at B55 and deboard at B66 - MAP: http://www2.lbl.gov/Workplace/Facilities/Support/Busses/off-site_blue.html

The schedule for the Blue shuttle is at http://www2.lbl.gov/Workplace/Facilities/Support/Busses/off-site_blue.html and the schedule for the Orange shuttle is at http://www2.lbl.gov/Workplace/Facilities/Support/Busses/off-site_orange.html

Banquet and Poster Venue

The poster session and workshop banquet will be held at the David Brower Center (https://

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The David Brower Center provides a home for the environmental movement by advocating for the beauty, diversity and ecological integrity of Earth. The center contains a Conference Center that hosts more than 300 events every year for nonprofit and private businesses, and strengthening the green event industry by requiring clients to abide by low-waste, green principles. Transportation to and from the Brower Center will be provided. The address of the center is

David Brower Center
2150 Allston Way, Suite 100
Berkeley, CA 94704

San Francisco Bay Area

Berkeley ([https://en.wikipedia.org/wiki/Berkeley,_California](https://en.wikipedia.org/wiki/Berkeley,_California)) is located in the San Francisco Bay area. It is known for its university (the oldest campus in the UC system), for being an intellectual center, a hub for entertainment and gourmet dining. It has a number of parks, a botanical garden, and offers stunning panoramic views. See, e.g., [http://www.planetware.com/tourist-attractions-/berkeley-us-ca-bk.htm](http://www.planetware.com/tourist-attractions-/berkeley-us-ca-bk.htm).

San Francisco, with its well-known attractions ([http://www.planetware.com/tourist-attractions-/san-francisco-us-ca-sf.htm](http://www.planetware.com/tourist-attractions-/san-francisco-us-ca-sf.htm)) is a quick (~30 min) BART ride away, and half-day or day trips take visitors to Muir Woods, home to old-growth redwoods ([https://www.nps.gov/muwo/index.htm](https://www.nps.gov/muwo/index.htm)), or the wine country of Napa Valley ([https://en.wikipedia.org/wiki/Napa_County,_California](https://en.wikipedia.org/wiki/Napa_County,_California)).

### CODE OF CONDUCT

It is the policy of CNR*18 that all participants, including attendees, vendors, staff, volunteers, and all other stakeholders at CNR*18 will conduct themselves in a professional manner that is welcoming to all participants and free from any form of discrimination, harassment, or retaliation. Participants will treat each other with respect and consideration to create a collegial, inclusive, and professional environment at the workshop. Creating a supportive environment to enable scientific discourse at CNR*18 is the responsibility of all participants.

Participants will avoid any inappropriate actions or statements based on individual characteristics such as age, race, ethnicity, sexual orientation, gender identity, gender expression, marital status, nationality, political affiliation, ability status, educational background, or any other characteristic protected by law. Disruptive or harassing behavior of any kind will not be tolerated. Harassment includes but is not limited to inappropriate or intimidating behavior and language, unwelcome jokes or comments, unwanted touching or attention, offensive images, and stalking.

Violations of this code of conduct policy should be reported to meeting organizers. Sanctions may range from verbal warning, to ejection from the meeting without refund, to notifying appropriate authorities. Retaliation for complaints of inappropriate conduct will not be tolerated. If a participant observes inappropriate comments or actions and personal intervention seems appropriate and safe, they should be considerate of all parties before intervening.

### ACKNOWLEDGEMENTS

This work performed in part under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Work at Brookhaven National Laboratory was sponsored by the Office of Nuclear Physics, Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-98CH10886 with Brookhaven Science Associates, LLC.
Figure 1: Lawrence Berkeley Laboratory site map. Building 66, where the meeting is held, is at coordinate D6. The reception on Monday night will be held at Perseverance Hall in the Cafeteria (Building 54), at coordinates C2 and C3. For those staying on-site at the Guest House, this is Building 23 at coordinate C3.
Figure 2: Lawrence Berkeley Laboratory Orange and Blue shuttle maps. Building 66, where the meeting is held, is reachable with either shuttle. Perseverance Hall in the Cafeteria (Building 54) is reachable on the Blue route.
MEETING AGENDA

Monday, 24 September 2018

All meeting events in Building 66, Room 317 unless otherwise noted.

Opening Chair: J. Escher (08:15 - 08:30)
   Welcome Symons, James Associate Laboratory Director for Physical Sciences
   Announcements Escher, Jutta CNR* 2018 Chair

Compound Reactions Chair: J. Escher (08:30 - 09:30)
   Overview (1 hr.) Hilaire, Stèphane Towards more predictive nuclear reaction modelling

Hauser-Feshbach Codes I Chair: G. Nobre (09:30 - 10:00)
   Invited (30 min.) Koning, Arjan Towards TALYS-2.0

Break (10:00 - 10:30)

Hauser-Feshbach Codes II Chair: G. Nobre (10:30 - 12:00)
   Invited (30 min.) Kawano, Toshihiko CoH₃: The Coupled-Channels and Hauser-Feshbach Code
   Invited (30 min.) Carlson, Brett Modelling compound nuclear reactions with EMPIRE
   Discussion (30 min.) Moderator: G. Nobre

Working Lunch (12:00 - 14:00)

Beyond Hauser-Feshbach Chair: T. Kawano (14:00 - 15:30)
   Invited (30 min.) Bertsch, George Beyond Hauser-Feshbach in the compound nucleus
   Contributed (20 min.) Fanto, Paul Neutron width statistics in a realistic resonance-reaction model
   Contributed (20 min.) Brown, David Moldauer’s sum rule implies superradiance in compound nuclear reactions
   Discussion (20 min.) Moderator: T. Kawano

Break (15:30 - 16:00)

Experiments I Chair: P. Talou (16:00 - 17:30)
   Invited (30 min.) Gade, Alexandra FRIB: Scientific opportunities and status
   Invited (30 min.) Jones, Kate Single-nucleon transfer reactions
   Invited (30 min.) Casperson, Robert Capabilities of the NIFFTE fissionTPC

Reception (18:00 - 19:30) Building 54, Perseverence Hall
Tuesday, 25 September 2018

All meeting events in Building 66, Room 317 unless otherwise noted.

Nuclear structure I (Level Densities) Chair: D. Brown (08:30 - 10:00)

Overview (1 hr.) Alhassid, Yoram Nuclear level densities: from empirical models to microscopic methods

Invited (30 min.) Voinov, Alexander Problem of level densities in compound nuclear reactions

Break (10:00 - 10:30)

Nuclear structure II (Gamma strengths) Chair: A. Simon (10:30 - 12:00)

Invited (30 min.) von Neumann-Cosel, Peter Gamma Strength Functions and the Brink-Axel Hypothesis

Contributed (20 min.) Utsunomiya, Hiroaki γ-ray Strength Functions and Partial GDR Cross Sections in the IAEA Photonuclear Data Project

Contributed (20 min.) Midtboe, Joergen E. Systematic investigations of γ-ray strength functions across the nuclear chart within the shell model

Contributed (20 min.) Nobre, Gustavo Constraining level densities using spectral data

Working Lunch (12:00 - 14:00)

Reaction mechanisms I Chair: A. Gade (14:00 - 15:30)

Invited (30 min.) Chiba, Satoshi Multinucleon transfer mechanisms studied by antisymmetrized molecular dynamics

Invited (30 min.) Dupuis, Marc Microscopic modeling of direct and pre-equilibrium mechanisms for nucleon induced reactions

Contributed (20 min.) Chimanski, Emanuel Multi-step direct reaction models including collectivity in nucleon induced reactions

Discussion (10 min.) Moderator: A. Gade

Break (15:30 - 16:00)

Experiments II Chair: S. Siem (16:00 - 17:40)

Contributed (20 min.) Wiedeking, Mathis Constraining astrophysical processes through statistical decay data

Contributed (20 min.) Zeiser, Fabio Impact of restricted spin-ranges in the Oslo Method on the example of (d,p)240Pu

Contributed (20 min.) Ullmann, John Neutron Capture on Actinides studied with DANCE

Contributed (20 min.) Knapová, Ingrid Statistical gamma decay of $^{168}$Er from resonance neutron capture
Wednesday, 26 September 2018

All meeting events in Building 66, Room 317 unless otherwise noted.

Fission I Chair: S. Chiba (08:30 - 10:00)

Overview (1 hr.) Younes, Walid A Grand Tour of Nuclear Fission Physics

Invited (30 min.) Loveland, Walter The role of spin in compound nuclear reactions leading to heavy element formation

Break (10:00 - 10:30)

Fission II Chair: L. Bernstein (10:30 - 12:00)

Invited (30 min.) Schunck, Nicolas Theoretical Description of Fission at Increasing Excitation Energy

Contributed (20 min.) Vogt, Ramona Event-by-Event Fission Modeling with FREYA

Contributed (20 min.) Zhao, Kai The investigation of properties of scission point in reactions of $^{48}\text{Ca}+^{208}\text{Pb}$

Contributed (20 min.) Görgen, Andreas The Evolution of Triaxial Shapes in $A\approx110$ Fission Fragments

Group Photo (12:00 - 12:05)

Working Lunch (12:05 - 14:00)

Nuclear structure III (Level densities) Chair: Y. Alhassid (14:00 - 15:30)

Contributed (20 min.) Firestone, Richard Deconvolution of the Photon Strength Function

Contributed (20 min.) Koehler, Paul Attempting to close the loop on the Oslo technique at $^{198}\text{Au}$: Constraining the nuclear spin distribution

Contributed (20 min.) Grimes, Steven M. Rotational enhancement factor for nuclear level densities

Contributed (20 min.) Al Mamun, Md Abdullah Pairing properties from random distributions of single-particle energy levels

Discussion (10 min.) Moderator: Y. Alhassid

Lightning talks Chair: Y. Alhassid (15:30 - 16:00)

1 min. talks introducing selected posters ahead of the poster session.

Transport to Brower Center (16:00 - 16:30)

Poster Session (16:30 - 19:00) Brower Center

Bhuyan, Mrutunjaya Symmetry energy: A source for determining the surface properties of finite nuclei

Roy, Pratap Temperature dependence of nuclear level density and the role of collective excitations.

Gustavino, Carlo Underground Nuclear Astrophysics: present and future of the LUNA experiment

Ummel, Chad A Cross Section Measurement of the $^{13}\text{C}(d,n)^{14}\text{N}$ Reaction—A Beam-Induced Background in Underground Nuclear Astrophysics Experiments
Hagiwara, Masayuki Measurement of the excitation functions on zirconium induced by alpha particles up to 46 MeV

Yashima, Hiroshi Excitation function measurements of alpha-induced reaction on natural copper and titanium up to 46 MeV

Gull, Muntazir Systematic of fusion suppression in reaction induced by α cluster projectile

Singh, BirBikram Clustering effects in the reaction mechanism of very light mass composite nuclei

Gorton, Oliver Neutron capture cross sections from surrogate reaction data and theory: connecting the pieces with a Markov-Chain Monte Carlo approach

Gull, Muntazir Systematic study of incomplete fusion reactions: Role of various entrance channel parameters

Yadav, Abhishek Quasi-elastic excitation function for $^{16}$O+$^{169}$Tm system: role of hexadecapole deformation

Morrell, Jonathan Measuring La(p,x) Cross Sections from 35-60 MeV by Stacked Foil Activation

Gueorguiev, Vesselin Neutron Transfer Reactions for Deformed Nuclei Using Sturmian Basis

Deshayes, Quentin Characterization of the FALSTAFF spectrometer first arm: Study of 252Cf and $^{235}$U fission fragments

Manfredi, Juan Testing (p,d) Transfer Reaction Consistency at 70 MeV/u

Kuvin, Sean Constraining the νp-process through the study of neutron-induced charged-particle reactions on short-lived $^{56}$Ni

Whitehead, Taylor Elastic Proton Scattering on Calcium Isotopes from Chiral Microscopic Optical Potential

Dutta, Saumi Radiative neutron capture in folding model with a microscopic optical model potential and application of the reaction rates to astrophysical s-process

Kaur, Mandeep Evolution of symmetric decay in $A = 60$ compound nuclei

Cherevko, Kostyantyn On the role of the curvature corrections to the surface tension coefficient upon the orientation effects in the fusion reactions

Lewis, Amanda Direct $^{157}$Gd($^3$He,α,2n)$^{154}$Gd reaction as a surrogate for $^{155}$Gd(n,2n)$^{154}$Gd

Rusev, Gencho Prompt and delayed fission gamma rays from 252Cf(sf) and $^{235}$U(n,f)

Solders, Andreas Measurements of isomeric yield-ratios in fission and estimates of the average angular momentum of the initial fragments

Kausal, Pooja Dynamical Cluster-decay Model applied to decay of $^{202}$Po* formed via $^{48}$Cu$^{154}$Gd reaction

Davis, Edward Probing the explanatory power of statistical reaction theory via cross section correlation functions

Jimenez-Bonilla, Pablo Experimental measurements of the 197Au(n,γ) Maxwellian-averaged cross section at $kT = 30$keV by activation method.

Kaur, Sarbjeet Exploring shell effects in the decay of compound nucleus $^{200}$Pb* within collective clusterisation approach.
Kaur, Manpreet *Emission of complex fragments in the decay of $^{44}$Ti* within collective clusterization approach*

Chopra, Sahila *Synthesis of $Z=120$ via $^{54}$Cr+$^{248}$Cm using Dynamical Cluster-decay Model*

**Conference Dinner** Chair: P. Talou (19:00 - 21:30) Brower Center

Fryer, Chris *Nuclear Physics and Astronomy: A Growing Partnership*
Thursday, 27 September 2018

All meeting events in Building 66, Room 317 unless otherwise noted.

Applications I (Astrophysics) Chair: G. Perdikakis (08:30 - 09:30)

  Overview (1 hr.) Frohlich, Carla Astrophysics - An Application of Nuclear Physics

Nuclear structure IV (Level Densities) Chair: G. Perdikakis (09:30 - 10:00)

  Invited (30 min.) Zelevinsky, Vladimir Shell-Model Level Density and Underlying Physics

Break (10:00 - 10:30)

Applications II Chair: C. Frölich (10:30 - 12:00)

  Invited (30 min.) Hayes, Anna Studies of the Transition to a Fermi Degenerate Plasma at the National Ignition Facility
  Contributed (20 min.) Lemaître, Jean-François Microscopic description of fission for the r-process in neutron-star mergers ejecta
  Contributed (20 min.) Ahn, Sunghoon (Tony) The first experimental (α,xn) compound reaction study using neutron-rich nuclei
  Contributed (20 min.) Perdikakis, Georgios Neutron-induced reaction rates away from stability for astrophysics applications: Uncertainties in statistical model calculations and implications for neutron-induced nucleosynthesis.

Working Lunch (12:00 - 13:00)

Excursion to Muir Woods (13:00 - 18:00) Muir Woods
Friday, 28 September 2018

All meeting events in Building 66, Room 317 unless otherwise noted.

**Resonances** Chair: G. Bertsch (08:30 - 10:00)

- **Invited** (30 min.) Brune, Carl *The Transition from Isolated Resonances to the Continuum*
- **Contributed** (20 min.) Thompson, Ian *Recent Advances in R-matrix Data Analysis*
- **Contributed** (20 min.) Mercenne, Alexis *New ab initio approach for nuclear reactions based on the symmetry-adapted no-core shell model*
- **Contributed** (20 min.) Blain, Ezekiel *Experimental Nuclear Data Measurements and Capabilities at RPI*

**Break** (10:00 - 10:30)

**Indirect Measurements** Chair: K. Jones (10:30 - 12:00)

- **Contributed** (20 min.) Henriques, Ana *Investigation of the surrogate-reaction method through simultaneous gamma-decay and fission probability measurements*
- **Contributed** (20 min.) Escher, Jutta *Neutron Capture Cross Sections for Short-Lived Nuclei from Surrogate Reaction Data and Theory*
- **Contributed** (20 min.) Ratkiewicz, Andrew *Demonstrating the (d,p) Reaction as a Surrogate for (n,γ)*
- **Contributed** (20 min.) Cizewski, Jolie *Prospects for surrogate neutron capture measurements with radioactive ion beams and GODDESS*

**Discussion** (10 min.) Moderator: K. Jones

**Working Lunch** (12:00 - 13:30)

**Optical model** Chair: Ch. Elster (13:30 - 14:30)

- **Invited** (30 min.) Dickhoff, Willem *Linking nuclear reactions and nuclear structure to study exotic nuclei*
- **Contributed** (20 min.) Blanchon, Guillaume *News from Gogny based optical potential*

**Discussion** (10 min.) Moderator: Ch. Elster

**Break** (14:30 - 15:00)

**Reaction mechanisms II** Chair: M. Dupuis (15:00 - 16:00)

- **Invited** (30 min.) Elster, Ch. *Faddeev Approach to (d,p) Reactions as Tool to Study Exotic Nuclei*
- **Contributed** (20 min.) Potel Aguilar, Gregory *Using (d,p γ) reactions as surrogates for neutron capture*

**Discussion** (10 min.) Moderator: M. Dupuis

**Outlook and closing** Chair: TBD (16:00 - 17:00)
Towards more predictive nuclear reaction modelling

Stéphane Hilaire

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Nuclear reaction modeling relies on three main theoretical models connected together, namely the optical model, the pre-equilibrium model and the compound nucleus model. Each of these model makes use of various input data, which can either be directly obtained from experiment or from experimentally-based systematics, fine tuned to reproduce data of interest, or deduced from more fundamental bases. For well measured nuclei, one usually adopts phenomenological approaches consisting in fine tuning input parameters to fit at best important experimental measurements. However, when dealing with reactions on exotic targets far from the valley of stability, alternatives to risky input data extrapolation have to be considered.

Thanks to the high computer power available nowadays, all the input data required to model a nuclear reaction can now be (and have been) microscopically (or semi-microscopically) determined starting from the information provided by a nucleon-nucleon effective interaction. This concerns nuclear masses, optical model potential, total nuclear level densities, photon strength functions, as well as fission paths.

I will discuss both the quality of these ingredients and the impact of using them instead of the usually adopted phenomenological parameters, and I will draw perspectives for the coming years on the improvement one can expect with respect to the quality of these ingredients or to the theoretical models using them.

Towards TALYS-2.0

Arjan Koning

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Towards TALYS-2.0

Arjan Koning
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The nuclear model code TALYS is designed to analyse and predict nuclear reactions. TALYS has been extensively validated over the past 20 years, by the authors and thousands of users, in fields ranging from fundamental nuclear reaction studies to nuclear data evaluation for applications. A major upgrade is in progress, TALYS-2.0, comprising among others a complete rewrite in Fortran-95 and unprecedented documentation of all its options, and full capabilities regarding Bayesian Monte Carlo based uncertainty quantification and ENDF data library production. For CNR’18, I will focus on the status and future of the implemented physics:

- Gogny-Hartree-Fock-Bogoliubov based nuclear structure data tables
- More consistent microscopic approach to photonuclear and neutron capture reactions
- Global comparison of TALYS with the EXFOR database
- Uncertainties from nuclear models and parameters
- What can TALYS not (yet) do

**Hauser-Feshbach Codes / 93**

**Modelling compound nuclear reactions with EMPIRE**

Brett Carlson¹ ; Roberto Capote² ; Mike Herman³

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² IAEA NDS  
³ NNDC, Brookhaven National Laboratory

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EMPIRE [1] is a modular system of nuclear reaction codes, comprising various nuclear models, and designed for calculations over a broad range of energies and incident particles. A projectile can be a neutron, proton, an ion or a photon. The energy range extends from the beginning of the unresolved resonance region for neutron-induced reactions and goes up to several hundred MeV for heavy-ion induced reactions.

The code accounts for the major nuclear reaction mechanisms, including direct, pre-equilibrium and compound nucleus ones. Direct reactions are described by a generalized optical model or by a coupled-channels approach. The pre-equilibrium mechanism can be treated by several quantum mechanical and semiclassical models. The compound nucleus decay is described by a full featured Hauser-Feshbach model with γ-cascade and width-fluctuations. Advanced treatment of the fission channel takes into account transmission through a multiple-humped fission barrier with absorption in the wells.

We concentrate our attention here on the basic features of precompound and compound nuclear decay contained in the code, as well as on newer related features, such as inclusion of the Engelbrecht-Weidenmueller transformation and the complete and incomplete fusion channels of deuteron-induced reactions.


**Hauser-Feshbach Codes / 48**

**CoH₃: The Coupled-Channels and Hauser-Feshbach Code**

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The optical model and Hauser-Feshbach theory code, CoH (Compact optical model and Hauser-Feshbach), was developed at Kyushu Univ. in Japan, and first released in 1992 to small communities of nuclear technology and astrophysics. The original code was written in C and was limited to binary reactions only. This was largely extended to calculate general nuclear reaction cross sections and related quantities, such as the particle energy spectra and angular distributions, in 2009 by adopting the C++ object-oriented programming style. CoH₃ focuses on the nuclear reaction calculations in the keV to tens of MeV region. The code consists of three major sections that undertake the one-body potential mean-field theory, the coupled-channels optical model, and the Hauser-Feshbach
statistical theory. There are other segments to complete the whole reaction mechanisms, such as the direct/semidirect radiative capture process, pre-equilibrium process, and prompt fission neutron emission. Albeit capabilities of CoH3 for calculating the compound nuclear reactions are similar to other Hauser-Feshbach codes currently available in the market, several advantages make a distinction. The advantages include a consistent description of the width fluctuation correction with the random matrix theory, a rigorous treatment of the direct reaction channels in the compound reaction, an internal solver of the optical model that is tightly connected with the statistical decay part, and so on. We outline these special features in CoH3, as well as some satellite tools, and summarize challenges beyond the standard applications of Hauser-Feshbach theory.

**Beyond Hauser-Feshbach / 40**

**Beyond Hauser-Feshbach in the compound nucleus**

George Bertsch

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The Hauser-Feshbach formula (HF) with its complete factorization between different channels has limitations beyond the well-known width fluctuation correction that is often included in the theory. Still, there are difficulties with the HF as normally applied which are revealed by a pure Hamiltonian approach. This is seen in two examples I will present. The examples are the n + 235-U fission cross section at low neutron bombarding energies [1] and the n + 192-Pt total cross section, also at low neutron energies [2]. Our Hamiltonian approach is implemented in the publicly available computer code "Mazama".


**Beyond Hauser-Feshbach / 12**

**Neutron width statistics in a realistic resonance-reaction model**

Paul Fanto1 ; George Bertsch2 ; Yoram Alhassid3

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2. *Institute for Nuclear Theory and University of Washington*

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A fundamental prediction of the statistical model of compound nucleus reactions is that the reduced widths for any reaction channel fluctuate according to the Porter-Thomas distribution (PTD). However, in a recent experiment on s-wave neutron scattering from Pt isotopes, it was found that the distributions of the reduced neutron widths were much broader than the PTD [1]. It is important to understand whether such PTD violation can occur within the statistical model. Several explanations have been proposed for this finding within the statistical model [2-4], but none has definitively resolved the issue. We have studied s-wave neutron scattering from 195Pt within a model that combines a realistic description of the entrance neutron channel with the usual description of the compound nucleus states by the Gaussian orthogonal ensemble (GOE) of random matrices [3]. This model includes all aspects of the statistical model for a single-channel reaction and enables us to calculate reaction cross sections and resonance widths within the same framework. We determine a baseline set of model parameters from the literature, and then vary these parameters to study possible mechanisms for PTD violation. Our main conclusion is that the PTD is an excellent description...
of the neutron width fluctuations within the reasonably large parameter range considered, provided that the secular energy dependence of the average neutron width is correctly described. This result indicates that the non-statistical interactions among the resonances due to coupling to the neutron channel do not significantly perturb the GOE in this reaction. Within our model, there can be a near-threshold bound or virtual state of the neutron channel that changes the energy dependence of the average neutron width from the usual $\sqrt{E}$ form, as proposed by H. A. Weidenmüller [2]. In this case, the reduced neutron width distribution extracted with the $\sqrt{E}$ form is significantly broader than the PTD. We identify a narrow range of model parameters for which this effect is significant, as well as a measurable signature of such a near-threshold state.


**Beyond Hauser-Feshbach / 45**

**Moldauer’s sum rule implies superradiance in compound nuclear reactions**

Brown David$^1$; Mike Herman$^1$; Gustavo Nobre$^1$

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We apply Moldauer’s “sum rule for resonance reactions” to compute the neutron transmission coefficients in the Resolved and Unresolved Resonance regions, allowing a direct comparison with the transmission coefficients computed using an optical model potential. For nuclei for which there are no measured resonances, our approach provides a scheme to predict the average neutron resonance parameters directly from the optical model and level densities. Our approach is valid in both the strong and weak coupling limits (i.e., any value of $\langle \Gamma_0/D \rangle$). Finally, our approach suggests that superradiance, that is, the quantum chaotic enhancement of certain channels, may be a common phenomena in nuclear collisions and our approach suggests why it has been previously overlooked. We apply our approach to neutron reactions on the closed shell $^{90}$Zr nucleus.

**Experiments / 84**

**FRIB: Scientific opportunities and status**

Alexandra Gade$^1$

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One goal of nuclear physics is a comprehensive understanding of the properties of nuclei and nuclear matter from the interactions of the constituent proton and neutron degrees of freedom. This quest for a reliable model of the atomic nucleus is at the brink of a revolution. An ever increasing range of rare isotopes becomes available for highly sensitive experiments that isolate specific features of the nuclear many-body problem. This presentation will showcase some of the opportunities that will advance our understanding of nuclear structure and reactions once the Facility for Rare Isotope Beams (FRIB) comes online at Michigan State University. The present status of the facility will be presented.
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**Single-nucleon transfer reactions**

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Over the last two decades transfer reactions have seen a resurgence following developments in methods to use them with exotic beams. Our collaboration took an important step in this evolution by using the (d,p) reaction on fission fragment beams in inverse kinematics [1-3].

There has been renewed interest in using (9Be, 8Be) and (13C, 12C) reactions to selectively populate single-particle like states that can be studied via their subsequent \(\gamma\) decay. These reactions have been successfully utilized in the 132Sn region [4-6]. Another direction we have been pursuing is measuring neutrons from (d,n) reactions, performed in inverse kinematics, with the VANDLE array of plastic scintillators. I will present an overview of these new techniques and the complementary information that can be gained from transfer reactions in relation to compound nuclear reactions.

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**Capabilities of the NIFFTE fissionTPC**

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The fissionTPC is a compact, two-volume time-projection chamber built by the Neutron-Induced Fission Fragment Tracking Experiment (NIFFTIE) collaboration, and is designed to enable precise fission cross section ratio measurements such as \(238\text{U(n,f)}/235\text{U(n,f)}\) and \(239\text{Pu(n,f)}/235\text{U(n,f)}\). The reconstruction of three-dimensional charge clouds provides the energy, angle, and specific ionization of detected charged-particles, which can be used for particle identification. The differential contributions to the fission cross section are integrated using the distributions of target material, neutron beam, and detected fissions fragments. The unique information available with fissionTPC measurements allows for precise determination of particle detection efficiency, but reveals a need for nuclear theory even during data analysis, e.g. the impact of pre-equilibrium neutron emission on the detected fission distribution. A description of fissionTPC measurements, along with the capabilities and limitations of the technique will be presented. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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Nuclear level densities: from empirical models to microscopic methods

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The level density is among the most important statistical nuclear properties. It is required in the calculation of transition rates using Fermi’s golden rule, and is an important input to the Hauser-Feshbach theory of compound nuclear reactions. It has many applications in diverse areas such as stellar nucleosynthesis and nuclear reactor technology. We discuss the experimental techniques used to measure level densities and the main theoretical approaches to calculating them. Phenomenological models of level densities are often based on empirical modifications of the Fermi gas model and on the constant temperature formula. The microscopic calculation of level densities in the presence of correlations is a challenging many-body problem. Mean-field and combinatorial methods have been applied across the nuclear chart, but often have to be augmented with empirical collective enhancement factors. The moment method and the auxiliary-field quantum Monte Carlo (AFMC) method have been formulated in the context of the configuration-interaction (CI) shell model approach, and include correlations beyond the mean-field approximation. The moment method has been applied to light and medium-mass nuclei, while AFMC has been applied to nuclei as heavy as the lanthanides. We also present a novel method for calculating the dependence of the level density on deformation in the rotationally invariant framework of the CI shell model without invoking a mean-field approximation.

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Problem of level densities in compound nuclear reactions

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Different level density models are used as an input in Hauser-Feshbach model to calculate reaction cross section for various needs. All models are mainly based on Fermi-gas or Gilbert and Cameron prescriptions. The parameters such as the level density parameter \( a \), the pairing shift \( \Delta \), the spin cutoff parameter \( \sigma \), the temperature \( T \) are found using experimental data on neutron resonance spacings and the density of discrete low-lying levels known from spectroscopic experiments. There are many different parameterizations developed to calculate the nuclear level density in a wide mass range. The vulnerability of such approach consists of the fact that neutron resonance spacings are known only for a very limited spin and excitation energy range. Such limitations might lead to uncertainties of calculated level densities in other spin and excitation energy ranges important for reaction cross section calculations. There are also uncertainties associated with an analysis of neutron resonance data which requires accurate accounting for missing resonances which is not always a straightforward procedure. The experimental information on the spin distribution is scarce so purely model approach is used. The question that will be addressed in this talk is to what extent available models based on neutron resonance data are able to describe double differential cross sections of nuclear reactions involving light particles, specifically particles evaporating from compound nuclear reactions. Recent experimental data obtained from the Edwards Accelerator Laboratory on particle evaporation spectra will be shown in comparison with calculations based on widely used level density models. Discrepancies were found and possible source of these discrepancies will be discussed.

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Gamma Strength Functions and the Brink-Axel Hypothesis

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Basically all applications of gamma strength functions (GSFs) for the calculation of statistical reaction cross sections depend on the Brink-Axel (BA) hypothesis, which states that the GSF is independent of initial and final states. There are two major sources of experimental data on the GSF, viz. measuring the γ cascade after compound reactions and extracting the distribution of primary γ rays (the so-called Oslo method) and ground-state absorption experiments using either real or virtual photons. Since most available data are of the latter type, it is of crucial importance whether the BA hypothesis holds for photabsorption from the ground state. Recent experimental results clearly indicate violations of the BA hypothesis like a systematic low-energy enhancement of the GSF in Oslo-type data and a much larger orbital M1 strength (scissors mode) in γ decay compared to absorption experiments. In my contribution I will discuss recent experimental tests of the BA hypothesis with an emphasis on the energy region near neutron threshold, which is of particular importance for astrophysical reaction network calculations of neutron-induced nucleosynthesis in the s- and r-process.

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γ-ray Strength Functions and Partial GDR Cross Sections in the IAEA Photonuclear Data Project

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We review the latest development of measuring γ-ray strength functions and partial GDR cross sections for the IAEA photonuclear data project [1] at the NewSUBARU synchrotron radiation facility. γ-ray strength functions (γSFs) are investigated with the γSF method [2] and the Oslo method [3,4]; (γ,n) cross sections are used as experimental constraints on the model E1 and M1 γSFs from the Hartree-Fock- Bogolyubov plus quasi particle-random phase approximation based on the Gogny D1M interaction supplemented with the M1 upbend in the former and on the experimental information on γSFs below neutron threshold deduced by the Oslo method in the latter. The investigation includes isotopic chains of Ni, W, Zn, and Gd. Partial GDR cross sections are measured for 11 nuclei from 98Be to 209Bi by direct neutron-multiplicity sorting with a flat-response neutron detector [5] toward a goal of resolving the long-standing discrepancy between the Livermore and Saclay data [6]. We present γSFs and partial GDR cross sections, including those for the Ni isotopic chain [7] and updated for 209Bi [8].

[1] https://www-nds.iaea.org/CRP-photonuclear/

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Systematic investigations of γ-ray strength functions across the nuclear chart within the shell model

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γ-ray strength functions are one of the key nuclear physics inputs to constrain \((n, \gamma)\) cross-sections for unstable nuclei relevant to different neutron-capture nucleosynthesis processes. This is of particular importance for the \(r\) process, where the process flow proceeds through neutron-rich nuclei far from stability. It has been shown that the presence of a low-energy enhancement, seen experimentally in many nuclei including neutron-rich ones, could impact the capture cross sections by orders of magnitude, which could in turn severely impact reaction network model predictions.

I present a systematic study using large-scale shell model calculations of the low-energy \(M1\) γ-ray strength function for many isotopic chains above the \(^{16}\text{O}\) and \(^{56}\text{Ni}\) doubly-magic closed cores. The strength and slope of the low-energy enhancement varies with proton and neutron number in systematic ways, from being very pronounced near shell closures to almost disappearing in mid-shell regions. I compare the calculations to strength functions compiled from experimental data in the different mass regions and observe excellent agreement. I discuss possible explanations for the systematic behaviour, its connection to other facets of nuclear structure such as deformation and magnetic rotations, and the implications if this behaviour extends all across the nuclear chart.

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Constraining level densities using spectral data

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Several models of level densities exist and they often make simplified assumptions regarding the overall behavior of the total level densities and the intrinsic spin and parity distributions of the excited states. Normally, such LD models are constrained only by the measured \(D_0\), i.e. the density of levels at the neutron separation energy of the compound nucleus (target plus neutron), and the sometimes subjective extrapolation of discrete levels. In this work we use microscopic Hartree-Fock-Bogoliubov (HFB) level densities, which intrinsically provide more realistic spin and parity distributions, and associate variations predicted by the HFB model with the observed double-differential cross sections at low outgoing neutron energy, region that is dominated by the LD input. With this approach we are able to perform fits of the LD based on actual experimental data, constraining the model and ensuring its consistency. This approach can be particularly useful in extrapolating the
LD to nuclei for which high-excited discrete levels and/or values of $D_0$ are unknown. It also predicts inelastic gamma ($\gamma, n'$) cross sections that in some cases can differ significantly from more standard LD models such as Gilbert-Cameron.

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**Multinucleon transfer mechanisms studied by antisymmetrized molecular dynamics**

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Recently, a group in Japan is actively pursuing the surrogate method using $^{18}$O projectile on heavy nuclei $^{232}$Th, $^{238}$U, $^{237}$Np and $^{242}$Cm to extract fission properties such as mass distribution of fission fragments and prompt neutron spectra over many populated compound nuclei, and Langevin theory is applied to analyze the data. In this analysis, however, we need detailed knowledge on the population mechanisms of each compound nucleus, which are populated by multinucleon transfer reactions induced by $^{18}$O. Especially, the spin distribution of each compound nucleus at specific excitation energy bin must be properly understood. We will present our resent analysis based on antisymmetrized molecular dynamics.

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**Microscopic modeling of direct and pre-equilibrium mechanisms for nucleon induced reactions**

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The modeling of direct inelastic and pre-equilibrium nuclear reaction mechanisms play a key role to account for nucleon induced reaction observables for incident energies above a few hundred keV. Microscopic models have been developed to describe those mechanisms using a description of target states provided by beyond mean field approaches, such as the (quasi-particle) random-phase approximation [(QRPA)] [1]. Direct inelastic scattering to target excitations built from one-phonon (QRPA) states account simultaneously for direct inelastic scattering to discrete states, and pre-equilibrium emission as far as second order processes, that involve more complex excitations, and multiple emission remain negligible.

In this talk, we will review the work performed on proton or neutron induced reaction on spherical [2] and axially deformed nuclei [3] based on the modeling described above. For spherical nuclei, DWBA calculations were performed and simultaneously account for direct inelastic scattering to low energy collective states and giant resonances, and for the one-step-direct component of pre-equilibrium emission. According to the nucleon incident energy, various effective in-medium NN interactions, that represent the residual interaction between the nucleon projectile and one target nucleon, are considered. For energies below $40$–$MeV$, we used the Melbourne g-matrix, and for lower energies, the density dependent M3Y interactions and/or the effective interaction from the JLM folding model. For axially deformed target, calculations were performed for neutron induced reaction...
below 30-MeV. In this case, we used the JLM folding model, and the rotational approximation, to obtain the coupling potentials relevant to the scattering problem within the coupled channel framework. We will focus on the last results obtained for $^{232}$Th and $^{238}$U(n,2n$^{\gamma}$) reactions. Finally, we will discuss the ongoing work performed to account for two-step direct processes considering two-particle two-hole/two phonons excitations. We will also discuss various possible improvements of the present modeling of the one-step process such as a microscopic calculation of energy shift and damping widths of (Q)RPA states, and of non-natural parity excitations in the case of axially deformed nuclei.


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Multi-step direct reaction models including collectivity in nucleon induced reactions

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Nucleon-induced pre-equilibrium reactions are now recognized as consisting almost exclusively of direct reactions in which incident nucleons induce excitations over a wide range of energy in the target nuclei. At low energies, one step reactions dominate. As the incident energy increases, multi-step reactions become important too. Tamura, Udagawa and Lenske pioneered the use of the RPA response function to describe the nuclear excitation in calculations of one-plus-two-step reactions of this type [1]. Modern calculations can describe both the excitation of low-energy collective states and the more uniform higher energy part of the spectrum, but are limited to a single direct interaction step [2]. However, it has been argued that the time scale of the two-step reaction is too short to permit the residual interaction to modify the response function to the RPA one [3]. Explicit calculations corroborate this conclusion [4]. The response function in this case would then be better approximated by the bare particle-hole one [5, 6]. Our objective here is to analyze the properties of the RPA response function and compare these to those of the bare particle-hole one.

We used the Skyrme RPA code of G. Coló and collaborators [7] to study the collective and non collective excited states within the RPA for several nuclei and spin/parity from 1+ to 5−. By our definition, collective states show larger (or smaller) than average transition strengths, spread over a large number of particle-hole states and tend to be shifted in energy. We find them to be interspersed with non-collective state up to an energy of about 20 MeV in our calculations, although we could define no clear separation point between the states we considered collective and those we did not. At higher energies, the RPA excited states are predominantly well-localized particle-hole states of an average width that grows roughly with the square of the excitation energy. The non-collective states satisfy the statistical assumption of Tamura, Udagawa and Lenske in the sense that an average over the RPA modes in an energy range of a few times the average width of the modes reduces to an incoherent sum over the underlying particle-hole modes. The average RPA transition strengths and widths of the states were found to be independent of the spin and parity .

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Constraining astrophysical processes through statistical decay data

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iThemba LABS has embarked on an extensive renewal program with the ultimate goal to provide the users with competitive and state-of-the-art research facilities for nuclear physics experiments. In particular, significant developments on the high-energy neutron beam facility, the K600 spectrometer and the ALBA and AFRODITE gamma-ray arrays have taken place. These are anticipated to significantly improve and make possible new measurements of nuclear properties which are of relevance to nucleosynthesis. For instance, the development of the inverse-Oslo method [1] to extract the photon strength function (PSF) and nuclear level density (NLD) from inverse kinematic reactions provides a powerful tool to study statistical properties for a wide range of nuclei, which were previously inaccessible at stable and radioactive ion beam facilities. Several such PSF and NLD measurements on Kr and Xe isotopes, which are of interest to s-process nucleosynthesis, have already been performed. Furthermore, measurements of the PSF and NLD at the University of Oslo have recently provided new constraints on the production of the p-nuclei 138La [2,3] and 180Ta [4].

In this presentation, I will provide an overview of our experimental capabilities at iThemba LABS, in particular in the context of ongoing and future measurements to obtain PSF, NLD and resonance data which are of importance to nucleosynthesis studies. I will further discuss our work to use the electromagnetic responses of the 138La and 180Ta p-nuclei to constrain reaction rates at p- and s-process temperatures.

References

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Impact of restricted spin-ranges in the Oslo Method on the example of (d,p)240Pu

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The Oslo Method [1, 2] can be used to extract nuclear level (NLD) densities and $\gamma$-ray strength function ($\gamma$SF) below the neutron separation energy from transfer reactions. Over the last decade, data for various nuclei has been obtained using the (d, p) reaction, where the reaction is chosen mostly for its high cross-sections and ease of beam production. However, it was also recognized that deuterons induced reactions transfer little spin, thus populating only a fraction of the available levels in the nucleus [3, 4]. The difference depends on the specific nucleus and excitation energy considered and may limit the validity of the Oslo Method.

This contribution is the first systematic analysis of the impact of the populated ($J_{\text{pop}}$) vs. underlying ($J_{\text{int}}$) spin distribution on the NLD and $\gamma$SF retrieved through the Oslo Method. Here, the case of (d, p)$^{240}$Pu with a 12 MeV deuterium beam is considered, but the presented approach is generally applicable. The Monte-Carlo nuclear decay code RAINIER [5] is used for a sensitivity study: Provided with an underlying NLD and $\gamma$SF model, $\gamma$-decay cascades are generated for either i) $J_{\text{pop}} = J_{\text{int}}$ or ii) $J_{\text{pop}}$ derived from theory. To calculate the latter, we used the distorted-wave Born approximation in prior form [6, 7]. The Oslo Method is performed on each of the cascades and the resulting NLD and $\gamma$SF are compared to the known ("true") input. The results confirm the importance of knowledge of the populated spin distribution $J_{\text{pop}}$ and shows that without correction, the NLD and $\gamma$SF may deviate significantly for nuclei in the actinide region.


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Neutron Capture on Actinides studied with DANCE
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Neutron capture cross sections in the continuum region above 1 keV have been difficult to calculate accurately. Measurements are usually relied on for accurate cross sections, although calculations normalized to the measured resonance parameters \( \langle l \rangle / \langle l \rangle \) can give reasonable estimates. The Detector for Advanced Neutron Capture Experiments (DANCE) has been used to make neutron capture measurements on \( ^{234,235,236,238} \text{U} \) and \( ^{238,239,242} \text{Pu} \) at neutron energies up to 500 keV, and has resolved some discrepancies in the \( ^{235} \text{U} \) and \( ^{239} \text{Pu} \) capture cross sections. In addition, measurements of the gamma-ray emission spectra from capture have provided constraints on the radiative strength function used in calculations. Some previous results and \( \text{U} \) and \( \text{Pu} \) capture cross sections and spectra will be reviewed, and new results for gamma-ray spectra from \( ^{239} \text{Pu} \) will be presented.

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**Statistical gamma decay of \( ^{168} \text{Er} \) from resonance neutron capture**

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Analysis of \( \gamma \)-ray spectra from slow neutron radiative capture is one of the methods to study \( \gamma \) decay in heavy nuclei. The Detector for Advanced Neutron Capture Experiments (DANCE), the ball of \( \text{BaF}_2 \) crystals located at Los Alamos National Laboratory, is then a very good instrument for precise coincident detection of complete \( \gamma \) cascades because of its high segmentation and efficiency.

The DANCE detector was used for a measurement of \( \gamma \)-ray spectra for different multiplicities following the radiative capture on well-isolated \( s \)-wave neutron resonances of \( ^{167} \text{Er} \). The resonances were identified using the time-of-flight technique. The main aim of our analysis is to get information on nuclear level density and photon strength functions - quantities that are used in description of the \( \gamma \) decay within the statistical model of the nucleus. To obtain results on these quantities, experimental spectra were compared with statistical model simulations using DICEBOX code. It was found that the photon strength functions describing the coincidence \( ^{168} \text{Er} \) spectra are consistent with those reproducing such spectra in other well-deformed rare-earth nuclei.

Our experimental data also allow to check the population of \( K \) isomer at excitation energy 1094 keV in \( ^{168} \text{Er} \) whose half-life is about 100 ns. The measured population shows up to be significantly higher than the population predicted within the statistical model using reasonable models of nuclear level density and photon strength functions.

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**A Grand Tour of Nuclear Fission Physics**
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From its discovery in the 1930’s to the present day, understanding nuclear fission remains a daunting challenge for theorists and experimentalists alike. At the same time, the fission process plays an important role in a variety of basic and applied nuclear science problems. For experimentalists, fission produces a treasure trove of observable signals, including gammas, neutrons, and a wide range of fission fragments that can be recorded and studied. The simultaneous detection of these signals provides an invaluable window into the fission process, but is difficult to carry out in practice. For theorists, the challenge lies in describing a complex, dynamical process that represents one of the more extreme examples of large-amplitude collective motion. This talk will present a brief overview of both experimental and theoretical investigations of the fission process, in order to showcase the richness of this phenomenon and its connection to a variety of nuclear physics topics.

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The role of spin in compound nuclear reactions leading to heavy element formation

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Compound nuclear reactions (CNRs) are characterized by the fact that the mode of decay of the compound nucleus is independent of the mode of formation, the so-called Bohr Independence Hypothesis or “amnesia assumption”. However, when considering CNRs to synthesize the heaviest nuclei, it is important to recognize the limits on the entrance channel of the reaction imposed by the spin-dependent survival probabilities of the products. The cross section for producing a heavy evaporation residue, $\sigma_{\text{EVR}}$, in a fusion reaction can be written as

$$\sigma_{\text{EVR}}(E) = \frac{\pi \hbar^2}{2mE} \sum_{\ell = 0}^{\infty} (2\ell + 1)T(E, \ell)P_{\text{CN}}(E, \ell)W_{\text{sur}}(E, \ell)$$

where $E$ is the center of mass energy, and $T$ is the probability of the colliding nuclei to overcome the potential barrier in the entrance channel and reach the contact point. $P_{\text{CN}}$ is the probability that the projectile-target system will evolve from the contact point to the compound nucleus. $W_{\text{sur}}$ is the probability that the compound nucleus will decay to produce an evaporation residue rather than fissioning. However, one must remember that the $W_{\text{sur}}$ term effectively sets the allowed values of the spin, which in turn, restricts the values of the capture cross sections and fusion probabilities. For a series of ~ 250 reactions leading to heavy evaporation residues with $Z_{\text{CN}} \leq 112$, we point out the implications of this fact. The survival-mediated capture cross sections for a series of ~ 250 heavy-element synthesis reactions have a mean associated spin of ~ $\sim 5$ $\hbar$ even though the capture cross sections have mean spins ranging from 10 $\hbar$ to 70 $\hbar$. Similar constraints can be be placed on the outcome of multi-nucleon transfer reactions used to synthesize new $n$-rich heavy nuclei. By comparing measured and calculated values of evaporation residue cross sections, one can deduce the fusion probabilities for heavy element reactions where $P_{\text{CN}} \approx 1$.

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Theoretical Description of Fission at Increasing Excitation Energy

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Since its discovery in the late nineteen thirties, nuclear fission has remained one of the most complex and elusive problems in physics. Gaps in our understanding of this phenomena can impact progress in other areas ranging from simulations of nucleosynthesis in astrophysical environments to energy production. In an ideal world, a predictive theory of fission should be based solely on quantum many-body methods and our best knowledge of nuclear forces. Today, there is a consensus that the nuclear energy density functional theory (DFT) is probably the best framework to achieve a microscopic description of fission. The computing power available at existing leadership computing facilities is now sufficient to test the predictive power of DFT and this has triggered a spectacular renaissance of fission studies. After a brief introduction to the DFT description of fission and a quick survey of recent results, I will discuss in more details some current problems related to computing fission properties at low- to moderate excitation energies.

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Event-by-Event Fission Modeling with FREYA

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For many years, the state of the art for handling fission in radiation transport codes has involved sampling from average distributions. However, such “average” fission models have limited interaction-by-interaction capabilities. Energy is not explicitly conserved and no correlations are available because all particles are emitted isotropically and independently. However, in a true fission event, the energies, momenta and multiplicities of emitted particles are correlated.

Recently, several Monte Carlo codes have become available that calculate complete fission events. Event-by-event techniques are particularly useful because it is possible to obtain the fission products as well as the prompt neutrons and photons emitted during the fission process, all with complete kinematic information. It is therefore possible to extract any desired observables, including correlations.

The fast event-by-event fission code FREYA (Fission Reaction Event Yield Algorithm), one such code, generates large samples of complete fission events. FREYA employs only a few physics-based parameters. We discuss recent results on parameter optimization and validation. We compare our FREYA results with available data on prompt neutron and photon emission, including available correlation data.

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The investigation of properties of scission point in reactions of $^{48}$Ca$^{+208}$Pb

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The understanding of properties of scission point is an important aspect in the study of spontaneous fission and induced fission reactions. They play an essential role in the production of fission fragments from the separation of parent nuclei. However, the formation process of scission point is very complicated and closely related with the effects of the interplay between nuclear structure and nuclear reaction mechanisms. It is difficult to directly investigate the properties of scission points. The only way so far is to derive them from the observations of fission fragments. Since 1970s, different observations, including the angle between emitting $\alpha$ particle and light fragments and the velocities of fragments, had been used to reconstruct the configuration of scission point.

Angular correlations between fission partners in each event can be directly related to the dynamical process of the separation of parent nuclei and used to understand the properties of scission point in fission reactions. In this work, angular correlations between fission fragments produced in $^{48}$Ca$^{+208}$Pb performed at Argonne National Laboratory at incident energies of 285MeV are measured. In order to reproduce the experimental data of angular correlations between fission partners, the microscopic transport model (Quantum Molecular Dynamics model) are applied to simulate the reactions from the collision between projectile and target to the formation of scission point and the production of primary fragments. We find that angular correlations between fission fragments are directly related with the configuration of scission point and the scission point is further sensitive to the properties of nuclear matter.

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The Evolution of Triaxial Shapes in A$\approx$110 Fission Fragments

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Neutron-rich nuclei with mass around A$\approx$100 exhibit a rapid change of nuclear deformation and collectivity. A sudden onset of deformation is observed for the Sr and Zr isotopes at neutron number N=60, whereas the transition is more gradual for elements with higher atomic number around A$\approx$110. The measurement of electromagnetic transition rates in this sensitive region sheds more
light on the shape of these fission fragments and represents a stringent test for predictions of theoretical nuclear structure models.

Neutron-rich nuclei were produced in experiments at GANIL by fusion-fission reactions between $^{238}$U projectiles and a $^{9}$Be target at 6.2 MeV per nucleon. The fission fragments, which were identified in mass, charge, and atomic number using the magnetic spectrometer VAMOS++, were correlated with prompt $\gamma$ rays that were detected around the target position. A first experiment used the EXOGAM array of Ge Clover detectors for the detection of $\gamma$ rays, which was later replaced by the $\gamma$-ray tracking array AGATA in a second experiment. The velocity of the fission fragments exiting the target foil was slowed down using a degrader foil at variable short distances from the target to determine lifetimes of excited states in the picosecond range using the recoil-distance Doppler shift method. The settings of the VAMOS++ magnetic spectrometer were chosen to maximize the transmission of the most neutron-rich fission fragments ranging from Sr (Z=38) to Pd (Z=46). The first experiment with EXOGAM has so far yielded more than 30 new lifetimes in both even-even and odd-even nuclei [1-4]. The second experiment with AGATA yielded much higher statistics, which will allow extracting many more lifetimes.

In this contribution we will focus on odd-mass isotopes of Y, Nb, Tc, and Rh with N≥60. These nuclei exhibit a variety of rotational bands based on the coupling of the odd proton with the strongly deformed even-even core. From the measured lifetimes and branching ratios it was possible to extract absolute $B(M1)$ and $B(E2)$ transition probabilities, which yield information about the underlying proton configuration and deformation of the core, respectively. A comparison between the experimental results and triaxial particle-rotor calculations indicates a gradual increase of triaxiality with atomic number Z from axially symmetric shapes for $^{99}$Y and $^{101}$Y to almost maximum triaxiality for $^{111}$Rh and $^{113}$Rh. In addition to lifetimes and spectroscopic nuclear structure data, the $\gamma$-ray data for mass-identified fission fragments may contain also information that can contribute to a better understanding of the fusion-fission process.


Nuclear structure / 57

Deconvolution of the Photon Strength Function

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The photon strength function, commonly measured in photonuclear and charged particle reaction experiments, is actually a product of gamma-ray strength and level density. At higher energies it is dominated by E1 transitions whose average photon strength is well described by the Brink-Axel equation based on the energy, width, and cross section for the Giant Dipole Resonance (GDR). Individual photon strengths vary by a Porter-Thomas distribution about the average photon strength. Remarkably this E1 photon strength function depends only on the gamma-ray energy and GDR properties. It is independent of all other nuclear structure considerations. Average transition strengths for other multipo极ities and other kinds of E1 transitions do not follow a giant resonance description and their individual photon strengths do not follow a Porter-Thomas distribution. In this talk I will describe how to deconvolute the photon strength function into its component gamma-ray strength and level density functions. This provides new insight into the origin of the GDR. The gamma-ray strength functions for the isotopes $^{92-101}$Mo are shown to be remarkably similar and consistent with Average Resonance Capture (ARC) photon strengths after correction for their expected spin dependence. I will also show how Oslo reaction data, which correctly describes the photon strength function below the neutron separation energy, can be deconvoluted to determine the gamma-ray strength. These results show excellent agreement with E1(GDR) predictions at intermediate energies, excess gamma-ray strength at low energies, possibly due to M1 enhancement, and, in some
cases, excess gamma-ray strength near the neutron separation energy, possibly due to the contribution of spin-flip and/or pygmy resonances.

Nuclear structure / 49

**Attempting to close the loop on the Oslo technique at 198Au: Constraining the nuclear spin distribution**

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The Oslo technique obtains energy-dependent nuclear level densities (NLD) and photon strength functions (PSF) after calibration of the data to the average spacing and total radiation width for s-wave neutron resonances in the same nuclide. It is straightforward [1] to use the obtained NLD and PSF to calculate, in the framework of the nuclear statistical model (NSM), the expected distributions of total radiation widths in the same nuclide. From simultaneous R-matrix analysis of new neutron total-cross-section data at the Los Alamos Neutron Science Center and previous total and capture data [2,3], we obtained total radiation widths for 77 (33 J=1 and 44 J=2) 197Au+n resonances. Total-radiation-width distributions calculated according to the NSM using the Oslo NLD [4] and PSF [5] disagree with our data; the calculated distributions are too narrow and too close together for the two spins. The calculation can be brought into agreement with the data by substantial modifications to the spin distribution in 198Au as a function of excitation energy. As far as we know, the spin distribution currently is otherwise poorly constrained. However, this technique could be applied to other odd-A nuclides to test and constrain spin-distribution models (e.g. [6]). The modified spin distribution changes the shapes of the NLD and PSF extracted using the Oslo technique and so could have broad implications.


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**Rotational enhancement factor for nuclear level densities**

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Analysis of nuclear level densities for deformed nuclei based on resonance counting for low-energy neutron resonances have tended to show a low rotational enhancement factor. A recent paper concluded that Bethe spin distribution formula does not apply for deformed nuclei. Use of a corrected form produces enhancement factors more consistent with theoretical expectations.
Pairing properties from random distributions of single-particle energy levels

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Exploiting the similarity between the bunched single-particle energy levels of nuclei and of random distributions around the Fermi surface, pairing properties of the latter are calculated to establish statistically-based bounds on the basic characteristics of the pairing phenomenon. When the most probable values for the pairing gaps germane to the BCS formalism are used to calculate thermodynamic quantities, we find that while the ratio of the critical temperature \( T_c \) to the zero-temperature pairing gap is close to its BCS Fermi gas value, the ratio of the superfluid to the normal phase specific heats at \( T_c \) differs significantly from its Fermi gas counterpart. The largest deviations occur when a few levels lie closely on either side of the Fermi energy but other levels are far away from it. The influence of thermal fluctuations, expected to be large for systems of finite number of particles, were also investigated using a semiclassical treatment of fluctuations. When the average pairing gaps along with those differing by one standard deviations are used, the characteristic discontinuity of the specific heat at \( T_c \) in the BCS formalism was transformed to a shoulder-like structure indicating the suppression of a second order phase transition as experimentally observed in nano-particles and several nuclei. Contrasting semiclassical and quantum treatments of fluctuations for the random spacing model is currently underway.

Poster Session / 7

Symmetry energy: A source for determining the surface properties of finite nuclei

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The present study establish a correlation between the neutron skin thickness and the nuclear symmetry energy for the even–even isotopes of Fe, Ni, Zn, Ge, Se and Kr. The axially deformed self-consistent relativistic mean field for the non-linear NL3* and density-dependent DD-ME1 interaction parameters are used for the analysis. The coherent density functional method is adopted to formulate the symmetry energy, the neutron pressure and the curvature of finite nuclei as a function of the nuclear radius. We have performed broad studies for the mass dependence on the symmetry energy in terms of the neutron-proton asymmetry for mass \( 70 \leq A \leq 96 \). From this analysis, we found a notable signature of a shell closure at \( N = 50 \) in the isotopic chains of Fe, Ni, Zn, Ge, Se and Kr nuclei. The present study reveals an interrelationship between the characteristics of infinite nuclear matter and the neutron skin thickness of finite nuclei

Poster Session / 13

Temperature dependence of nuclear level density and the role of collective excitations.

Pratap Roy¹
Study of nuclear level density (NLD) has been an old but active area of research in nuclear physics. An accurate determination of NLD is required for the quantitative estimation of a number of nuclear processes like evaporation, fission, multi-fragmentation, and spallation. Moreover, knowledge of NLD, in turn, provides useful information about the nuclear structure and n-n interaction. There have been many recent investigations that generated renewed interest in investigating the dependence of NLD on different nuclear factors. The excitation energy (U) or temperature (T) dependence of the level density parameter (a) has recently been investigated experimentally by measuring neutron evaporation spectra in case of several nuclei using $^4$He-ion beams from the K130 cyclotron at VECC. The nuclei studied can be categories into two groups (1) spherical or near-spherical nuclei and (2) nuclei having large ground state deformation. It is observed that the general trend of the experimental data on energy dependence can reasonably be described by the relationship $k(U) = k_0 + \kappa(U/A)$, where $k = (A/a)$ is the inverse level density parameter. The value of $\kappa$ was found to be strongly dependent on the mass number (A). It is also observed that the temperature dependence of $\kappa$ can mainly be accounted for by the temperature dependence of the effective nucleon mass ($m^*$). Interesting fluctuations of the extracted $k$-values and the measured temperatures were observed in case of nuclei having large ground state deformations. The observed nature could be connected with the fadeout of collective enhancement in NLD where the level density is expected to exhibit a kink or at least a plateau as a function of excitation energy. The existence of collective enhancement in NLD at low energies was also confirmed from the simultaneous measurement of high energy $\gamma$-ray (GDR) and neutron evaporation spectra in case of highly deformed $^{169}$Tm compound nucleus. Large yields in both the neutron energy spectrum (beyond 5 MeV) and the GDR $\gamma$-ray spectrum (around 16 MeV) was observed. The enhancement could only be reproduced by including a collective enhancement factor in the Fermi gas model of NLD to explain the neutron and GDR spectra simultaneously. The experimental observations were compared with recent theoretical calculations. The detail of the experiment and important results will be discussed during the conference.

Poster Session / 18

Underground Nuclear Astrophysics: present and future of the LUNA experiment

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The evolution of all the celestial bodies is regulated by gravitation and thermonuclear reaction rates, while the Big Bang nucleosynthesis is the result of nuclear processes in a rapidly expanding Universe. The LUNA Collaboration has shown that, by exploiting the ultra low background achievable deep underground, it is possible to study the relevant nuclear processes down to the nucleosynthesis energy inside stars and during the first minutes of Universe. In this talk the main results obtained by LUNA are overviewed, as well as the scientific program of LUNA with the forthcoming 3.5 MV underground accelerator. In particular I will discuss the recent study of the $d(p, \gamma)^3He$ reaction, whose cross section has been measured around $E_{cm}=100$ keV, i.e. inside the Big Bang Nucleosynthesis energy region. The importance of this measurement in cosmology, particle physics and theoretical nuclear physics is also discussed.

Poster Session / 22

A Cross Section Measurement of the $^{13}C(d, n)^{14}N$ Reaction—A Beam-Induced Background in Underground Nuclear Astrophysics Ex-
Permutations

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The $^{13}$C($\alpha$,n)$^{16}$O reaction is the primary source of neutrons for the main branch of the slow neutron capture process (s-process) of stellar nucleosynthesis. At stellar temperatures, the reaction proceeds at very low energies, and as such, direct measurement of the cross section within the Gamow window (140-230 keV) is difficult due to low yields. Previous measurements of the $^{13}$C($\alpha$,n)$^{16}$O reaction have constrained the cross section down to 279 keV in the center-of-mass frame, but with large statistical uncertainties [1]. These uncertainties, compounded by the unknown influence of a $^{17}$O near the $\alpha$-capture threshold, make extrapolation into the Gamow window unreliable, necessitating further measurements at low energies. Measurement is additionally complicated by beam-induced background from the $^{13}$C($d,n)$¹⁴N reaction, the result of deuterium contamination in the $\alpha$-particle beams of most accelerators. At astrophysical energies, the $^{13}$C($d,n)$¹⁴N cross section is many orders of magnitude greater than that of $^{13}$C($\alpha$,n)$^{16}$O, thus requiring direct measurement of $^{13}$C($d,n)$¹⁴N in the energy range of interest. Accordingly, the $^{13}$C($d,n)$¹⁴N cross section was measured at laboratory energies between 165 and 250 keV—corresponding to $\alpha$-beam energies between 230 and 500 keV—at Oak Ridge National Laboratory’s Multicharged Ion Research Facility. An array of NaI(Tl) scintillators was mounted for direct measurement of the characteristic $\gamma$-decay of excitations populated in $^{14}$N and as active shielding from cosmic rays. Preliminary results and the implications of this work are discussed.

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Poster Session / 23

Measurement of the excitation functions on zirconium induced by alpha particles up to 46 MeV

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$^{99}$Tc/$^{99}$Mo is one of the most important radioisotopes used in nuclear medicine for common diagnostic imaging technologies such as single photon emission computed tomography (SPECT). After the worldwide shortage of $^{99}$Tc/$^{99}$Mo due to the long shutdowns of major nuclear research reactors in 2009-2010, some alternate sources of $^{99}$Tc/$^{99}$Mo using accelerators have been investigated for stable supply of $^{99}$Tc/$^{99}$Mo. In this study, we focused on the production route of $^{99}$Mo via the $^{96}$Zr($\alpha,n$)$^{99}$Mo reaction using a low energy accelerator. In order to estimate the production yield of
99Mo and the byproduct radioisotopes, we irradiated 24.6 and 46.4 MeV alpha particles onto stacked natZr targets at a cyclotron facility (NIRS-930), National Institutes for Quantum and Radiological Science and Technology, Japan. The stack targets were composed of natural zirconium foils (0.005 mm) and natural titanium foils (0.005 mm) which acted as a beam monitor. The total target thickness was thicker than the range of projectile alpha particles to measure the beam current on the targets. After irradiation, gamma-rays from each foil were measured with a HPGe detector. The production rates of radionuclides as well as 99Mo in natZr samples are determined by a gamma-ray spectroscopy. The excitation function was deduced from the production rates of radionuclides by taking into account the projectile energies on each natZr foil degraded in the stacked target. In this workshop, we will present these experimental data, in comparison with other experimental data and calculations.

**Poster Session / 25**

**Excitation function measurements of alpha-induced reaction on natural copper and titanium up to 46 MeV**

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The activation cross section data are required for isotope production, activation detector, residual activity assessment and so on, although experimental data are very scarce for heavy ions. We therefore irradiated a target with 46.4 MeV alpha beam to obtain excitation functions of residual radionuclides in Ti and Cu. Irradiation experiment was performed at cyclotron facility (NIRS-930), National Institutes for Quantum and Radiological Science and Technology, Japan. The stacked-foil activation method was employed. After irradiation, radioactivities of produced nuclides on Ti and Cu samples are determined by a HPGe gamma-ray spectrometry. The excitation functions of alpha-induced reaction on the Ti and Cu samples by taking into account the projectile energy degradation in the target are estimated. In this workshop, we will present these experimental cross section data, combined with previous experimental data and calculations.

**Poster Session / 26**

**Systematic of fusion suppression in reaction induced by α cluster projectile**

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In recent past study of fusion reaction induced by α cluster projectile have created a resurgent in the study of nuclear reaction. Fusion reaction induced by α cluster projectile provides an ample opportunity for exploring the detail structure and properties of the incident projectile. The α cluster nature of the incident projectile is quite helpful in the study of massive transfer reaction as well as in exploring the parameters influencing the degree of fusion suppression. Classically, fusion reaction takes place when incident projectile with kinetic energy sufficiently above the Coulomb barrier interacts...
with the target nucleus either directly or indirectly. Direct complete fusion (DCF) reaction involves the fusion of incident projectile as a single entity with the target nucleus resulting in total transfer of incident momentum to the resulting compound system. However, it is also possible that the incident projectile breakup into fragments due to excessive Coulomb repulsion between the projectile and target nuclei. Sequential complete fusion (SCF) involves the fusion of all the breakup fragments with the target nucleus one after the other. On the other hand incomplete fusion (ICF) reaction involves the fusion of only a part of the incident projectile with the target nucleus while the remaining fragments moves in the forward direction with the same velocity as that of incident beam. As SCF and DCF results in same compound nucleus with same degree of momentum transferred, thus the complete fusion (CF) is the algebraic sum of SCF and DCF i.e. \( \sigma_{CF} = \sigma_{SCF} + \sigma_{DCF} \).

In the present work study of fusion reaction has been carried out by using the \(^{20}\)Ne projectile over the \(^{165}\)Ho target at Elab = 90-145 MeV. Experimentally measure reaction cross section is compared with the coupled channel calculations performed using the code CCFULL. The observed suppression in fusion cross section with respect to CCFULL calculation was explored in the light of fusion cross section data available for other \(\alpha\) cluster projectile induced reaction.

**Poster Session / 27**

**Clustering effects in the reaction mechanism of very light mass composite nuclei**

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Within the quantum mechanical fragmentation theory based dynamical cluster decay model (DCM) the decay of number of light mass composite nuclei (CN) \(A\sim 20\sim 40\) have been investigated for competing reaction mechanisms fusion-fission (FF) and deep inelastic orbiting (DIO) along with the role of clustering effects for the same \([1]\). In some cases we have observed competition between FF and DIO contributions \((20,21,22) Ne^{\ast}, 28 Si^{\ast}, 32 S^{\ast}, 39 K^{\ast} \text{ and } 10 Ca^{\ast})\), and also evaluated the same, while in other \((20\sim 29) Al^{\ast}, 51 P^{\ast}\) FF have the only contribution in the decay of intermediate mass fragments, IMF, within collective clusterization approach of DCM. It makes an interesting case to study few more composite nuclei, using DCM, in this mass region to develop a systematics. The preliminary results for IMF emissions \((3 \leq Z \leq 5)\) in the decay of CN \(^{24} Mg^{\ast}\) and \(^{25} Mg^{\ast}\) formed in the reactions \(^{12,13}C + ^{12}C\) at \(E_{lab} \sim 6\) MeV/nucleon, respectively, IMF \(^{6}Li\), \(^{8}Be\), \(^{10}B\) and neutron rich \(^{7}Li\), \(^{8}Be\), \(^{11}B\) are highly preformed in comparison to the neighbouring ones, in line with the experimental observation \([2]\). Work is in progress.


**Poster Session / 88**

**Neutron capture cross sections from surrogate reaction data and theory: connecting the pieces with a Markov-Chain Monte Carlo approach**

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Neutron capture cross sections can be measured by bombarding a sample of target nuclei with neutrons and detecting decay products. Such measurements cannot be completed in the laboratory when the target isotopes have half-lives which are small compared to timescales relevant to the experiment. This leaves critical gaps in libraries of nuclear data. To predict the missing data, nuclear cross section calculations for neutron capture reactions are carried out using statistical Hauser-Feshbach models [1]. These models depend on a number of nuclear structure inputs including nuclear level densities, and gamma-ray strength functions. Each of these depend on some model for which the input parameters are not well constrained. The ‘surrogate reaction method’ [2] allows us to obtain statistical constraints on model parameters by fitting to experimentally accessible cross sections involving the same compound nucleus. These experimental constraints are then used to predict cross sections which are not directly measured.

The $^{90}$Zr(n,γ) cross section has recently been determined from $^{92}$Zr(p,dγ) data [3]. That calculation used an approximate fitting method based on Bayesian Monte Carlo sampling. We now employ a Markov Chain Monte Carlo (MCMC) [4] sampling to produce our probability distribution of parameters: the statistical constraints we need to predict neutron capture cross sections in the surrogate method. This approach is statistically rigorous and this work represents a reusable structure for future applications of the surrogate method. Here we recompute the same benchmark case, $^{90}$Zr(n,γ) from $^{92}$Zr(p,dγ) data and report preliminary results.


Systematic study of incomplete fusion reactions: Role of various entrance channel parameters

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Extensive efforts have been put forth experimentally and theoretically to understand the heavy ion induced reaction dynamics at energies less than 10 MeV/nucleon. As discussed in some recent studies complete fusion (CF) and incomplete fusion (ICF) reactions are the most dominant reaction modes above the Coulomb barrier energies [1-3]. However, the dependence of entrance channel parameters on relative contributions of the two processes is still unclear and demands more systematic measurements. Therefore, to understand the effect of two neutron excess projectile on low energy ICF reaction dynamics an experiment have been carried out at Inter University Accelerator Center, New Delhi. The evaporation residues populated through complete and incomplete fusion processes
in the reaction of $^{18}$O+$^{165}$Ho have been analysed from excitation function measurements at projectile energies $\approx$ 4-7 MeV/nucleon. Recoil catcher activation technique followed by off-line $\gamma$-ray spectrometry has been used. The cross sections measured experimentally are compared with the predictions of the compound nucleus model code PACE4 [4] which only takes complete fusion reaction cross sections into consideration. The experimental cross section of evaporation residues populated through xn and pxn channels matches well with the theoretical model code PACE4. On the other hand, incase of $\alpha$-emitting channels, an enhancement observed in the measured cross section over PACE4, reveals the occurrence of incomplete fusion at the studied energy range. The relative percentage of incomplete fusion have also been calculated from the experimental data and its dependence on various entrance channel parameters like projectile energy, mass-asymmetry, $\alpha$-Q value, and Coulomb effect (ZPZT) are studied.

Present data analysis reveals that the incomplete fusion probability becomes more and more dominant as incident projectile energy increases. The strength of incomplete fusion function obtained in the $^{18}$O+$^{165}$Ho interaction are compared with the previously studied systems involving the same target with $^{12}$C, $^{13}$C, $^{16}$O, $^{20}$Ne as projectiles [2,5-7]. Results of the present study indicates that $^{18}$O (two neutron excess) projectile shows more incomplete fusion contribution as compared to $^{12}$C, $^{13}$C, and $^{16}$O projectiles due to its relatively small negative $\alpha$-Q value. Furthermore, product of target charge ZT and projectile charge ZP have been calculated which results that the breakup probability increases with ZP ZT when compared with other previously studied systems available in the literature and shows a linear systematics.


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**Quasi-elastic excitation function for $^{16}$O+$^{169}$Tm system: role of hexadecapole deformation**

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In recent years, there is a great interest in fusion barrier studies due to advances in experimental methods and theoretical interpretations [1-7]. The heavy-ion collisions at energies around the Coulomb barrier are strongly affected by the internal structure of colliding nuclei [1-6]. The coupling between relative motion and internal degrees of freedom of colliding ions (such as static deformations, collective excitations; rotation and/or vibration, nucleon transfer, projectile break-up, etc.) results in a number of distributed barriers in place of a single potential barrier ($B_{fus}$). It is now well known that a barrier distribution (BD) can be extracted experimentally from the fusion excitation function $\sigma_{fus}(E)$, using the relation $D_{fus} = \frac{d^2(E\sigma_{fus})}{dE_2}$ [3]. The extracted BD can be treated as a fingerprint of the reaction mechanism characterizing the importance of channel couplings because the nature and strengths of the couplings lies in the distribution of barriers. Further,
it was suggested that the same information can also be obtained from the cross-section of quasi-elastic scattering (QE) (as the total flux is conserved) measured at large angles using the prescription

\[
D_{\text{QEl}} = -\frac{d(\sigma_{\text{QEl}}/d\sigma_{\text{R}})}{dE},
\]

which gives an alternative representation of fusion BD [5]. In the present work, the QE-measurements have been performed for the system \(^{16}\text{O} + ^{169}\text{Tm}\), which will be translated to BD. It should be noticed that the doubly closed \(^{16}\text{O}\) projectile will behave as an inert, and therefore any effect of the coupling of different degrees of freedom on BD should be pronounced for the target nuclei only.

The experiment has been performed at the IUAC, New Delhi using HYTAR detector system in GPSC [7]. Beam energy was varied in steps of 3 MeV ranging from 17% below barrier to 16% above barrier. Four telescope detectors each at an angle of 173° have been arranged in a symmetrical cone geometry to measure the back-scattered quasi-elastic events. Nine telescopes, six at angles from +60° to +160° with angular separation of 20° and other three telescopes at angles -110°, -122° and -134°, were placed. Two monitor detectors have been placed at ±10° for normalization purpose. The QE-excitation functions have been obtained and the experimental BD for the \(^{16}\text{O} + ^{169}\text{Tm}\) system has been derived. The nuclear potential parameters will be extracted from angular distribution measurements for theoretical calculations. Further, analysis of the data is underway and the details will be presented during the conference.

REFERENCES

Poster Session / 44

Measuring La(p,x) Cross Sections from 35-60 MeV by Stacked Foil Activation

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In this experiment we use the stacked foil activation technique to measure cross sections for the La(p,x) reaction, with proton energies in the 35-60 MeV range. The primary motivation for this measurement is to quantify the production of \(^{133}\text{Ce}\), a positron-emitting analogue of the medical isotope \(^{225}\text{Ac}\), which has applications for kinetic bio-distribution assays of new radio-pharmaceuticals. The results of this measurement show significant deviations from the cross sections modeled by the TALYS and EMPIRE nuclear reaction codes using default parameters. There are no previous measurements of this reaction for comparison.

Poster Session / 46

Neutron Transfer Reactions for Deformed Nuclei Using Sturmian Basis

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We study the spin-parity distribution \( P(J^p,E) \) of \(^{156}\text{Gd}\) excited states above the neutron separation energy \( S_n = 8.536 \text{ MeV} \) [1] that are expected to be populated via the neutron pickup reaction \(^{157}\text{Gd}(^3\text{He},^4\text{He})^{156}\text{Gd}\). In analogy with the rotor plus particle model [2], we view excited states in \(^{156}\text{Gd}\) as rotational states built on intrinsic states consisting of a neutron hole in the \(^{157}\text{Gd}\) core; that is, a neutron removal from a deformed Woods-Saxon type single-particle state [3] in \(^{157}\text{Gd}\). To understand the impact of the deformation and what should be considered as a small deformation, calculations of Woods-Saxon type single-particle states were performed using several codes [4–10]. For small non-zero deformation we used the codes from Ref. [5–8], while for large deformation we selected only the code by Cwiok at al. [5]. The pairing effects within the core are accounted for through the BCS pairing model [11,12] while the particle-core interaction usually dominated by a Coriolis coupling are accounted via first or- der perturbation theory to the particle-core Coriolis coupling [12]. The reaction cross section to each excited state in \(^{156}\text{Gd}\) is calculated as coherent contribution using standard reaction code [10] based on spherical basis states. The spectroscopic factor associated with each state is the expansion coefficient of the de- formed neutron state in a spherical Sturmian basis along with the spherical form factors [12]. A smooth total cross section, as a function of the excitation energy, is generated using Lorentzian smearing distribution function. Our calculations show that, within the assumptions and computational modeling, the reaction \(^3\text{He} + ^{157}\text{Gd} \rightarrow ^4\text{He} + ^{156}\text{Gd}\) has a well-behaved formation probability \( P(J^p,E) \) within the energy range relevant to the desired reaction \(^3\text{He} + ^{157}\text{Gd} \rightarrow ^4\text{He} + ^{156}\text{Gd}\).

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References

Characterization of the FALSTAFF spectrometer first arm: Study of 252Cf and 235U fission fragments

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Due to its complexity, nuclear fission remains a topic of high interest, even after many decades of research. The study of fission fragment mass distribution can provide valuable information in the...
understanding of fission dynamics. The incoming Neutrons For Sciences (NFS) facility, built in the framework of the SPIRAL2 project (GANIL), will open new opportunities to measure these data. High intensity neutron beams will be produced over a large domain of energy, from some hundreds of keV up to 40 MeV. In this context, a new experimental setup, called FALSTAFF, dedicated to the study of fission is under development.

The FALSTAFF setup aims to investigate the fission of actinides in the fast-neutron energy domain. Once completed, this two-arm spectrometer will detect both fragments in coincidence and allow to measure their time of flight (ToF) and kinetic energy. The determination of the velocity of the two fragments (2V method) will allow us to reconstruct the mass before neutron evaporation and the measure of the energy will permit to determine the mass of the fragment after neutron evaporation (EV method). The correlation between the neutron multiplicities and the fragment masses is interesting to investigate the sharing of the excitation energy between the 2 fragments on one hand, and between different excitation modes on another hand. The evolution of this correlation according to the incident neutron energy could bring information on the role of the shell effects.

The first arm of the FALSTAFF spectrometer has been built. It is composed of two SED-MWPC (Multi-Wire Proportional Counter) detectors used to measure the time-of-flight as well as the position of the fragments, thus reconstructing their velocity, and an axial ionization chamber which gives the kinetic energy and the energy loss profile. This paper will, in the first place, describe the FALSTAFF setup. A study of $^{252}$Cf fragments will be presented, including kinetic energy and velocity distributions obtained with the first arm of FALSTAFF. The mass determination and some comparisons to simulations and data from the literature will also be presented. Preliminary results from the $^{235}$U thermal neutron induced fission experiment performed at the Orphée reactor will be exhibited.

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Testing (p,d) Transfer Reaction Consistency at 70 MeV/u

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Transfer reactions and knock-out reactions are both important experimental tools for many subfields in nuclear physics. Although these two techniques should give consistent results when measuring the same quantities, there is a well-established discrepancy between transfer and knock-out measurements of spectroscopic factors for asymmetric nuclei (including, for instance, in some argon isotopes). In nuclear structure studies, knock-out reactions are typically measured at higher energies than transfer reactions. To test the consistency of the currently understood transfer reaction mechanism, we measured the transfer reactions $^{34}$Ar(p,d) and $^{40}$Ar(p,d) at the National Superconducting
Cyclotron Laboratory using the same beam energy (70 MeV/u) as from a previous knockout measurement. Spectroscopic factors were extracted from angular distributions via ADWA calculations using global and microscopic optical models. A broader discussion of the validity of the single-nucleon transfer reaction mechanism will also be presented.

This work was supported by the NSF (PHY 1102511) and the DOE NNSA Stewardship Science Graduate Fellowship.

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Elastic Proton Scattering on Calcium Isotopes from Chiral Microscopic Optical Potential

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We formulate a microscopic optical potential from chiral two and three nucleon interactions. The real and imaginary volume terms and the imaginary surface term are obtained from the single-particle energy, which is calculated self-consistently for infinite isospin-asymmetric nuclear matter. The real spin-orbit term is calculated from the nuclear energy density functional. The density dependent optical potential is then folded with a nuclear density profile giving a potential in the following form: U Optical=U(E,r). The improved local density approximation is utilized to account for the non-zero range of the nuclear force. Proton-nucleus scattering cross sections are calculated for the microscopic optical potential and compared to those of phenomenological models and experimental data. The cross sections for Ca40,42,44,48 at energies in the range of 25sEs160MeV compare favorably to cross sections calculated using phenomenological models.

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Constraining the νp-process through the study of neutron-induced charged-particle reactions on short-lived $^{56}$Ni

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We formulate a microscopic optical potential from chiral two and three nucleon interactions. The real and imaginary volume terms and the imaginary surface term are obtained from the single-particle energy, which is calculated self-consistently for infinite isospin-asymmetric nuclear matter. The real spin-orbit term is calculated from the nuclear energy density functional. The density dependent optical potential is then folded with a nuclear density profile giving a potential in the following form: U Optical=U(E,r). The improved local density approximation is utilized to account for the non-zero range of the nuclear force. Proton-nucleus scattering cross sections are calculated for the microscopic optical potential and compared to those of phenomenological models and experimental data. The cross sections for Ca40,42,44,48 at energies in the range of 25sEs160MeV compare favorably to cross sections calculated using phenomenological models.
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Radiative neutron capture in folding model with a microscopic optical model potential and application of the reaction rates to astrophysical s-process

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The radiative neutron capture reactions have been studied in statistical compound nuclear Hauser-Feshbach formalism with a novel optical model potential constructed in microscopic folding model prescription using the reaction code TALYS. The reactions are germane to slow neutron capture process nucleosynthesis. Many times, reaction cross sections or rates relevant to various astrophysical processes have to be obtained theoretically due to a number of reasons. The cross sections or reaction rates cannot be measured at all astrophysical energies and for all nuclei. Many nucleosynthesis processes involve unstable and exotic radioactive nuclei that are not accessible to terrestrial laboratories for measurements. For example, branching phenomena in the s-process path involve unstable radioactive nuclei. The analysis of branching that depends on neutron capture cross sections/rates of these radioactive nuclei is crucial from the astrophysical point of view. The significant gaps in the experimental datasets can only be compensated by theoretical statistical model predictions. The optical potential, in the present work ($V_{omp}$), has been constructed by folding a well-known effective nucleon nucleus interaction, namely, the density-dependent M3Y interaction ($V_{NN}$) with the radial matter densities of the target nuclei ($\rho(\vec{r}')$). The interaction is supplemented by a zero-range pseudo-potential ($J_{00}$). A spin-orbit term $U^{SO}_{n(p)}(r)$ is also included in the potential.

$$V_{NN} = 7999\frac{e^{-4r}}{4r} - 2134\frac{e^{-2.5r}}{2.5r} + J_{00}\delta(r);$$

$$J_{00} = -276(1 - 0.005E/A);$$

$$V_{fold} = \int V_{NN}|\vec{r} - \vec{r}'|\rho(\vec{r}')d\vec{r};$$

$$V_{omp} = N_{r}V_{fold} + jN_{im}V_{fold};$$

$$U^{SO}_{n(p)}(r) = (\lambda_{nso}(E) + j\lambda_{nso}(E))\frac{1}{2}\frac{d}{dr}\left[2\rho_{p(n)} + \frac{1}{3}\rho_{n(p)}\right].$$

Here, $\lambda_{nso}$ and $\lambda_{nso}$ are energy dependent phenomenological potential well-depths.

$$\lambda_{nso} = 130e^{-0.013E} + 40 \text{ MeV},$$

$$\lambda_{nso} = -0.2(E - 20) \text{ MeV}.$$
feasibility and predictive power of our model. The Maxwellian-averaged cross section values over s-process energies and astrophysical reaction rates over s-process temperatures for the relevant nuclei (including unstable isotopes) taking part in s-process are presented.

Next, these statistical model $(n, \gamma)$ rates have been applied to study the sensitivity of these rates in the main component of s-process. The s-process is subdivided into the weak and the main components. The nuclei in the mass range $56 \leq A < 90$ are produced in the weak component. On the other hand, nuclei with $A > 90$ are produced in the main component that occurs in radiative conditions during the interpulse phases of subsequent He-shell burning in the thermally pulsating asymptotic giant branch (TP-AGB) stars of masses in between $1 \leq M/M_\odot \leq 3$ ($M_\odot$ being the solar mass). Neutrons are released in two source reactions, one is $^{13}\text{C}(\alpha, n)$ and another is $^{22}\text{Ne}(\alpha, n)$. However, the $^{22}\text{Ne}(\alpha, n)$ reaction is only marginally activated in low mass AGB stars during the last few thermal pulses. We have built up and solved a large network for s-process, starting with the Fe group nuclei as seeds, where, we have applied our statistical model $(n, \gamma)$ rates as inputs. We have taken suitable time-varying neutron densities provided by $^{13}\text{C}(\alpha, n)$ reaction and time-variation of temperature for an inter-pulse period of 20000 years, characteristics of a typical TP-AGB star.

Finally, we have studied the sensitivity for $(n, \gamma)$ rates to identify the reactions that have the strongest global impact on s-process abundance in the main component. Sensitivity $(s_{ij})$ is defined as the ratio of the relative change in abundance of isotope $j$ to the relative change in the rate of isotope $i$;

$$s_{ij} = \frac{\Delta N_j/N_j}{\Delta r_i/r_i}.$$  

Hence, sensitivity gives the coupling between the change in the reaction rate and the change in the final abundances. For the sensitivity analysis, the $(n, \gamma)$ rate of each isotope has been changed individually by $20\%$ and the corresponding changes in isotopic abundances are observed. The degree of sensitivity is determined by the number of affected isotopes over a threshold of $s_{ij} = \pm 0.1$. A positive (negative) sensitivity indicates the increase (decrease) in abundance with the increase in rate.

We have found that among all the neutron capture reactions, only a few have a significant global impact over the entire abundance distribution. The impact is determined by the number of affected isotopes over a threshold value of $s_{ij} = \pm 1$. The interesting fact is that these rates are for the reactions on magic nuclei acting as bottlenecks to the s-process reaction flow.

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**Evolution of symmetric decay in A = 60 compound nuclei**

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The quantum mechanical fragmentation theory based dynamical cluster decay model (DCM) [R. K. Gupta, et al., PRC 71, 014601 (2005)] has been applied to study the symmetric decay of compound nuclei (CN) $^{60}\text{Zn}^*$, $^{60}\text{Ni}^*$ and $^{60}\text{Fe}^*$ [M. Kaur, et al., NPA submitted; Proc. of DAE Symposium on Nuclear Physics 60, 598 (2015)]. The effect of the neutron to proton (N/Z) ratio in the decay of CN with $A = 60$, but formed through different reactions induced by same projectile $^4\text{He}$ having same incident energy, have been investigated. Although the contributions of light particles and intermediate mass fragments are more prominent than Symmetric mass fragments (SMFs) in this mass region, but in the present work, we have explored the evolution of symmetric decay with changing N/Z for $A = 60$ CN, under study. We see that the value of preformation probability $P_0$ and penetrability $P$ for SMFs decreases with increase in N/Z ratio, consequently symmetric breakup goes out of favor for higher N/Z values, i.e., symmetric decay is highly favored in the case of $^{60}\text{Zn}^*$ only having N=Z. Hence, the SMFs cross section $\sigma_{SMF}$ decreases with increasing N/Z, i.e., highest
for N/Z = 1. The effect of rising temperature on SMFs cross sections αSMFs have also been studied at three different values. Quite interestingly, the symmetric channel $^{30}\text{P} + ^{30}\text{P}$, $^{30}\text{Si} + ^{30}\text{Si}$ and $^{30}\text{Al} + ^{30}\text{Al}$, respectively, from CN $^{60}\text{Zn}^+$, $^{60}\text{Ni}^+$ and $^{60}\text{Fe}^+$, in the $\sigma_{\text{SMF}}$, is largest for $^{60}\text{Zn}^+$ and smallest for $^{60}\text{Fe}^+$. Moreover, the contributions of symmetric channels increase with increasing temperature of CN, except in the case of Fe$^+$, for which it decreases with rising temperature.

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**On the role of the curvature corrections to the surface tension coefficient upon the orientation effects in the fusion reactions**

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The present study addresses the phenomena observed in the collisions of the deformed, oriented nuclei. The main aim is to define the role of the surface energy dependence on the surface curvature in altering the fusion barriers and cross sections of the deformed nuclei depending on their mutual orientation. To perform this task we analyze the barrier heights and position dependence on orientation and the surface curvature of the projectile and the target. In order to calculate the changes in the surface energy the previously introduced approach allowing to define the Tolman $\delta$-correction to the surface tension coefficient from the equation of state of the nuclear matter [1] is used. Within that approach it is possible to link the bulk and the surface properties of the nuclear matter and to define the curvature correction term on the coexistence curve in a form

$$\delta = \frac{2}{3} \frac{1}{\rho_0} \times \frac{-3t_0 - 160W \rho_0^{-1/2} t_2 (1 + \alpha) \rho_0^5}{(15t_0 + t_2 (1 + \alpha)((3t_0 + 6) - (3t_0 + 6)^2))} \sigma_{\infty},$$

$$W = \frac{h^2}{10m} \left( \frac{f}{8\pi^2} \right)^{\frac{3}{2}} \left( \frac{5 - 3\frac{\sigma_0}{\sigma_{\infty}}}{5} \right)$$

for the equation of state with a Skyrme type parametrization [2]. In the study several Skyrme parameterizations are analyzed and the surface tension of the semi-infinite matter at $T = 0$ is calculated within the restricted extended Thomas-Fermi approach [3].

In evaluating the barrier heights and positions different nuclear potentials based on the proximity concept are used. The performed analysis shows the strong influence of the curvature effects on interaction of the deformed nuclei. The obtained results show good correspondence with the available data for the interaction potential dependence on the mutual orientation of the projectile and the target. It is shown that in describing the fusion reactions of the deformed nuclei it is important accounting for the curvature correction terms in the surface tension coefficient.


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**Direct $^{157}\text{Gd}(^{3}\text{He},\alpha 2n)^{154}\text{Gd}$ reaction as a surrogate for $^{155}\text{Gd}(n,2n)^{154}\text{Gd}$**

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The surrogate reaction method has shown success for fission, but is more challenging when used to predict neutron-induced reactions that are more dependent on angular momentum. In this work, the reaction $^{157}$Gd($^3$He,α2n)$^{154}$Gd is studied as a surrogate for $^{155}$Gd(n,2n)$^{154}$Gd, measuring only reactions with forward-scattered alphas to better reproduce the angular momentum brought in by a neutron. The experiment was performed at the 88-inch Cyclotron at Lawrence Berkeley National Laboratory, utilizing the STARS-LiBerAce detector for the measurement of the alphas and gammas. Contamination in the alpha spectrum from ($^3$He,α) reactions on oxygen and carbon in the environment was corrected for in post-processing using the shape of the alpha-gamma coincidence spectrum. Coincidences between forward-scattered alphas and gamma-rays de-exciting $^{154}$Gd were measured and used to calculate the probability of the excited $^{155}$Gd nucleus decaying by emission of two neutrons. The measured probability of decay to $^{154}$Gd, converted into a $^{155}$Gd(n,2n)$^{154}$Gd cross section using an optical model calculation, compared favorably to a direct measurement of the cross section in the energy region between 6 and 14 MeV.

**Prompt and delayed fission gamma rays from $^{252}$Cf(sf) and $^{235}$U(n,f)**

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Two measurements of the prompt fission gamma rays from $^{252}$Cf(sf) and $^{235}$U(n,f) have been performed at LANSCE of LANL. The gamma rays were measured with the 4pi spectrometer DANCE consisting of 160 BaF2 detectors. An array NEUANCE of 21 stilbene detectors surrounding the target provided the fission trigger by measuring the prompt fission neutrons. In addition, we used four Si detectors to measure the total kinetic energy of the fission fragments from $^{252}$Cf(sf). We will report results for the gamma-ray energy spectra and gamma-ray multiplicity distributions of prompt and delayed fission gamma rays from the two experiments. We will also present observed correlations between the prompt fission gamma rays and prompt fission neutrons and fission fragments total kinetic energy. The experimental results are compared with predictions from the CGMF code.

**Probing the explanatory power of statistical reaction theory via cross section correlation functions**

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Our understanding of compound nucleus cross sections rests heavily on statistical theories of reactions, a key component of which is the Porter-Thomas distribution (PTD) for reduced partial neutron widths. The existence of high quality data for Pt isotopes that is inconsistent with the PTD has prompted several studies of how this data is to be reconciled with statistical reaction theories. It has, for example, been suggested by Volya, Weidenmüller and Zelevinsky that the peculiarities of the Pt data can plausibly be attributed to some combination of the Thomas-Ehrman shift associated with coupling to the neutron channel and the non-statistical distribution of $\gamma$ decays to low-lying states. The question arises whether the influence of such effects could be discerned from other compound-nucleus data? It has been recognized for some time that the crossover region between isolated and strongly overlapping resonances offers unique possibilities for exploring the coupling of intrinsic states to the continuum and the degree of chaos of the system. We investigate the behavior of auto- and cross-correlation functions involving nuclear cross sections in the crossover regime when allowance is made for the effects highlighted by Volya et al.

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Dynamical Cluster-decay Model applied to decay of $^{202}$Po$^+$ formed via $^{48}$Ca+$^{154}$Gd reaction

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$^{48}$Ca+$^{154}$Gd reaction forming $^{202}$Po$^+$ compound nucleus (CN), decaying to ground state (g.s.) of $^{198}$Po by the emission of 4n and to meta-stable states (m.s.) $^{199m}$Po and $^{197m}$Po via (3n,5n) emission, respectively, has been analyzed recently within the Dynamical Cluster-decay Model (DCM) [R.K. Gupta, Lecture Notes in Physics 818, Clusters in Nuclei*, Editor: C. Beck Vol. 1 (2010) 223-262] at various CN excitation energies ($E_{CN}$) for quadrupole deformed ($\beta_{2q}$) and optimum oriented ($\beta_{2q}^{opt}$), coplanar nuclei ($\Phi=0^{\circ}$) [P. Kaushal et al, Phys. Rev. C 98, 014602 (2018)] . Note, the two different kinds of decays of the same CN are governed by different CN decay processes with g.s. to g.s. decay of $^{202}$Po$^+$ requiring quasi-fission-like (qf-like) non-compound nucleus (nCN) contribution and the g.s. to m.s. decay of $^{202}$Po$^+$ being a pure CN decay. In the present work, we investigate the role of inclusion of additional degrees-of-freedom, i.e., the higher multi-pole deformation ($\beta_{3l}$, $\beta_{4l}$), and “compact” orientations ($\theta_{i,n}$) together with the non-coplanar ($\Phi_e \neq 0$) on the nCN cross section observed in the g.s. to g.s. decay of $^{202}$Po$^+$ . We observe that the nCN content ($\sigma_{4n}^{nCN}$) remains the same irrespective of adding or not adding higher-multi-pole deformations in coplanar ($\Phi=0^{\circ}$) or non-coplanar ($\Phi_e \neq 0$) configurations, the magnitude of $\sigma_{4n}^{nCN}/\sigma_{4n}^{opt}$ as a function $E_{CN}$ varying from a zero to a maximum of $\sim 70\%$ of the channel cross section, $\sigma_{4n}^{opt}$ . Finally, possible synthesis of $^{202}$Po$^+$ CN via all the possible “cold” target-projectile combinations is also analyzed, $^3$He $^{197}$Pb identified as the optimum reaction with lowest interaction barrier and smallest (most compact) interaction radius.

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Measurements of isomeric yield-ratios in fission and estimates of the average angular momentum of the initial fragments

One of the open questions in fission is the origin of the angular momentum of the primary fission fragments, where competing theories have been proposed. Experimental information on the angular momenta of the fragments can thus provide insights to the properties of the dynamical evolution of the fissioning nucleus, from the saddle point until its descent to scission. However, this information can not be directly obtained but can be inferred through the population of different isomers of the final fission product.

We report the measurements of independent isomeric yield ratios, performed by direct ion counting at the Ion Guide Isotope Separator On-Line facility at the University of Jyvaskyla. The isomers have been produced in 25 MeV proton induced fission of Uranium and Thorium and separated by mass using the Penning trap JYFLTRAP. Employing the newly implemented Phase-Imaging Ion-Cyclotron-Resonance technique, isomers down to an excitation energy of 35 keV were successfully separated and counted. So far, 19 cases have been studied.

Using the nuclear reaction code TALYS, in combination with the fission code GEF, the experimental data have been used to estimate the average angular momentum of the corresponding fission fragments. The results show a tendency towards decreasing angular momentum with increasing neutron number, approaching the closed neutron shell configuration N=82. Moreover, an odd-Z effect on the angular momentum for nuclides with the same neutron number is observed.

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**Experimental measurements of the 197Au(n,γ) Maxwellian-averaged cross section at kT=30keV by activation method.**

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The 197Au(n,γ) cross section is considered a standard for neutron capture cross section measurements at thermal energy and in the energy range between 200 keV and 2.8 MeV. Last evaluation of this standard (2018) has also included the Maxwellian-averaged cross section (MACS) at kT=30 keV. MACS of gold at kT=30 keV is commonly used as reference for neutron-capture cross-section measurements in Nuclear Astrophysics. Neutron capture is the main mechanism responsible for the nucleosynthesis of the major part of the elements heavier than iron, and the Maxwellian-averaged cross-section (MACS) or stellar cross-section of the involved isotopes is a key parameter for modeling the stellar neutron-capture nucleosynthesis processes (s-process and r-process). A large effort has been made to solve the MACS30 recent discrepancies between different experiments and techniques, in particular between on the one hand evaluations and recent TOF measurements, and in the other hand the historical activation measurement of Ratinsky & Käppeler (1988). We have recently carried out absolute measurements of the MACS of 197Au(n,γ) at kT=30 keV in two activation experiments, at 3 MV Tandem Pelletron accelerator at CNA (Seville). Here we describe the experiments and discuss the analysis, including MCNPX simulations and a correction proposed for flat samples, and a comparison of our result with previous and recent measurements and standard evaluation.
Exploring shell effects in the decay of compound nucleus $^{200}$Pb* within collective clusterisation approach.

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The compound nucleus (CN) resulting from heavy ion reactions at low energy are perceptive towards the entrance and exit channels aspects such as excitation energy, entrance channel mass asymmetry, pairing energy, shell corrections, etc. For the shell corrections energies, which are microscopic component of fission barrier, there is an excellent theory that proton shell closure at $Z=82$ favors survival probability of CN against fission. In the present study, an attempt has been made to understand the stability of proton shell closure nucleus $^{200}$Pb* formed in $^{19}$F + $^{181}$Ta reaction at $E_{lab}$ ~ 85 MeV within the dynamical cluster decay model (DCM) [PRC 71, 014601 (2005)]. The light particles (LPs) cross sections ($\sigma_{LP}$) and fission cross section ($\sigma_{fis}$) are calculated for the decay of $^{200}$Pb* in reference to the available experimental data [NPA 385, 109 (1982)]. In DCM, the neck length parameter $\Delta R$, which is fitted to calculate $\sigma_{LP}$ and $\sigma_{fis}$ separately, for the decay of CN and nicely compared with the experimental data. Recently, within DCM, $\Delta R$ is uniquely fixed for a particular choice of projectile at same $E_{lab}$ on different targets [PRC 92, 024623 (2015)]. On this basis, a few other $^{19}$F induced reactions using the above fixed $\Delta R$ for LPs and fission, will be studied. The preliminary results show that the potential energy surface for the decay of $^{200}$Pb shows strong minima at magic or deformed magic nuclei. We intend to compare the results for the decay of $^{200}$Pb* with some neighboring CN.

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Emission of complex fragments in the decay of $^{44}$Ti* within collective clusterization approach

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The emission of complex or intermediate mass fragments in light mass composite nuclei with $A \leq 60$ has been a topic of immense interest during past decades. In $^{16}$O, $^{12}$C, $^{20}$Ne+$^{12}$C and $^{28}$Si+$^{12}$C reactions leading to alpha cluster nuclei, in addition to fusion-fission (FF), the deep inelastic orbiting (ADIO) process contributes competitively in complex fragments emission [1, 2]. Therefore, it’s quite motivating to look for persistence of such competing mechanisms in heavier alpha cluster nuclei. In the present work, with this motivation, the decay of $^{44}$Ti* - an alpha nuclear system formed in $^{32}$S+$^{12}$C reaction at $E_{lab}$ = 220 MeV has been explored within dynamical cluster-decay model [2, 3]. The results show that $^{6}$Li, $^{8}$Be, $^{12}$C and $^{14}$N are in strong competition with symmetric splitting fragment $^{22}$Na. Among the fragments, A = 11, 12, 13 corresponding to target like yield i.e. $Z = 6$, $^{12}$C is more stable. The results show compound nucleus origin of $Z = 6$ fragments in consonance with experimental data [4]. Further, the $\sigma$(fragment)/$\sigma$(12C) for Z = 4, 5 fragments in the decay of $^{44}$Ti* formed via $^{32}$S+$^{12}$C and $^{16}$O+$^{28}$Si reaction channels will be investigated to establish their origin i.e. whether compound nucleus or non-compound nucleus process is dominant in the fragment emission.

**Poster Session / 72**

**Synthesis of Z=120 via $^{54}\text{Cr}+^{248}\text{Cm}$ using Dynamical Cluster-decay Model**

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The question is: what is the next proton magic shell next to $Z=82$, i.e., 120, 122, or 126, and the role of magic shell reaction partner(s) over their being asymmetric need be established (Hemdeep, et al. Phys. Rev. C 95 014609 (2017)). In the present work, we study $Z=120$, $A=302$ via $^{54}\text{Cr}+^{248}\text{Cm}$ reaction using the Dynamical cluster-decay Model (DCM) [see, e.g., the recent review: R. K. Gupta, in “Nuclear Particle Correlations and cluster Physics”, ed. W. U. Schroeder, World Sc. Pub., (2017), Ch. 18], including deformation effects up to quadrupole deformations $\beta_2$, and with “optimum” orientations $\Theta_{opt}^\phi$ for coplanar ($\Phi = 0$) configurations. The only parameter of the model is the neck-length parameter $\Delta R$ whose value, for the nuclear proximity potential used here, remains within its range of validity ($\sim$ 2 fm). Experimentally, $Z=120$ is investigated at the velocity filter SHIP GSI, Darmstadt [S. Hofmann et al., Eur. Phys. J. A 52, 180 (2016)] for the energy range $E^* = 44$ to 40 MeV, where evaporation residue cross section $\sigma_{ER}$ measured for 3n and 4n decay channels. According to our preliminary DCM-calculations, this reaction is shown with asymmetric mass distribution, and the best possible target-projectile (t-p) combinations to form $Z=120$ are $^{92}\text{Sr}+^{210}\text{Pb}$, $^{136}\text{Xe}+^{166}\text{Dy}$ and $^{28}\text{Mg}+^{24}\text{Hs}$, and/or in their neighborhood. Interestingly, $Z=120$, was first pointed out by one of us [R. K. Gupta et. al J. Phys. G: Nucl. Part. Phys. 23 L13 (1997)], predicting $^{54}\text{Sr}+^{208}\text{Pb}$ as the best cold fusion reaction for producing the $A=302$, $Z=120$.

**Conference Dinner / 77**

**Nuclear Physics and Astronomy: A Growing Partnership**

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Nuclear Physics has played a leading role in Astronomy for over 6 decades. Nuclear burning powers stars throughout their lives and is the energy source behind type Ia, also known as thermonuclear, supernovae. In addition, the products of nuclear burning provide probes into the nature of an even broader range of astrophysical transients from the big bang to stellar outbursts, supernovae, and neutron star mergers. As astrophysical simulations improve and become more sophisticated, the details in the nuclear physics become increasingly important. Here I’ll review some of the recent successes coupling nuclear physics and astronomy and discuss some of the exciting future prospects. The partnership between these two fields continues to grow and the potential for further joint projects is increasing dramatically.

**Applications / 86**

**Astrophysics - An Application of Nuclear Physics**
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In this lecture, I will discuss the connections between nuclear physics, in particular reaction inputs, and astrophysics. For example, how sensitive are various nucleosynthesis processes and their results to the reaction inputs used? Or, how is the outcome of stellar evolution dependent on the reaction inputs? I will conclude by highlighting some current topics of research at this interface between nuclear physics and astrophysics.

Nuclear structure / 90

Shell-Model Level Density and Underlying Physics

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The knowledge of the level density as a function of excitation energy and nuclear spin is necessary for the description of nuclear reactions and in many applied areas. The level density problem is a part of the general physics of mesoscopic self-bound systems with strong interaction between the constituents. Large scale shell-model calculations provide the level density that has characteristic features in agreement with data. The underlying physics is that of quantum chaos and thermalization which allows one to use also statistical methods avoiding full diagonalization. The resulting level density is well described by the “constant temperature model” in agreement with latest experimental data. The effective temperature parameter is not related to the pairing phase transition being instead analogous to the limiting temperature in particle physics. Other aspects of underlying physics include the collective enhancement of the level density, random coupling of individual spins and the role of incoherent collision-like interactions. The discussion is based on recent publications:


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Studies of the Transition to a Fermi Degenerate Plasma at the National Ignition Facility

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The electrons in the cold fuels of NIF cryogenic capsules are partially quantum degenerate, and the degree of degeneracy can be varied by varying the laser pulse. We present results from measurements of rare nuclear reactions that probe the cold fuel and show evidence of this transition to degeneracy through a change in the plasma stopping power.

Applications / 6

Microscopic description of fission for the r-process in neutron-star mergers ejecta

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Nuclear fission is known to be of fundamental importance in many applications, for example for energy production applications, such as nuclear power reactors or nuclear waste recycling. In astrophysics, nuclear fission plays a significant role during the rapid neutron-capture process (r-process) of stellar nucleosynthesis by recycling the matter during the neutron irradiation occurring in a neutron star merger ejecta [1,2]. The recent observation of gravitational waves and its optical counterpart from a binary neutron-star merger proves that such events can provide a viable site for the production of heavy (and potentially super-heavy) nuclei by the r-process nucleosynthesis. During the r-process, heavy neutron-rich nuclei are produced and decay or fission. A reliable description of nuclear fission is needed to explain the fission of such heavy neutron-rich nuclei.

The description the nuclear fission is a theoretical challenge because the many-body problem has to be solved with an interaction between nucleons that is known in a phenomenologically way only. In addition of these static considerations there are dynamical effects which leads to the splitting of the nucleus. There are four major aspects that need to be described during the fission process, namely i) the fissioning nucleus formation, ii) the fission barrier penetration and transmission, iii) the fission fragment formation, and iv) the fission fragment de-excitation. Fissioning nucleus can be formed by neutron (neutron-induced fission), gamma capture (photofission), or beta decay (beta-delayed fission). The fission barrier can be crossed by tunnel effect like in spontaneous fission or be crossed over if the nucleus is sufficiently excited like in neutron/gamma-induced fission. When the barrier is crossed, nucleus can be splitted in many ways with different probabilities, called the fission yields. Finally fission fragments de-excite mainly by neutron and gamma evaporation.

All these aspects have to be properly and microscopically described for nucleosynthesis applications since they involve exotic neutron-rich nuclei that cannot be produced experimentally. The most recent theoretical and computational developments need to be considered for a reliable estimate. In the present paper, we will describe our effort to provide updated state-of-the-art models for the description of the fission process by exotic neutron-rich nuclei.

Concerning the fission path, new calculations have been performed, based on newly computed potential energy surfaces (PES) on the basis of Gogny HFB-calculations with beyond-mean-field corrections [3]. Results for all the 500 even-even nuclei from Th to Ds lying between the proton and the neutron drip lines will be compared with predictions obtained within the Skyrme-HFB or liquid-drop approaches. Moreover, through the determination of the inertia tensor at each point of the PES, the least action path can be determined and spontaneous fission half-lives deduced and compared with available experimental data. Based on these new non-trivial fission paths, all fission transmission coefficients have to be computed considering competition between fission and others possible channels to deduce fission cross sections. Recent results along those lines will be presented.

Finally we will present the scission-point model, called SPY [4], developed to estimate yields and kinetic energies of the fission fragments. To improve the description of the fissioning system at the
scission point, microscopic state densities, proton and neutron distributions as well as potential energy surfaces of each fragments are now considered within the mean-field approach. We will show that these new developments have a significant impact on the predictions of fission yields and fragment excitation energies. Implications for the r-process nucleosynthesis will be discussed.


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The first experimental $(\alpha, xn)$ compound reaction study using neutron-rich nuclei

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Recent sensitivity studies found charged-particle reactions, mainly $(\alpha, xn)$ reactions, are the main production mechanism of $Z=38-47$ abundances in neutron-rich neutrino driven winds during core-collapse supernovae scenario, called the weak r-process. While the calculated abundance pattern of the weak r-process could predict observations of metal poor halo stars relatively well, the uncertainty of the charged-particle reaction rates is critical to control the production of elements. Nevertheless, there are large uncertainties in the theoretical predictions of the rates using statistical Hauser-Feshbach (HF) models, and there is a lack of measurements with neutron-rich nuclei involved in the nucleosynthesis calculations.

In order to address these uncertainties, we have developed the Heavy ion Accelerated Beam induced (Alpha, Neutron) Emission Ratio Observer (HabaNERO) to study $(\alpha, xn)$ compound reactions of neutron-rich nuclei near $Z=26-40$ region including $^{75}$Ga$(\alpha, xn)$. The HabaNERO is a neutron long counter system which consists of $^3$He and BF$_3$ gas-filled proportional counters in a polyethylene matrix optimized to obtain a high average neutron detection efficiency as constant as possible in the wide neutron energy range ($E_n = 0.1-19.5$-MeV) that corresponds to the neutron energies of interest.

Preliminary results of the detector commissioning at Ohio University and $^{75}$Ga$(\alpha, xn)$ cross section measurement at ReA3, NSCL will be presented. This experiment was the first $(\alpha, xn)$ cross section measurement for neutron-rich nuclei in inverse kinematics.
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**Neutron-induced reaction rates away from stability for astrophysics applications: Uncertainties in statistical model calculations and implications for neutron-induced nucleosynthesis.**

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In the current multi-messenger era, a multitude of observational information offers exciting opportunities to piece together an answer to the puzzle of the synthesis of the elements. Such efforts many times depend critically on the microphysics input and particularly on our ability to reproduce in nucleosynthesis calculations complex features of abundance yield patterns to evaluate the yield outcome of various scenarios. For such comparisons to be meaningful, however, uncertainties in the nuclear input that affect nucleosynthesis calculations have to be identified, and their influence evaluated. In this talk, I take a look at the sources of uncertainty that are most influential to the extrapolation of Hauser-Feshbach calculations away from stability and trace them back to the modeling of model ingredients such as level densities, gamma-ray strengths, and optical potentials. An attempt at the quantification of uncertainties in Hauser-Feshbach theory extrapolations is presented together with examples of the ways such studies can inform current experimental and theoretical work related to neutron-induced nucleosynthesis.

Resonances / 92

**The Transition from Isolated Resonances to the Continuum**

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Many nuclear reactions of astrophysical importance are modeled by Hauser-Feshbach (HF) calculations, the well-established approach for computing average cross sections when many resonant levels are involved. This approach assumes that the density of levels is sufficient that only average properties, such as optical potentials and level densities, are sufficient to model the reaction. However, for intermediate masses or near the drip lines, these assumptions may break down. We have studied this transition using both a HF calculations and R-matrix calculations using resonance parameters sampled from distributions which are consistent with the level density and optical potentials involved. The R-matrix calculation includes interference effects between levels with the same spin and parity. These results provide a measure of the statistical error in the cross section or reaction rate prediction arising from low density of states. The case of the $^{34}$Ar($\alpha,p$)$^{37}$K reaction, which is an important reaction in x-ray bursts, will be used as an example.

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**Recent Advances in R-matrix Data Analysis**

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The analysis of resolved compound-nucleus resonances by the R-matrix method is a powerful technique. The existence of R-matrix data models can be proved for the case of Hamiltonians bounded inside some radial limit, at least over some energy range, and when only two-body channels are open. Given the fit parameters of pole energies and partial widths, we have very compact representation of the energy and angular dependences for resonances and their backgrounds.

A recent series of collaboration meetings organized by the IAEA have focused attention on the verification of R-matrix codes, on the validation of data fits using those codes. We have compared the results of codes from LLNL, ORNL, JAEA, along with Tsinghua and Notre Dame Universities. I will report on the results of these comparisons.

We investigate the B=S(E) approximation, which is to set the boundary constant to a different value S(E) for the shift function S. This approximation is very convenient for locating resonances while fitting, but we discovered it gives systematic differences between resonances that would have to be refit numerically. The Brune basis (from C. Brune and F. Barker) we find to be a good replacement for the B=S(E) approximation, one moreover on a solid foundation from the theoretical point of view.

The collaboration has mainly focused on charged-particle reactions. These often have experimental data from multiple transfer channels, and often have sub-threshold R-matrix poles in the composite system.

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New ab initio approach for nuclear reactions based on the symmetry-adapted no-core shell model

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I will discuss a new ab initio approach to reactions involving nuclei up to the medium-mass region. This approach is based on the ab initio symmetry-adapted framework [1], it combines the resonating group method, which has been successfully applied to ab initio reactions of light nuclei [2, 3], with the advantage of the SU(3) symmetry which provides a reorganization of the large-scale model space into physically relevant basis states. Such an additional feature which exploits the power of a group theoretical apparatus paves the way to ab initio reactions involving heavier and more exotic nuclei of astrophysical interest. In this model, the nuclear structure of the target and projectile is calculated by using a realistic nucleon-nucleon interaction and is based on the ab initio symmetry-adapted no-core shell model (SA-NCSM) [1, 4] which has provided results of energy and electromagnetic transition up through mass A = 48 and enables the description of spatially enhanced nuclear configurations. I will present the formalism that involves the expression of the norm and Hamiltonian kernels in the SU(3) symmetry-adapted basis, as well as preliminary results for the n-α scattering reaction for benchmarking purpose. I will then report on the application of the ab initio method, for the first time, to the largely deformed 20Ne nucleus with the view toward achieving descriptions of the n-20Ne reaction.


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Experimental Nuclear Data Measurements and Capabilities at RPI

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Improving the accuracy of nuclear data is a key component to increasing the accuracy of nuclear transport calculations for a wide variety of applications. Several nuclear physics models rely on experimental nuclear data in order to provide evaluations with sufficient accuracy for applications. The Gaerttner Linear Accelerator (LINAC) Center located at Rensselaer Polytechnic Institute (RPI) has been experimentally measuring nuclear data for nuclear data applications since its construction in 1961. These measurements are primarily focused on cross-section measurements using neutron time-of-flight utilizing the short neutron pulses provided by the electron LINAC. Currently a major upgrade to the existing accelerator is being performed which will increase the neutron production rate of the facility by a factor of 10 and is planned to be completed in 2020. The facility has several experimental setups operating in a broad energy range from thermal to 20 MeV and performs capture, fission, (n,α) and scattering measurements. For capture measurements a C0D0 array has been recently installed at a 40 m flight-path which has allowed for measurements to be performed up to 2 MeV. A measurement of 56Fe was completed and the data were used to help improve the ENDF/B-8.0 evaluation. The RPI gamma-multiplicity detector, a 4π segmented sodium iodide detector array, was used to simultaneously measure fission and capture in the energy range from 0.01 eV to 3 keV. This measurement was used to help resolve a discrepancy between the ENDF/B-7.1 and JENDL-4.0 evaluations. One of the unique measurement capabilities present at RPI is the Lead Slowing-Down Spectrometer (LSDS). This is a 1.8 m cube of high purity lead that provides (via neutron scattering in the lead) a very high neutron flux in the eV to keV range which is several orders of magnitude higher than a typical time-of-flight measurement. Recent measurements using the LSDS have included fission cross-section, fission fragment mass yields, (n,α) cross-sections and neutron capture yields. Additionally, for fission measurements, recent work has been done to measure, with high accuracy, the prompt fission neutron spectrum for the spontaneous fission of 252Cf, in the energy range from 50 keV to 15 MeV, using a multiple gamma tagging method. The RPI high energy scattering array has also been used recently to measure the neutron scattering and angular distributions, in the energy range from 20 MeV to 0.5 MeV, for several elements including 238U, Fe, Mo, Be, Zr and Pb. Some of these measurements were used in the recent ENDF/B-8.0 evaluation. A new scattering detector array is in development which will extend the scattering measurement capabilities into the keV region. A review of these measurements and the current and future capabilities of the RPI LINAC will be presented.

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Investigation of the surrogate-reaction method through simultaneous gamma-decay and fission probability measurements

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Neutron-induced cross sections of short-lived nuclei are important for fundamental physics, nuclear astrophysics and applications in nuclear technology. Nevertheless, these measurements can be extremely challenging or even impossible to perform due to radioactivity of the targets involved. Indirect measurements through the surrogate-reaction method can help to overcome these difficulties.

The surrogate-reaction method relies on the use of an alternative reaction that will lead to the formation of the same excited nucleus as in the neutron-induced reaction of interest. The method has some validity boundaries regarding the angular-momentum and parity of the formed nucleus via the neutron-induced and the surrogate reaction.

In this contribution we will present the results of recent studies where we measured for the first time simultaneously the fission and gamma-decay probabilities induced by different surrogate reactions with 3He and 4He beams impinging on 238U and 240Pu targets. These data are very useful to assess to which extent the surrogate method can be applied in regions of the nuclear chart where no data exists. We will also present future plans and developments towards surrogate-reaction studies in inverse kinematics with radioactive-ion beams at storage rings.

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Neutron Capture Cross Sections for Short-Lived Nuclei from Surrogate Reaction Data and Theory

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Obtaining reliable data for nuclear reactions on unstable isotopes remains an extremely important task and a formidable challenge. Neutron capture cross sections – crucial ingredients for models of astrophysical processes, national security applications and simulations of nuclear energy generation – are particularly elusive, as both projectile and target in the reaction are unstable. Various methods have been proposed for determining capture cross sections from indirect measurements. The "surrogate reaction method" [1] uses inelastic scattering or transfer ("surrogate") reactions to produce the compound nucleus of interest and measure its subsequent decay. In principle, this data provides constraints for the models describing the decay of the compound nucleus, which dominate the uncertainties of the cross section calculations. Past applications of the surrogate approach assumed the decay to be independent of the mechanism that formed the compound nucleus. This approximation, which neglects the need to describe the surrogate reaction, works reasonably well for (n,f) cross sections [2], but has long been known to break down for capture reactions [3].

This contribution demonstrates that a proper theoretical description of the surrogate reaction mechanisms is key to overcoming the limitations encountered previously. Specifically, theoretical descriptions of the (p,d) and (d,p) transfer reaction have been developed to complement recent measurements in the Zr-Y-Mo region. The procedure for obtaining constraints for unknown capture cross sections is illustrated and indirectly extracted cross sections for both known (benchmark) and
unknown capture reactions are presented. The method makes no use of auxiliary constraining quantities, such as neutron resonance data, or average radiative widths, which are not available for short-lived isotopes; thus it can be applied to isotopes away from stability.


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Demonstrating the (d,p) Reaction as a Surrogate for (n,γ)

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Neutron-capture reactions are critically important to stellar nucleosynthesis and are important for societal applications including nuclear power generation and stockpile-stewardship science. However, due to the short half-lives of the nuclei that participate in these processes, direct measurements of the (n,γ) reaction cross section are very challenging or impossible. The difficulty in directly determining the (n,γ) reaction cross section has motivated the development of several indirect techniques for constraining it, one of which is the surrogate reactions method. This method indirectly determines the $A Z(n,γ)^{A+1}Z$ cross section by measuring the decay of the compound nucleus formed in the $X(α, χ)^{A+1}Z$ reaction, where α and χ are the entrance and exit channels, respectively.

The present contribution will discuss the performance of the surrogate reactions method in determining the cross section for the $^{95}$Mo($n$,γ) reaction through a measurement of the $^{95}$Mo($d$,pγ) reaction with the STAR-LiTeR particle-gamma spectrometer at Texas A&M University. Recently the ($d$,p) reaction mechanism has been described by Potel et al. [1], which enables the determination of the entry spin-parity distribution of the compound nucleus formed this reaction as a function of excitation energy. A method for determining the (n,γ) cross section has been developed by Escher et al. [2], who fit calculated γ-ray emission probabilities for states populated by the surrogate reactions in the compound nucleus to experimentally-determined values. The calculated γ-ray emission probabilities depend on Hauser-Feshbach parameters such as the γ-ray strength function and nuclear level densities, which, when constrained by Bayesian fits to experimental data, are used to calculate the (n,γ) cross section.

The (n,γ) reaction cross section as a function of neutron energy extracted from these measurements of the $^{95}$Mo($d$,pγ)$^{96}$Mo reaction is in excellent agreement with the directly-measured cross section for $^{95}$Mo($n$,γ) [3]. The present talk will summarize the experimental results, the theoretical modeling of the surrogate data to deduce the gamma-decay probabilities as a function of Jπ, and the comparison with the measured (n,γ) cross sections.

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Prospects for surrogate neutron capture measurements with radioactive ion beams and GODDESS

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Neutron capture reactions are responsible for the synthesis of almost all of the elements heavier than iron through the slow s-process, that proceeds close to the line of stability, and the rapid r-process, with very neutron-rich waiting points. Uncertainties in (n,γ) rates in neutron rich nuclei, especially near closed neutron shells, can have significant impact [1] on the predictions of final abundances for different astrophysical scenarios for the r process. Understanding (n,γ) rates on neutron-rich fission fragments is also important for nuclear forensics and stockpile stewardship science. Ratkiewicz et al. [2 and references therein] has recently demonstrated that the (d,γ) reaction is a valid surrogate for (n,γ), where the formation of the compound nucleus from the breakup of the deuterium has been calculated in a reaction model and the subsequent measured gamma-decay probabilities are reproduced with standard level density and strength functions in a Bayesian approach. In parallel to the surrogate validation efforts, we have demonstrated that the (d,γ) reaction can be measured in inverse kinematics with Gammasphere ORRUBA: Dual Detectors for Experimental Structure Studies (GODDESS) [3] where the Gammasphere array of Compton-suppressed HPGe detectors is coupled to the Oak Ridge Rutgers University Barrel Array of position-sensitive silicon strip detectors. During the commissioning campaign we measured the (d,γ) reaction with 134Xe and 95Mo beams, the latter to demonstrate the surrogate method in inverse kinematics. The present talk will present preliminary results from this campaign including γ-decay probabilities and prospects for surrogate (n,γ) measurements with 143Ba fission-fragment beams.

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Reaction mechanisms / 65

Faddeev Approach to (d,p) Reactions as Tool to Study Exotic Nuclei

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It is a particular interesting time for rare isotope science. Facilities in many countries have been or are in the process of being upgraded or newly built, and the physics community prepares to address the challenging science. A large fraction of the physics programs involve direct reactions with rare isotope beams, reactions which leave a good part of the beam nuclei intact.

While compound nuclear reactions involve many nucleon-nucleon interactions, direct reactions are usually fast and are often viewed as single-nucleon interactions. For example, single particle transfer reactions (d,p) involving rare isotopes continue to be an important tool for extracting nuclear structure information such as asymptotic normalizations coefficients, and contribute to the understanding of the dynamics of the reactions. The (d,p) reaction may be viewed as a three-body n+p+A problem, in which the deuteron and the nucleus A act as participants in the reaction. It is advantageous to consider this reaction within a Faddeev framework, which allows treating all channels on the same footing, independent if the nucleus A is heavy or light.

As first application we concentrate on the deuteron-alpha system, for which we calculate d+α elastic scattering below and above the three-body breakup threshold, as well as reaction cross sections and benchmark with calculations in the literature. The interactions in the respective two-body subsystems are given by multi-rank separable representations of realistic interactions based on the Ernst-Shakin-Thaler formulation, which are also successfully applied in calculating the ground state of ⁶Li as three-body system [1]. We also show that at very low energy the d+α exhibits universal behavior. For this initial work the Coulomb interaction is omitted. However, we note that for taking the Coulomb interaction exactly into account for heavy nuclei without employing screening procedures, it is necessary to use separable interactions in the subsystems.

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From neutron-nucleus interactions to (d,p) cross sections

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Deuteron-induced reactions have a long and fruitful tradition in nuclear physics as an experimental tool for spectroscopy. They have been extensively used to study in detail the single-particle nature of the low-lying spectrum of the nuclear quantum many-body system. Standard reaction theory describing the direct population of sharp bound states have been very successful in extracting detailed structural information from the experimental data, in the form of spin, parities, spectroscopic factors, etc., of the populated bound states. The advent of high intensity exotic beams have granted experimental access to weakly bound systems with a Fermi energy close to the neutron-emission threshold, where the role of the continuum becomes important. Within this context, new theoretical developments are called for, such as a reaction framework able to account for the population of resonant and non-resonant states of the continuum, adapted to the associated structure description of the target-neutron interaction. Aside from paving the way to the description of (d,p) reactions in exotic loosely bound nuclei in terms of state-of-the-art neutron-target interactions, such a framework can also be used to describe the formation of a compound nucleus in the neutron+target channel.
The formalism presented here is thus also an important theoretical ingredient for the use of (d,p) reactions as surrogates for neutron capture processes.

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Linking nuclear reactions and nuclear structure to study exotic nuclei

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An analysis of the $^{40}$Ca$(\epsilon,\epsilon'p)$ reaction including unpublished data is presented\(^1\) to assess whether the distorted-wave impulse approximation (DWIA) provides the correct reaction model when consistent overlap functions and distorted waves are employed that are provided by the dispersive optical model (DOM)\(^2\), which provides a unified description of both elastic nucleon scattering and structure information related to single-particle properties below the Fermi energy\(^3\). Recent extensions of this framework have been introduced that include a fully nonlocal implementation for $^{40}$Ca\(^4\). For the first time properties below the Fermi energy like the charge density and the presence of high-momentum nucleons can be included in the DOM description. Application of the nonlocal DOM to $^{48}$Ca incorporates the effect of the 8 additional neutrons and allows for an excellent description of elastic scattering data of both protons and neutrons\(^6\). The corresponding neutron distribution constrained by all available data generates a prediction for the neutron skin of $0.249 \pm 0.023$ fm for this nucleus\(^6\) which is larger than most mean-field and available ab initio results.

We report on the most recent developments including a nonlocal DOM analysis for $^{208}$Pb, an extension to heavier Ca isotopes, an analysis of the energy density in comparison with ab initio nuclear matter calculations, applications to transfer reactions with DOM ingredients, extensions to $(p, p\pi)$ reactions and the aforementioned reanalysis of $(\epsilon, \epsilon'p)$ data\(^1\) to determine if experimental data can constrain the magnitude of absolute spectroscopic factors.

Probing the properties of nucleons in exotic nuclei mostly requires dealing with strongly interacting probes as for example in transfer or knock-out reactions. The present DOM analysis provides an excellent starting point for a consistent analysis.


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News from Gogny based optical potential

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We present new results obtained with the Nuclear Structure Method for scattering based on Gogny interaction. The method is extended to neutron and proton elastic scattering off $^{16}$O, $^{40-48}$Ca, $^{90}$Zr and
208 Pb targets for incident energy below 40 MeV. Then, we present a systematic protocol to compare nonlocal potentials obtained from different methods either microscopic or more phenomenological. Ongoing developments regarding target nuclei with pairing will be exposed.

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