利用中高能核反应研究原子核结构

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原子核结构与中高能重离子碰撞交叉学科理论讲习班 • 湖州 • 2021年7月10-23日

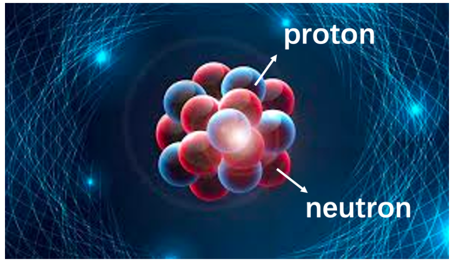
1. 这个暑期学校内容很好，重离子碰撞 ： 中低能核物理，输运模型
2. 实验 ： 理论
3. 嗓子疼，声音小的时候，请大家提醒我下
4. 如果有问题的话，欢迎随时打断

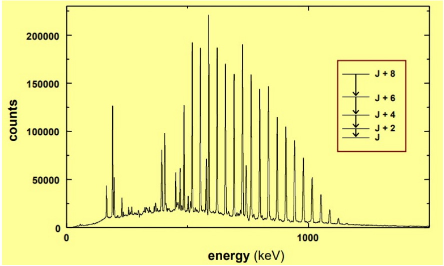
Content

- Basic concept
- Structure by intermediate and high energy nuclear reactions
- Summary & Perspective

Atomic nuclei

- One of the most complicate quantum many-body systems
  - Proton and Neutron
  - Strong force, weak force, electromagnetic force
  - isospin, spin, excitation energy …
  - single-particle vs. collective
  - … …



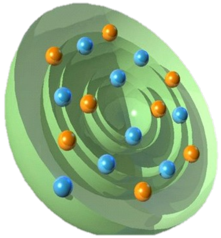


- Almost impossible to build an exact replica of nuclear system

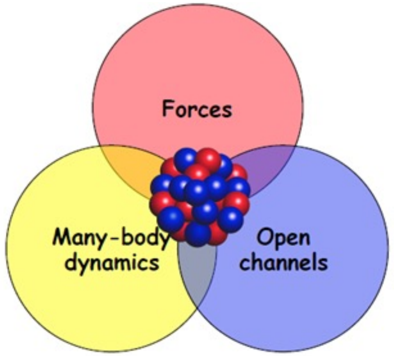
  for a medium-heavy nuclide with A~50,

  even only considering 2-body interaction,

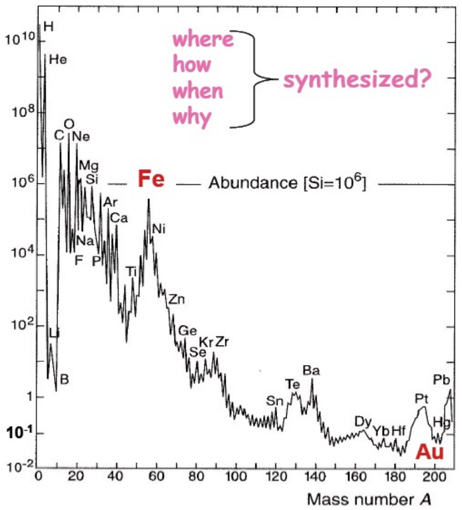
  this means $50!=10^{64}$ terms



Open questions in nuclear physics



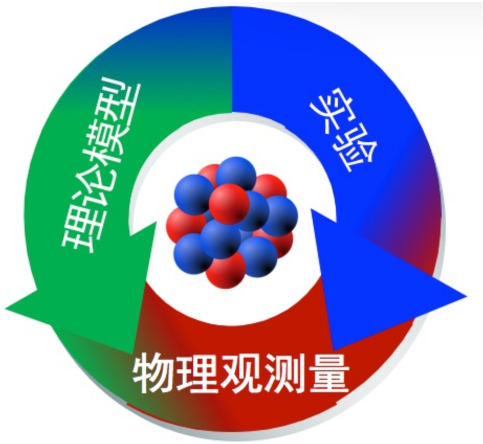
- How to describe nuclear force?
  - What are the limits to nuclear existence (dripline, heaviest system)?
  - How do the quantum levels evolve with isospin?
  - How do simple patterns appear in complex nuclei?
  - How do collective phenomena emerge from simple constituents?
  - ……
- How do nuclei shape the physical universe?
- What is the origin of elements in our universe?

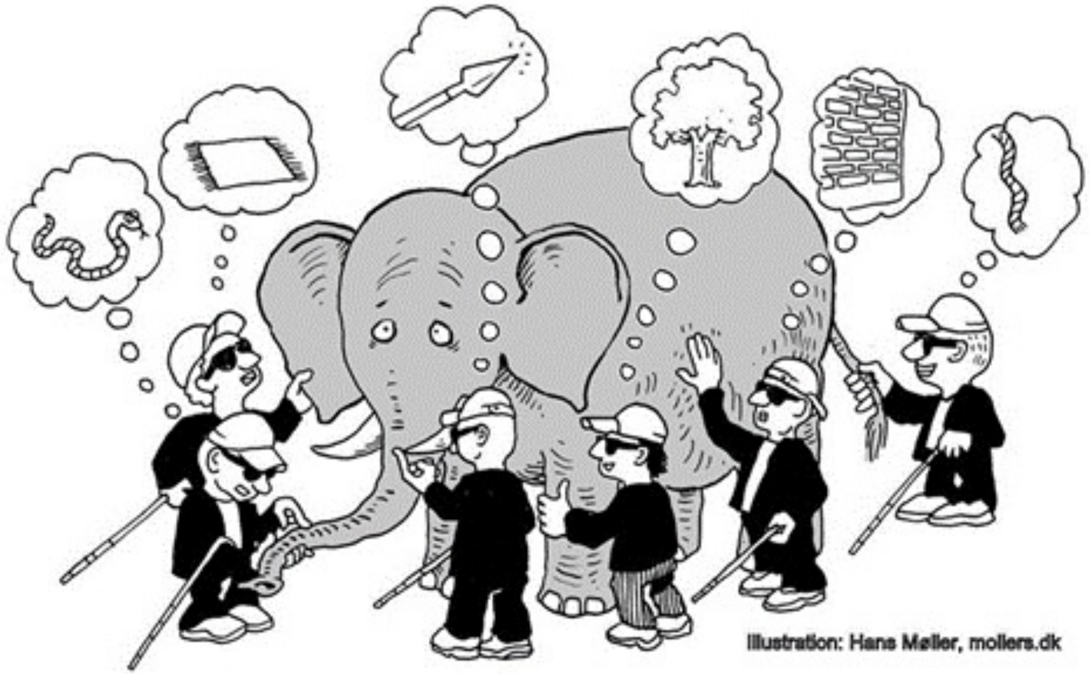


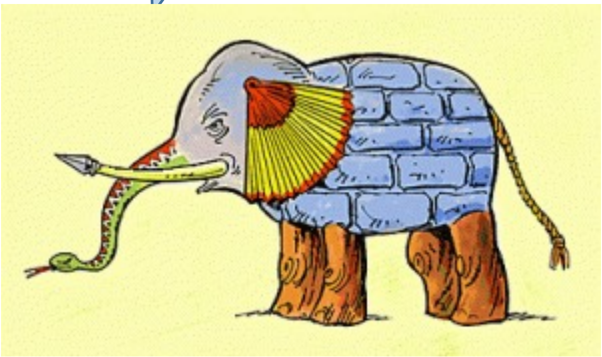
Nuclear experiments/theories are getting more and more complicated.

Putting puzzle pieces together, to see the full picture of the “atomic nuclide puzzle” emerge !

Mass,
decay,
size,
reaction,
etc.



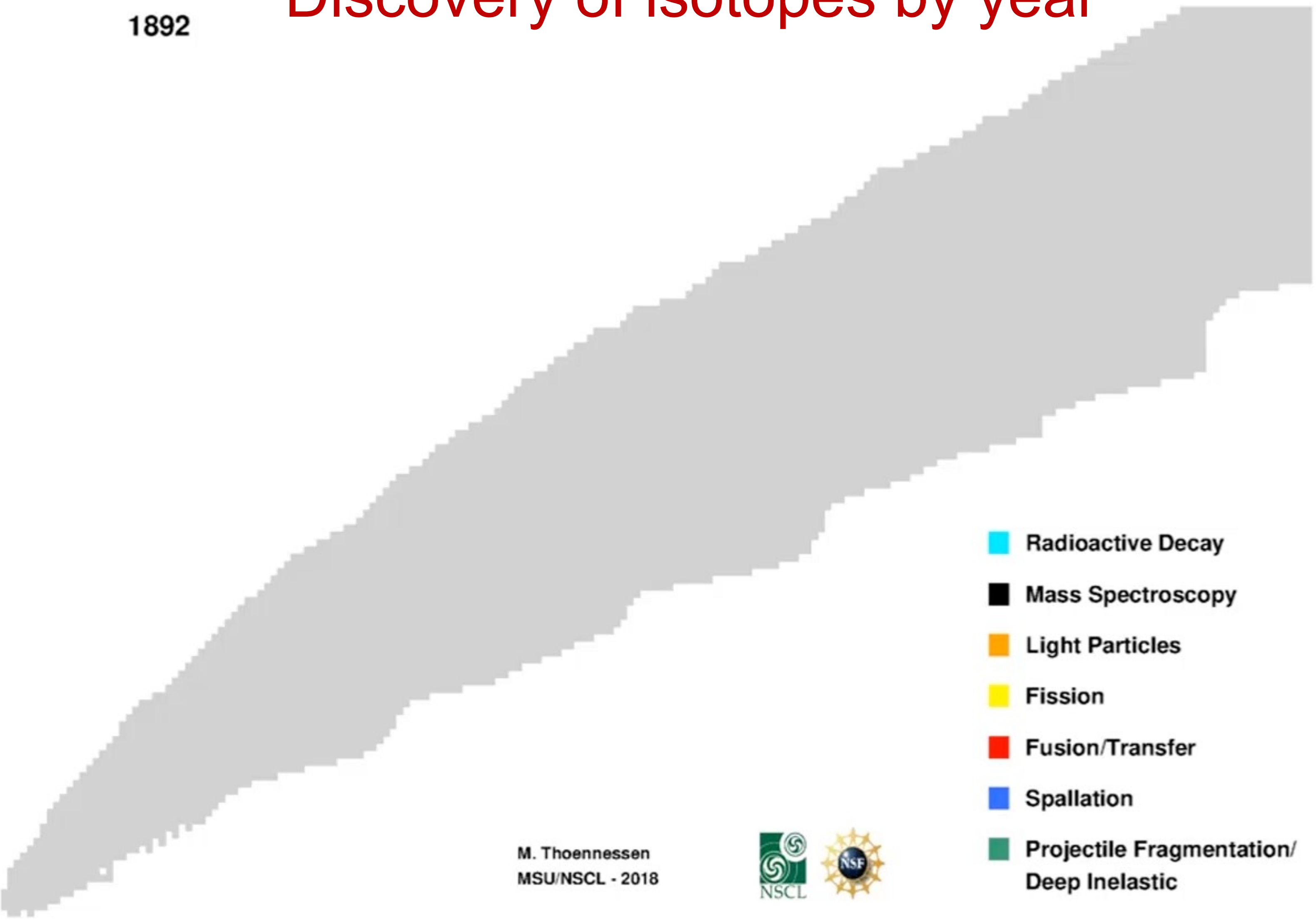




As an experimentalist, I like simple experiments and like to get a “simple” imagine of nuclide.

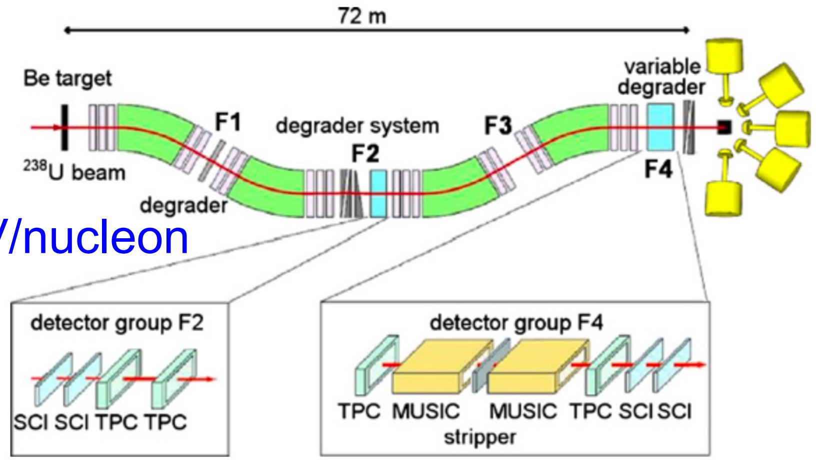
Nuclear reaction can not only be used to produce new isotopes, but also a crucial
way to reveal nuclear structure problems.

Discovery of isotopes by year



https://people.nscl.msu.edu/~thoennes/isotopes/

Projectile fragmentation cross section at FRS, GSI



1GeV/nucleon

60 new neutron-rich isotopes in the atomic number range of Z=[60-78]

Physics Letters B 717 (2012) 371–375

Contents lists available at SciVerse ScienceDirect

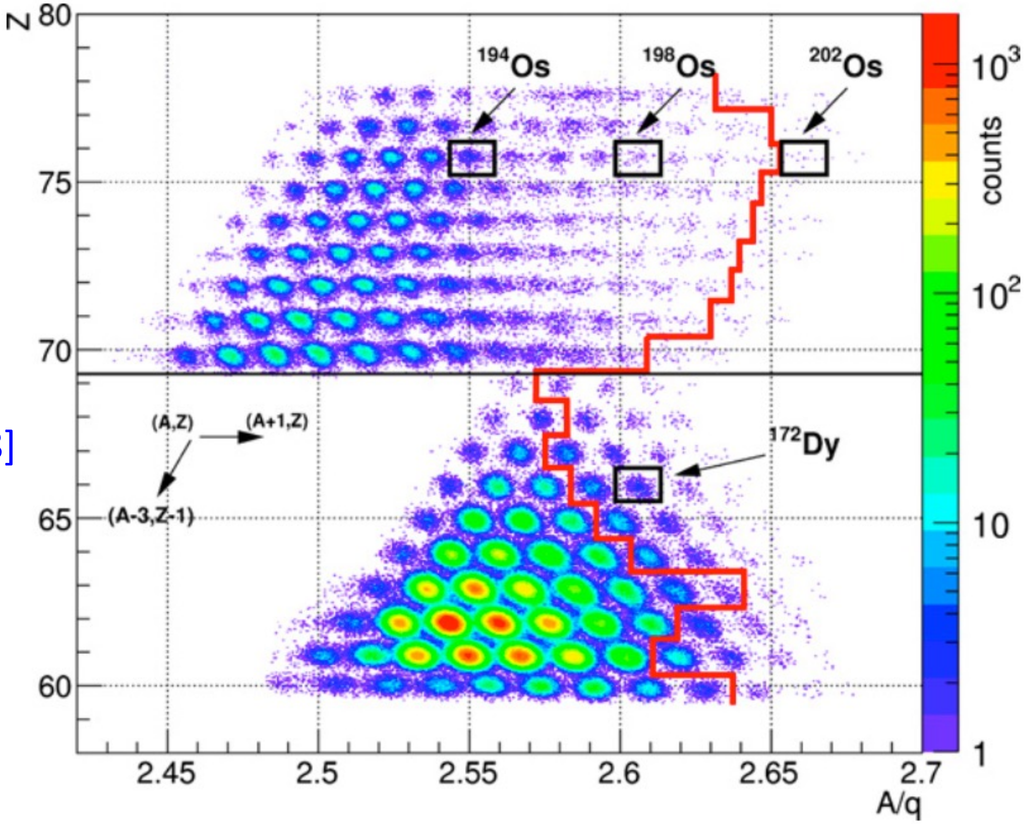
Physics Letters B

www.elsevier.com/locate/physletb

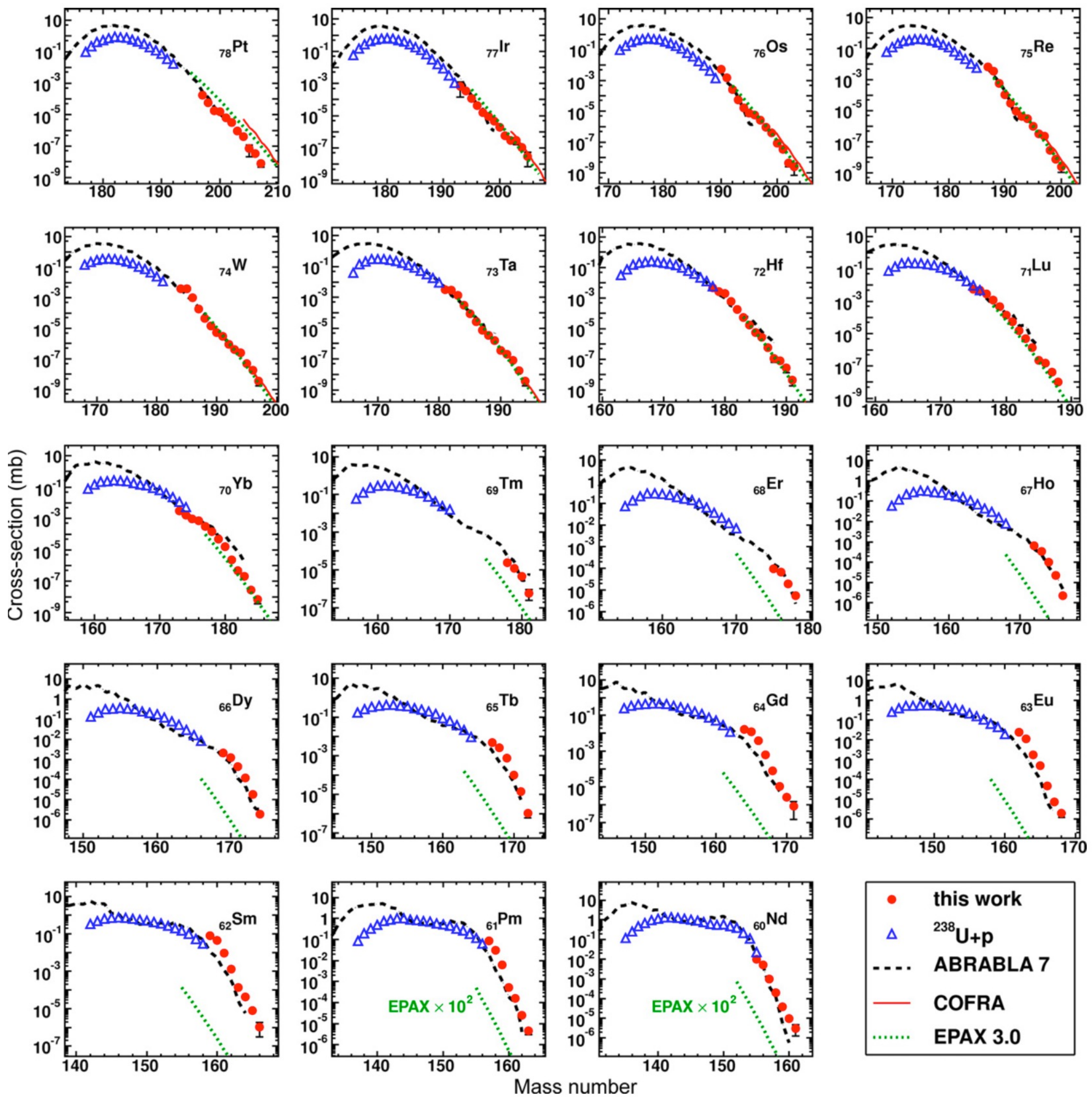
ELSEVIER

Discovery and cross-section measurement of neutron-rich isotopes in the elemen
range from neodymium to platinum with the FRS

J. Kurcewicz[a,*], F. Farinon[a,b,1], H. Geissel[a,b], S. Pietri[a], C. Nociforo[a], A. Prochazka[a,b], H. Weick[a], J.S. Winfield[a], A. Estradé[a,c], P.R.P. Allegro[d], A. Bail[e], G. Bélier[e], J. Benlliure[f], G. Benzoni[g], M. Bunce[h], M. Bowry[h], R. Caballero-Folch[i], I. Dillmann[a,b], A. Evdokimov[a,b], J. Gerl[a], A. Gottardo[j], E. Gregor[a], R. Janik[k], A. Kelić-Heil[a], R. Knöbel[a], T. Kubo[l], Yu.A. Litvinov[a,m], E. Merchan[a,n], I. Mukha[a], F. Naqvi[a,o], M. Pfützner[a,p], M. Pomorski[p], Zs. Podolyák[h], P.H. Regan[h], B. Riese[a,b], M.V. Ricciardi[a], C. Scheidenberger[a,b], B. Sitar[k], P. Spiller[a], J. Stadlmann[a], P. Strmen[k], B. Sun[b,q], I. Szarka[k], J. Taïeb[e], S. Terashima[a,l], J.J. Valiente-Dobón[j], M. Winkler[a], Ph. Woods[r]



$$\sigma_f = \frac{N_f}{N_p N_t \epsilon}$$



Deviation at most neutron-rich nuclei

Theoretical developments in China by

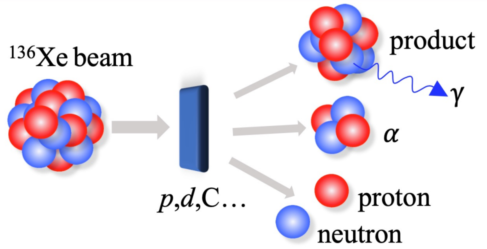
梅波

马春旺

等等

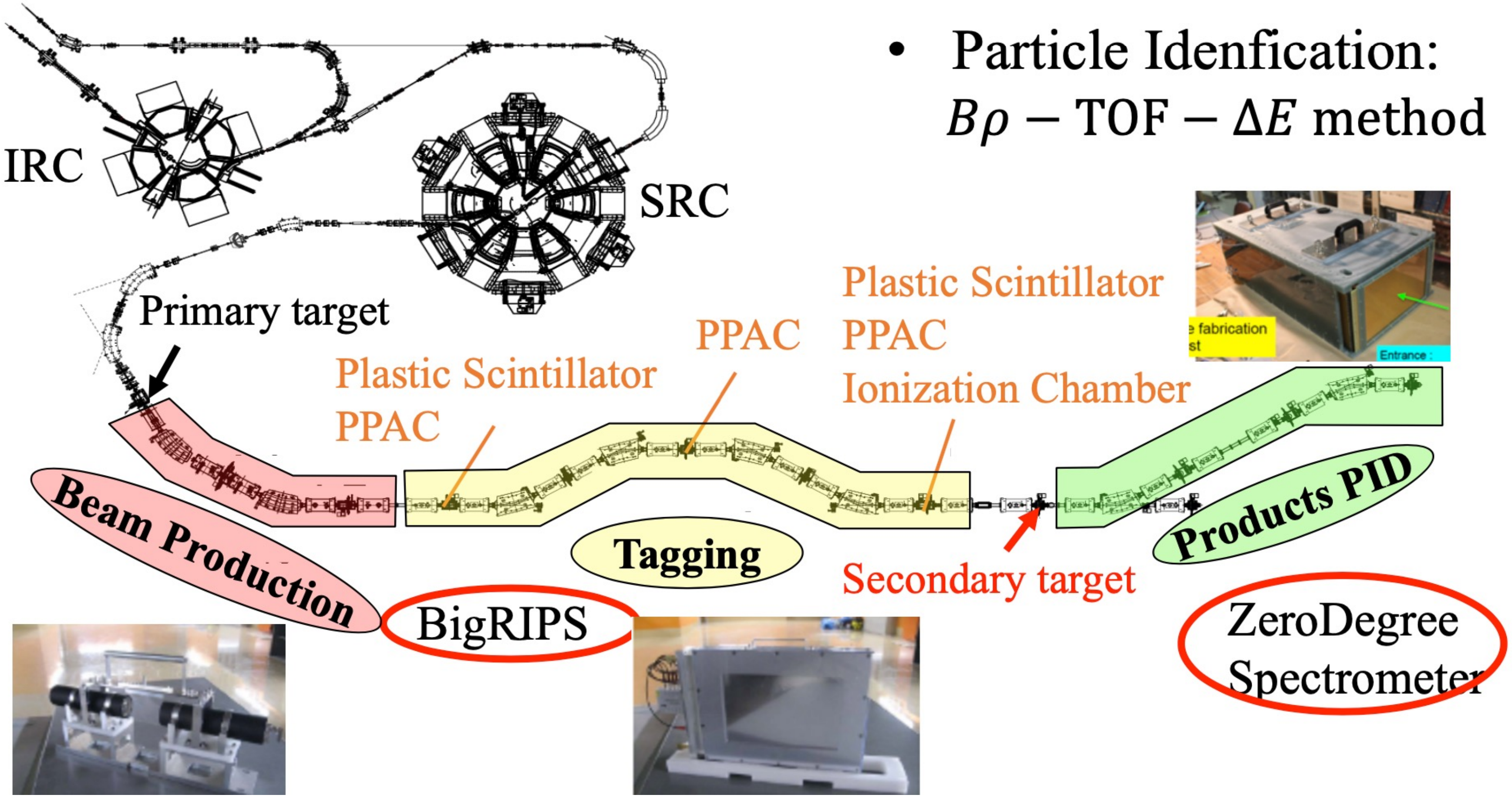
RIBF: BigRIPS + ZeroDegree

孙晓慧@湖州师范大学



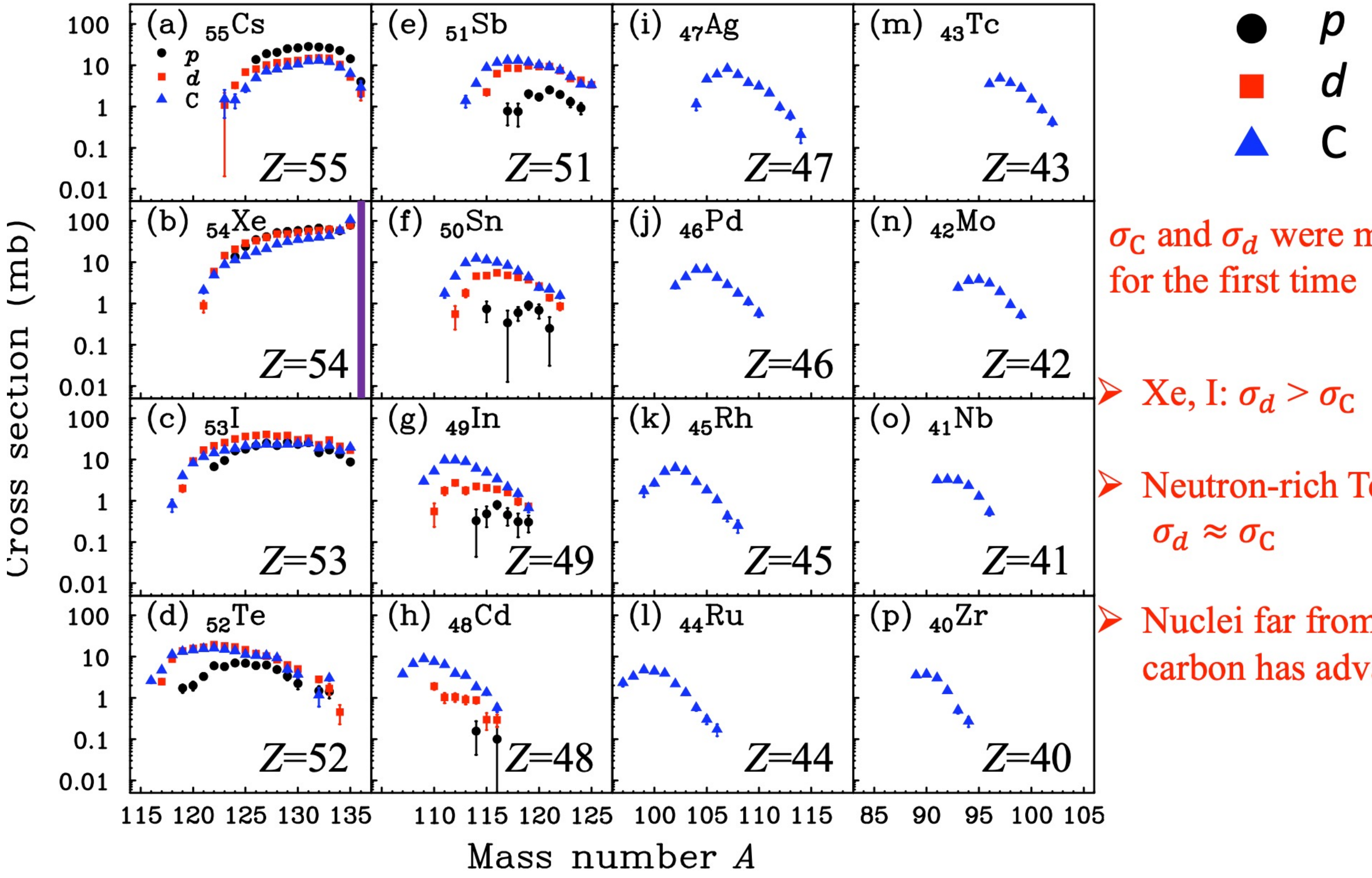
- Secondary beams (^{136}Xe/^{137}Cs/^{107}Pd…) were produced by 345 MeV/u ^{238}U + ^{9}Be.

- Particle Idenfication:
  $B\rho - \mathrm{TOF} - \Delta E$ method



^{136}Xe Results: $\sigma_p, \sigma_d, \sigma_C$ at 168 MeV/u

Obtained cross sections from Cs ($\Delta Z = +1$) to Zr ($\Delta Z = -14$)



σ_C and σ_d were measured for the first time

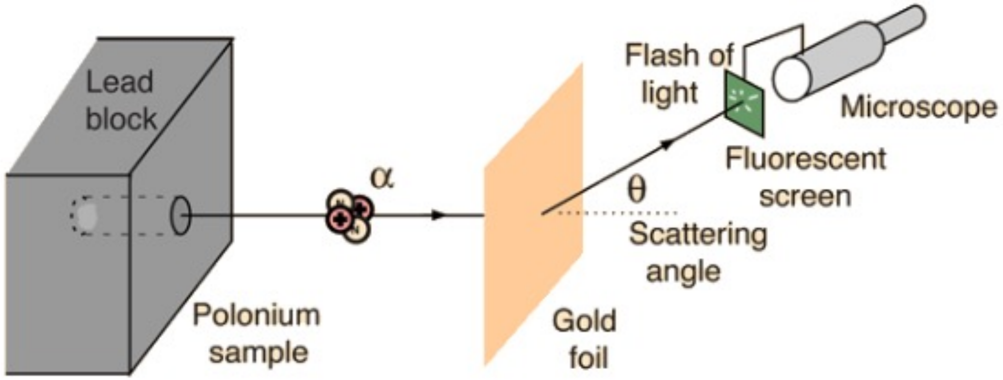
- Xe, I: $\sigma_d > \sigma_C$
- Neutron-rich Te-In: $\sigma_d \approx \sigma_C$
- Nuclei far from ^{136}Xe : carbon has advantage

A reliable mode to predicate the production rate of most n-rich nuclides is a key question.

It is essential for a reliable estimation of advance experiments!

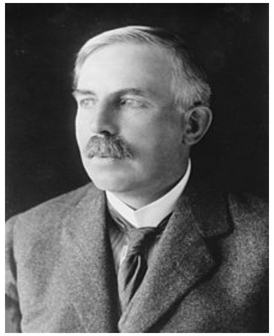
First nuclear size estimation ever

Rutherford scattering: alpha scattering on a gold foil



Hans Geiger
1882-1945

Ernest Marsden
1889-1970



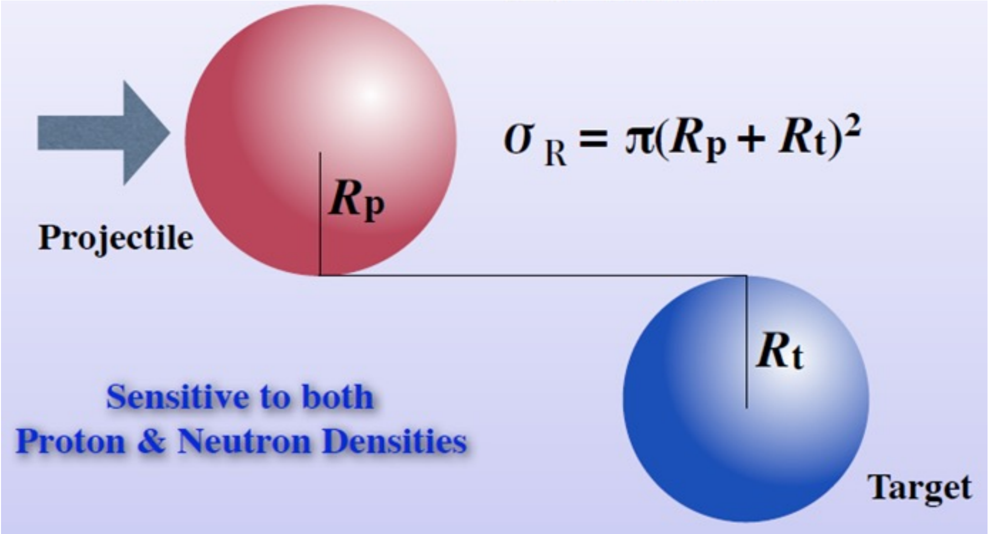
Ernest Rutherford
1871-1937

Geiger, H.; Marsden, E. (1909). "On a Diffuse Reflection of the α-Particles". Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences. 82 (A): 495–500.

Nuclear size from geometric model

- reaction cross section $\sigma_R = \sigma_{tot} - \sigma_{elastic}$

Hard sphere



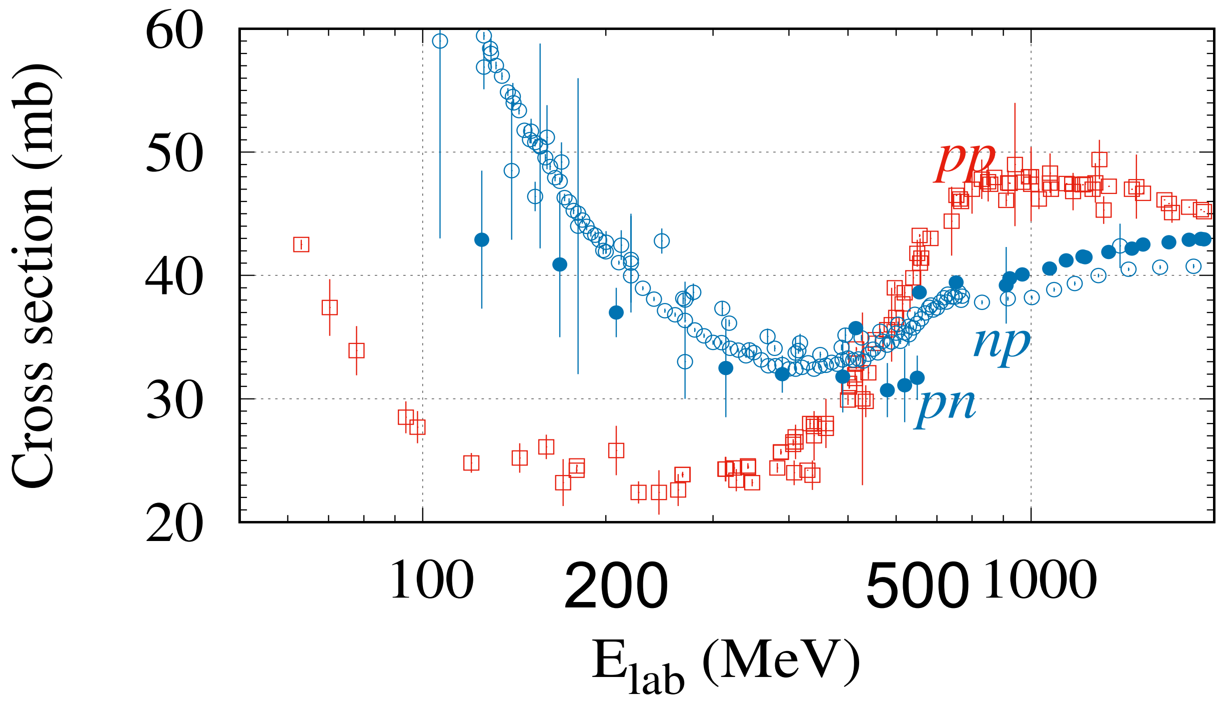
At high energy,

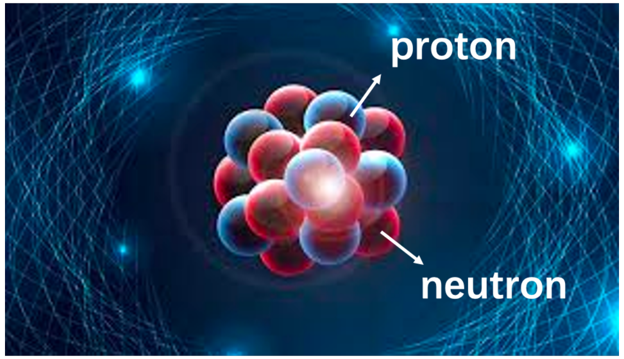
Interaction cross section σ_I,

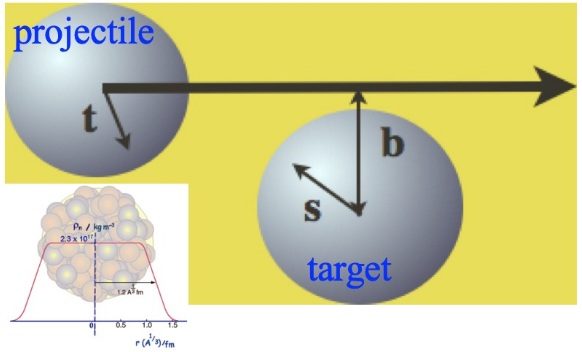
$\sigma_I = \sigma_R - \sigma_{inelastic} \approx \sigma_R$

Use hadronic probes (proton, alpha, heavy ions) to study atomic nuclei

Structure revealed by nuclear collisions







>200 MeV/nucleon: Eikonal model
(sudden approximation, Eikonal approximation)

Reaction cross section can be easily formulated in a microscopic way, relying only on the nuclear matter density distribution and the bare nucleon-nucleon interaction

Cross section and nucleon density/rms radii

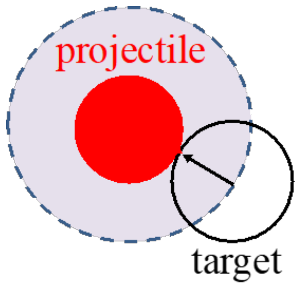
Glauber model for interaction (reaction) cross sections works very well from 30A to 1000A MeV. Energy dependence of the cross section provided a mean to determine the density distribution of nucleons.

Optical limit (an example)

$$\sigma_I(P,T) = \int [1 - T(b)]\, d\mathbf{b}$$

$$T(\mathbf{b}) = \exp[-\sigma_{pp} \int \{\rho_{Pp}(\mathbf{r}-\mathbf{b}) \cdot \rho_{Tp}(\mathbf{r}) + \rho_{Pn}(\mathbf{r}-\mathbf{b}) \cdot \rho_{Tn}(\mathbf{r})\} d\mathbf{r}$$

$$- \sigma_{pn} \int \{\rho_{Pp}(\mathbf{r}-\mathbf{b}) \cdot \rho_{Tn}(\mathbf{r}) + \rho_{Pn}(\mathbf{r}-\mathbf{b}) \cdot \rho_{Tp}(\mathbf{r})\} d\mathbf{r}]$$



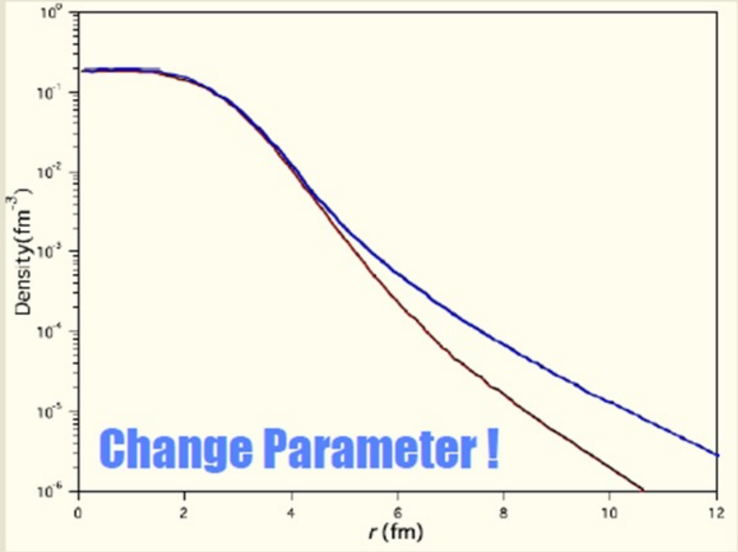
σ_{pp}, σ_{pn}: nucleon-nucleon total cross section

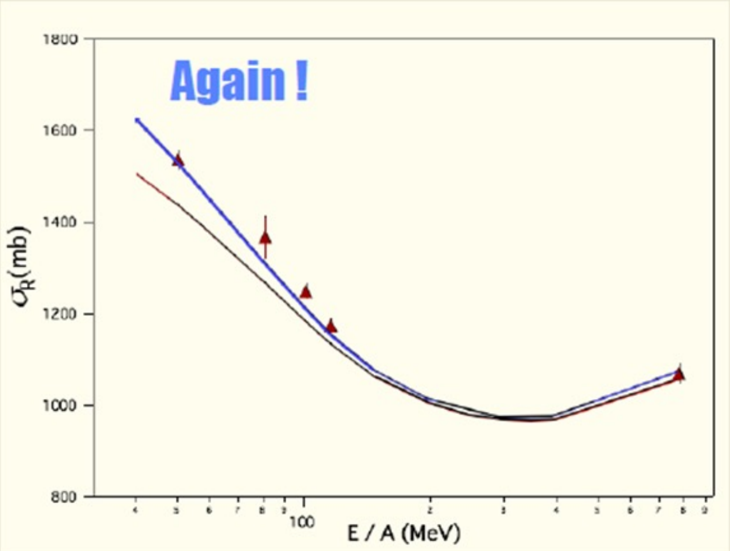
ρ_{Pp}, ρ_{Pn}: proton, neutron distribution of projectile

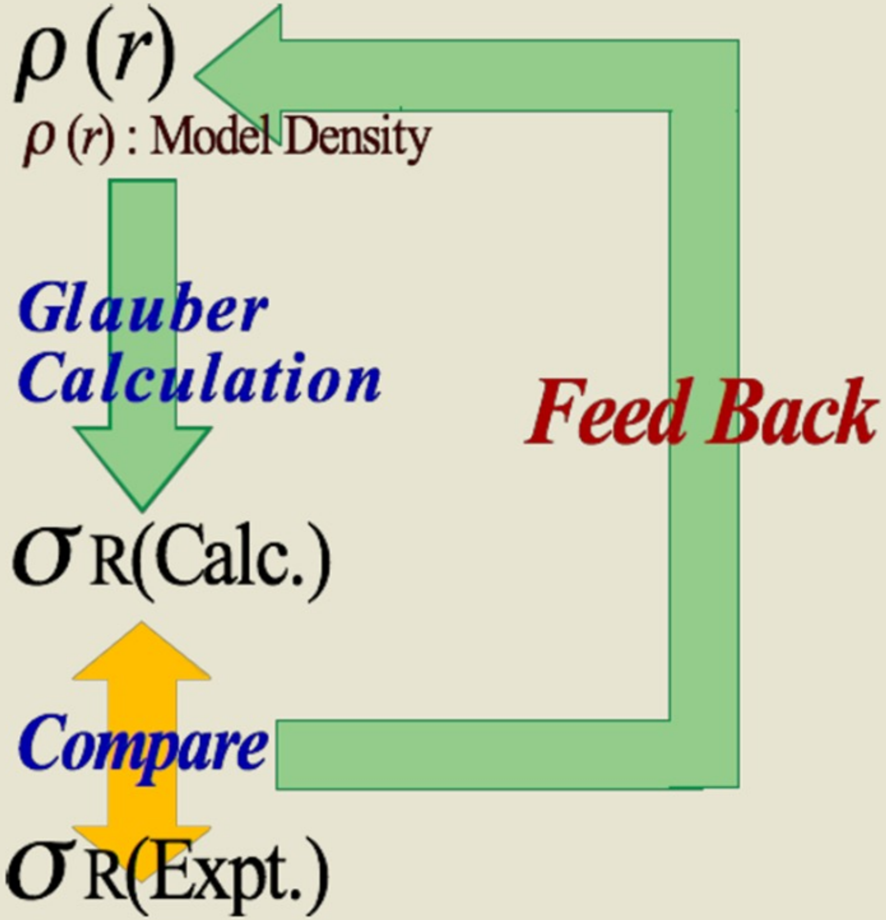
ρ_{Tp}, ρ_{Tn}: proton, neutron distribution of target

How to Deduce Nucleon Density

~ χ^2 fitting procedure ~







M. Fukuda

Properties can be revealed by various reactions

- 电荷改变反应：电荷半径，电荷密度分布
- 相互作用反应：物质分布半径，物质密度分布
- 同位素产生反应：Fragmentation/fission, 反应机制
- 电荷交换反应：弱相互作用强度，同位旋-自旋激发
- 敲出反应、动量分布：单粒子轨道，短程关联
- 核子拾取反应：短程关联，张量力
- 库伦激发：单粒子轨道，集体效应
- 单核子激发： 核子的介质效应
- …

Tensor force effect by $^{16}O(p, pd)$

S. Terashima et al., PRL121, 242501(2018)

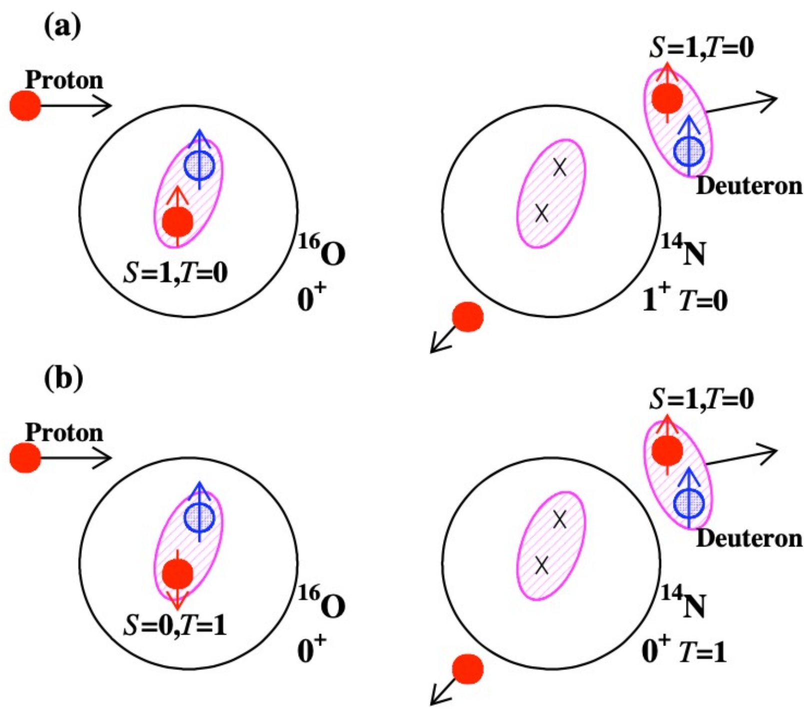


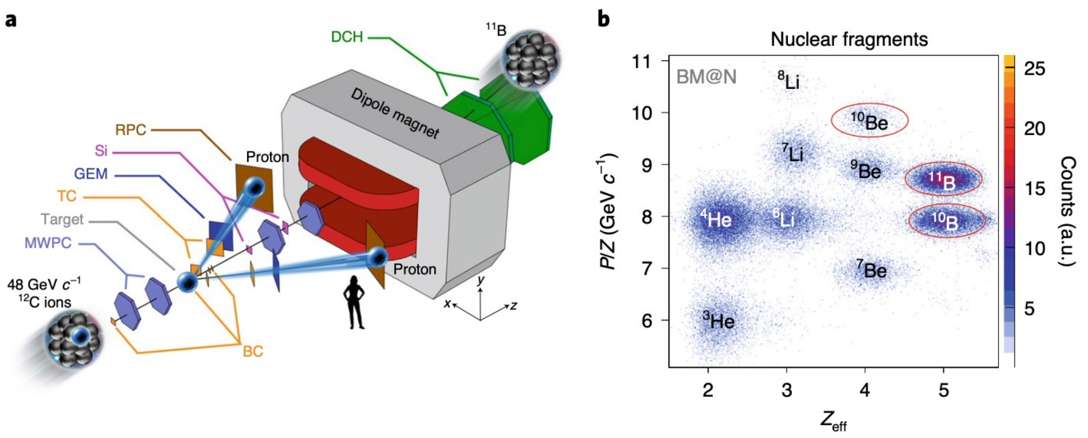
FIG. 1. Schematic view of neutron pickup reaction with coincidence with a proton assuming (a) a $S, T = 1, 0$ correlated pair and (b) a $S, T = 0, 1$ correlated pair at the initial states in the (p, pd) reaction.

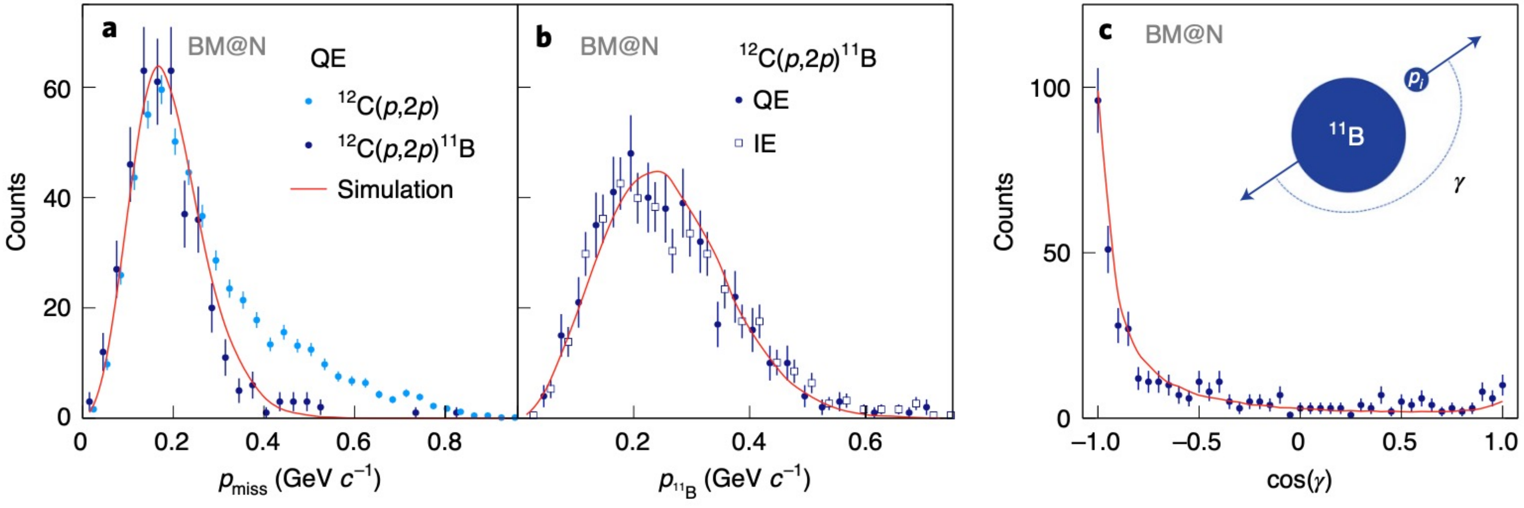
The isospin character of p-n pairs at large relative momentum has been observed for the first time in the ^{16}O ground state. A strong population of the J, T = 1; 0 state and a very weak population of the J, T = 0; 1 state were observed in the neutron pickup domain of $^{16}O(p,pd)$ at 392 MeV. This strong isospin dependence at large momentum transfer is not reproduced by the distorted-wave impulse approximation calculations with known spectroscopic amplitudes. The results indicate the presence of high-momentum protons and neutrons induced by the tensor interactions in the ground state of ^{16}O.

Short-range correlations by nucleon knockout measurements

Nature Physics, 17, 6930699(2021)

$^{12}C(p,2p)^{11}B$





Momentum distributions and angular correlation

identified short-range correlated nucleon–nucleon pairs and provide direct experimental evidence for separation of the pair wavefunction from that of the residual many-body nuclear system

重离子加速器装置

- GSI/FRS, RIKEN/BigRIPS, HIMAC, HIRFL/RIBLL2, >200 MeV/nucleon放射性次级束流线

Courtesy: 张玉虎

Content

- Basic concept
- Structure by intermediate and high energy nuclear reactions
  - Reaction cross section, charge-changing reaction
  - Nucleon removal reaction
  - Fragmentation cross section
  - Charge-exchange reaction
  - Complete-kinematics reaction

From simple to advanced
From integrated to differential cross sections
From inclusive to exclusive

- Summary & Perspective

按入射粒子能量分

- 低能核反应：入射粒子的单粒子能量 *E* 比靶核内的核子的费米动量（约 30 MeV）低。出射粒子的数目一般最多是 3~4 个。
- 中能核反应：指单粒子能量 30< $\frac{E}{A} < 1000$ MeV。可以使靶核散裂成许多碎片。当 $\frac{E}{A} > 200$ MeV，还可以产生介子。
- 高能核反应：指 $\frac{E}{A} > 1000$ MeV 的核反应。此时除可以产生介子外，还可以产生其它一些基本粒子和形成奇异核。

反应截面 (Cross section)

– 物理意义：一个粒子入射到单位面积内只含一个靶核的靶子上所发生的反应概率

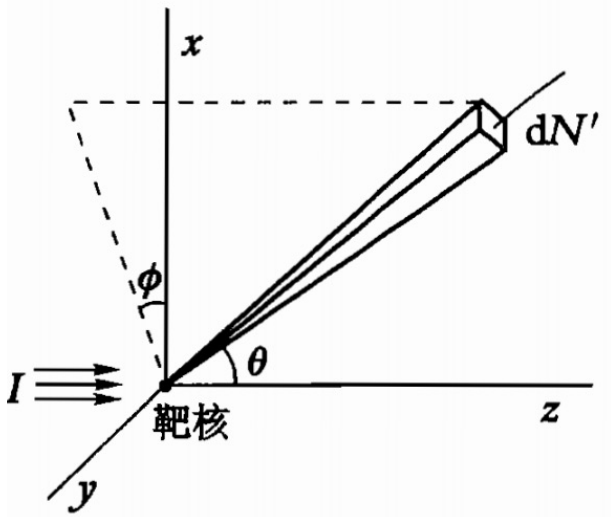
$$\sigma = \frac{N'}{IN_s} = \frac{\text{单位时间发生的反应数}}{\text{单位时间的入射粒子数} \times \text{单位面积的靶核数}}$$

– 或者说，一个入射粒子同单位面积靶上一个靶核发生反应的概率

– 具有面积的量纲。大多数情况下小于或等于原子核的横截面 $\boldsymbol{\pi R^2}$，即约 $\mathbf{10^{-24}}\mathrm{cm}^2$

- 单位：

1 靶（b） = 10^{-24} cm^2
1 毫靶（mb） = 10^{-27} cm^2
1 微靶（μb） = 10^{-30} cm^2



Cross section

– 微分截面(differential cross section)

$$\sigma(\theta,\phi)=\frac{d\sigma}{d\Omega}=\frac{\mathrm{dN}'}{N_0N_td\Omega}=\frac{\text{单位时间出射至}(\theta,\varphi)\text{方向单位立体角内的粒子数}}{\text{单位时间的入射粒子数}\times\text{单位面积的靶核数}}$$

$$\sigma(\theta)=\frac{d\sigma}{d\theta}=\int_0^{2\pi}\sigma(\theta,\phi)d\phi$$

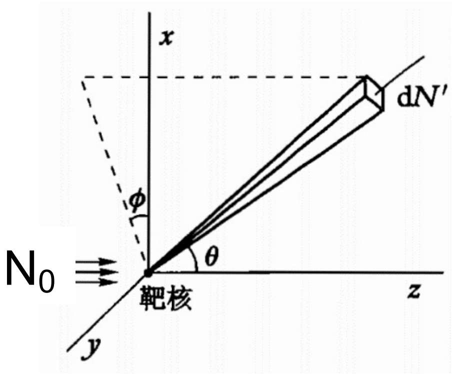
靶恩/球面度（$b\cdot \boldsymbol{sr^{-1}}$）

– 分截面 (partial cross section)

e.g., partial cross section $\sigma_{if}(Zi\to Z_f)$

charge-changing cross section $\sigma_{\mathrm{DZ}}=\sum_{f\neq i}\sigma_{if}(Zi\to Z_f)$

interaction cross section $\sigma=\sum\sigma_i=\frac{N\prime}{N_0N_t}$



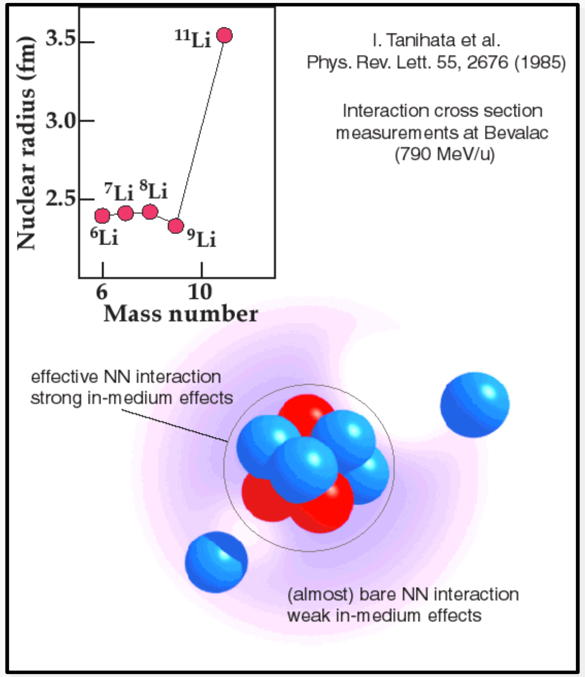
– 总截面（ total cross section ）

$$\mathrm{N}'=IN_s\int_\Omega\sigma(\theta,\phi)d\Omega=IN_s\int_0^{2\pi}\int_0^{\pi}\sigma(\theta,\phi)\sin\theta\,d\theta d\phi$$

Integrated cross sections:
Reaction cross section,
Interaction cross section,
Charge-changing cross section,
Total neutron removal cross section

Nuclear sizes:
rms proton radius
Rms matter radius
Neutron-skin thickness, Equation of state

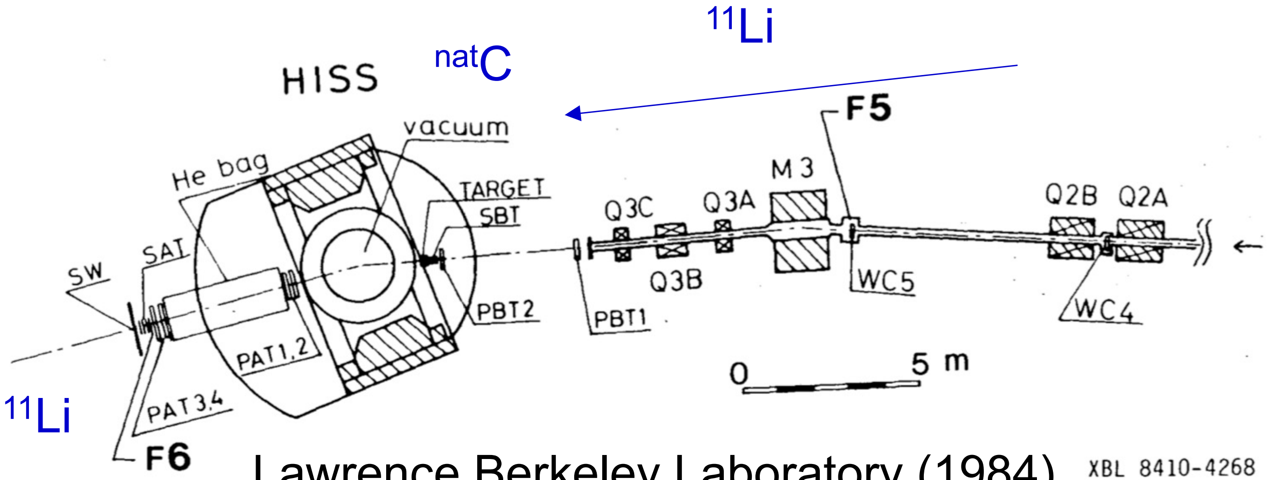
Discovery of halo-nuclide ^{11}Li



$R = r_0 A^{1/3}$

$r_0 = 1.2$ fm

Simple experiment!

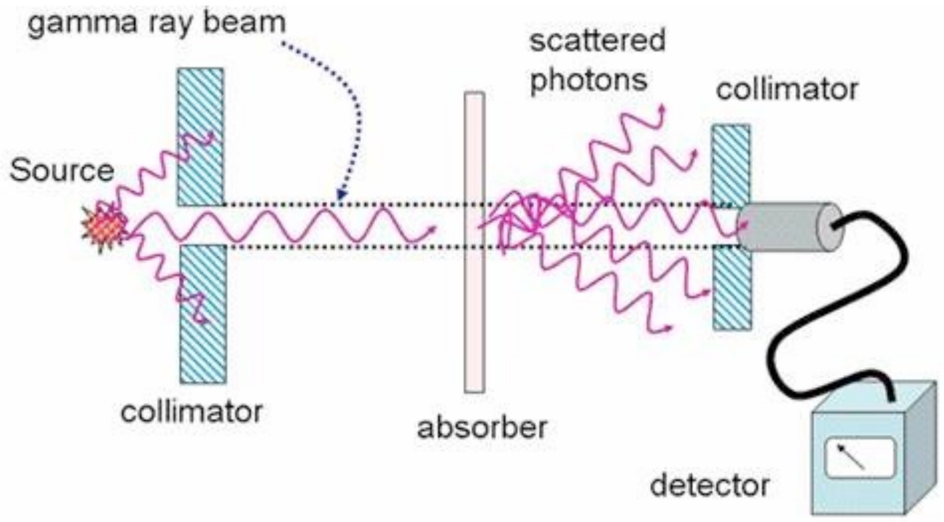


Lawrence Berkeley Laboratory (1984)

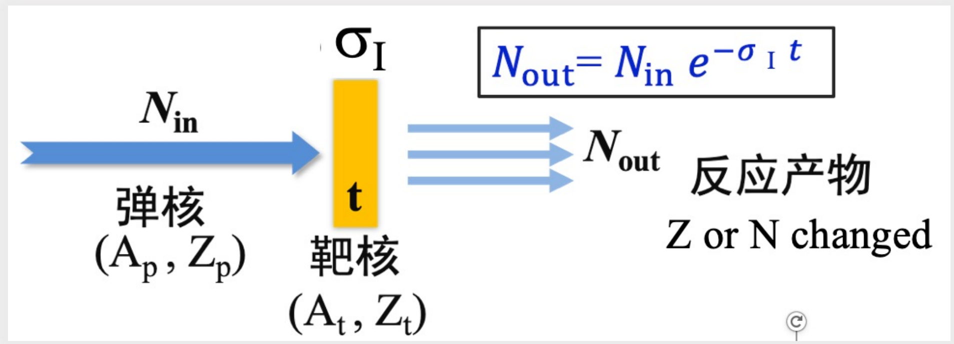
Tanihata et al., Phys. Rev. Lett. 55 (1985) 2676
Hansen & Jonson, Europhys. Lett. 4(1987)409

Nuclei far from stability line can show different structure or phenomenon as those stable nuclei, which triggered the radioactive ion beam physics

Interaction cross section by transmission method



$$N_{out} = N_{in} e^{-\mu t}$$

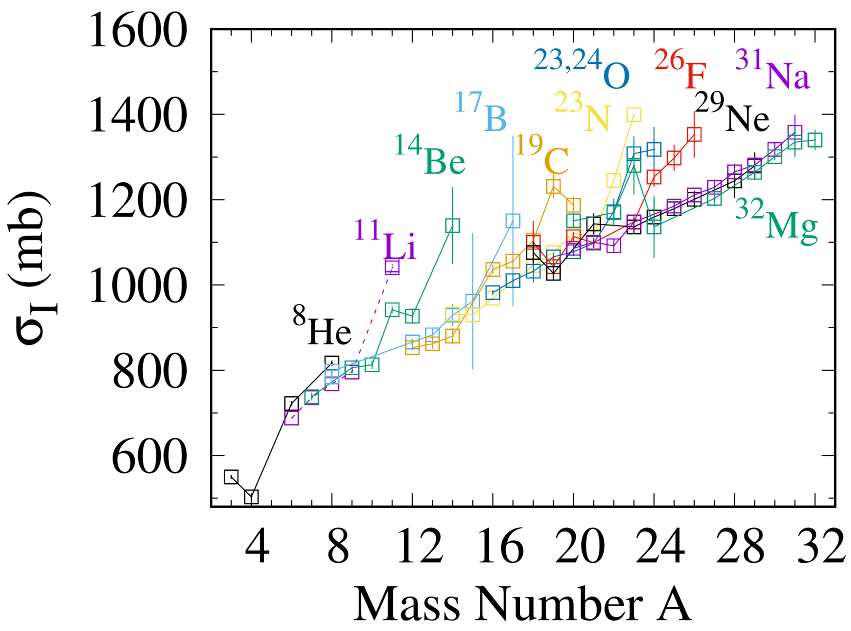


$\sigma_I \rightarrow R_m$

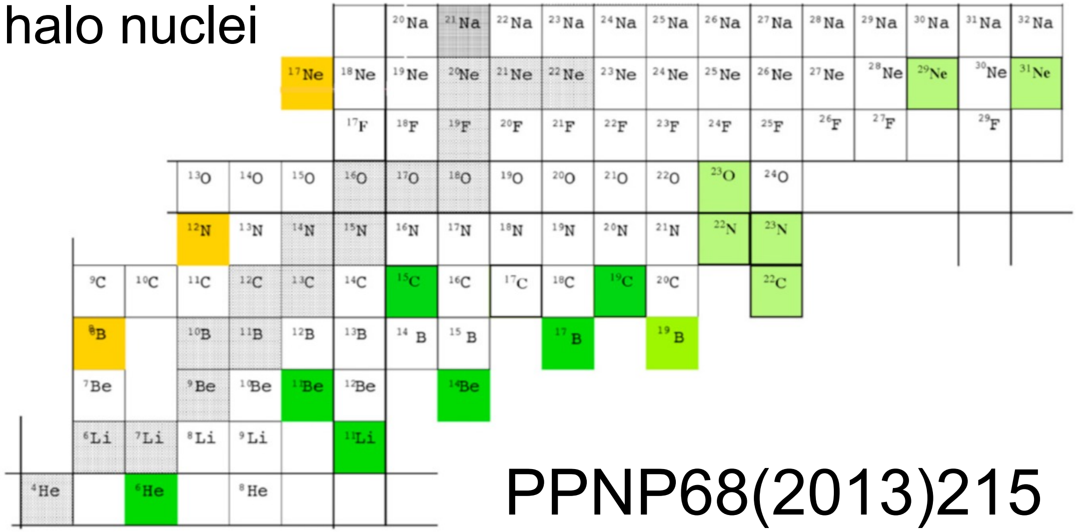
σ_I : the reaction probability of losing nucleons from the projectile nuclide after collision. Within the framework of Glauber model, it can be correlated with mass density distribution, and thus rms mass radii.

Systematic studies of Interaction cross sections over years

$\sigma_I \propto A^{2/3}$



halo nuclei



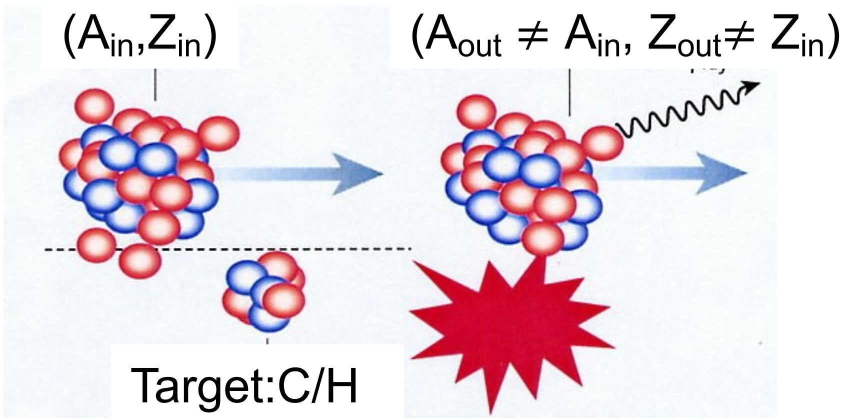
PPNP68(2013)215

Providing first hand information for most exotic light nuclei

reaction c.s. vs. charge changing c.s.

Hadronic interaction → Universal, simple and controllable, absolute measurements

- Reaction cross section: σ_R → nuclear matter radius



Integrated cross section

$$\sigma_R = \Sigma\sigma_i(Z_R \neq Z_p, A_R \neq A_p)$$

the reaction probability of changing nuclear species after collision, and are correlated with the nucleon density distribution in projectile

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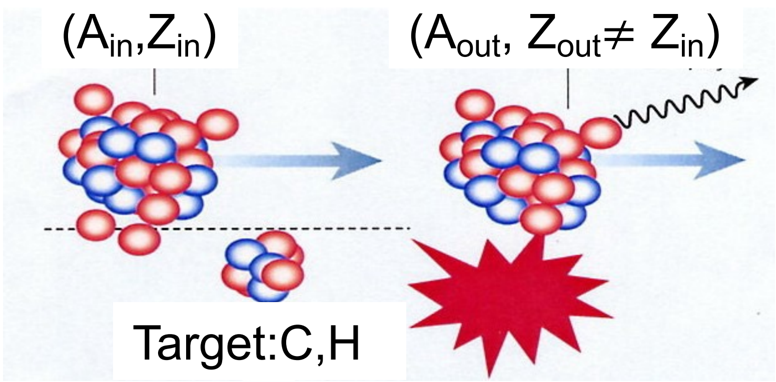
- Charge-Changing c.s. : σ_{cc} → nuclear charge radius

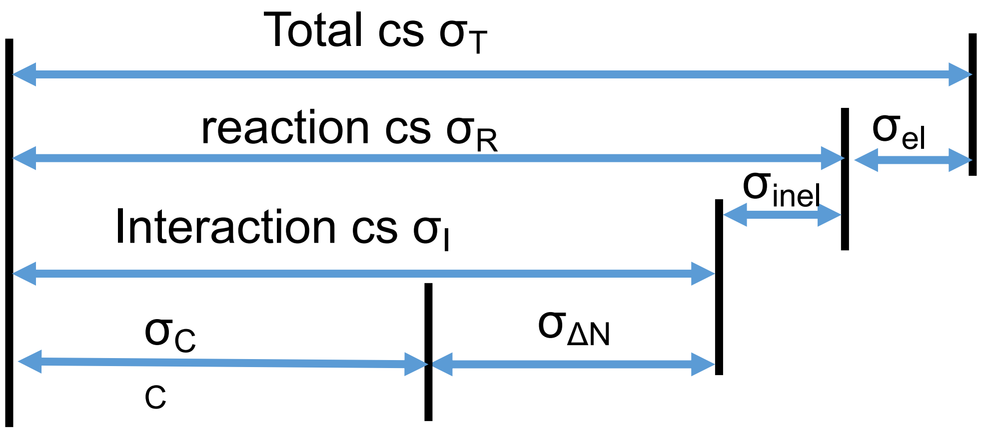


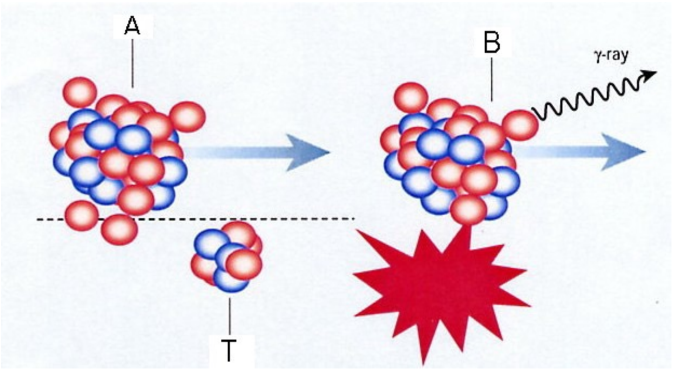
Integrated cross section

$$\sigma_{cc} = \Sigma\sigma_i(Z_R \neq Z_p)$$

the reaction probability of changing element after collision, and are correlated with the proton density distribution in projectile

Definition of cross sections





σ_T: total cross section

σ_R: reaction cross section, $\sigma_R = \sigma_T - \sigma_{el}$ (elastic scattering cross section)

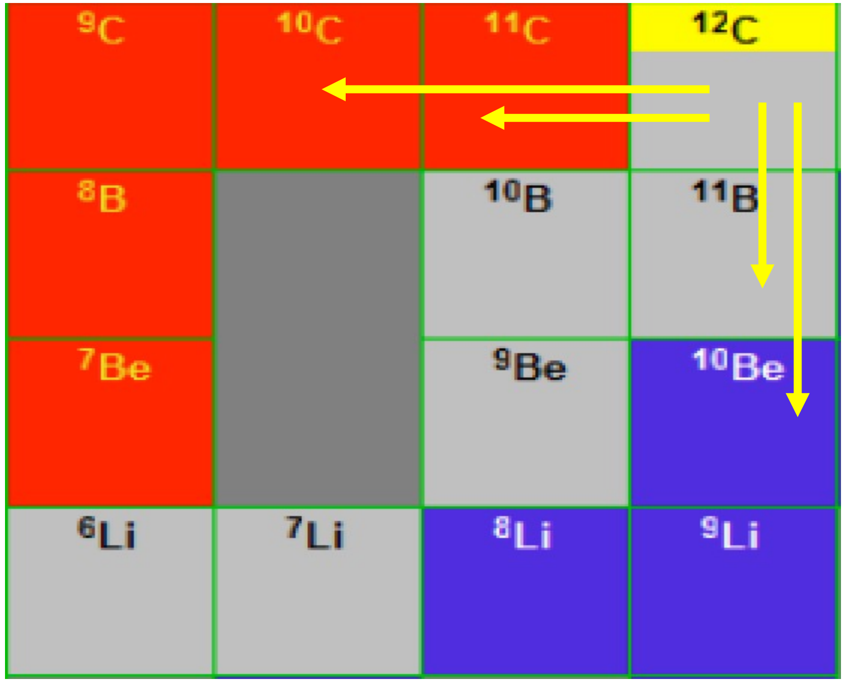
$\sigma_{inelastic}$: excitation to bound states

σ_I: interaction cross section: change of the nuclide (A, Z), ~ σ_R for several 100 AMeV energy

$\sigma_{cc}=\sigma_{\Delta Z}$: charge-changing cross section, change of the element (Z)

$\sigma_{\Delta N}$: total neutron removal cross section

Assuming a ^{12}C projectile beam at 900 MeV/nucleon on a C target



- Charge-changing cross sections

$\sigma_{\Delta Z} = \sigma\,(C\text{->}B) + \sigma(C\text{->}Be) + \sigma(C\text{->}Li) + \sigma(C\text{->}He) + \sigma(C\text{->}H) + \sigma(C\text{->}n)$

- Total neutron-removal cross section

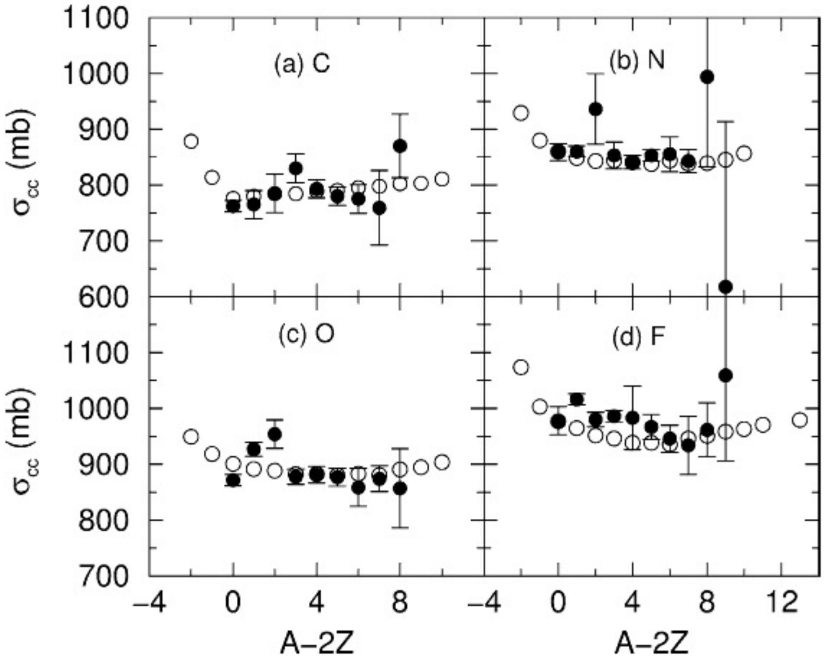
$\sigma_{\Delta N} = \Sigma\sigma_{-xn}$

- Interaction cross sections

$\sigma_I = \sigma_{CC} + \sigma_{\Delta N}$

Triggered theoretical discussions

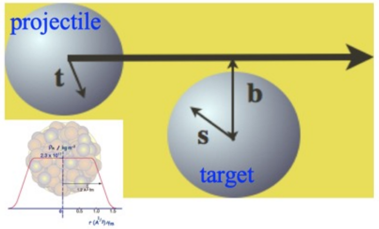
Glauber model + RCHB densities can reproduces well the experimental data.



Meng, Zhou, Tanihata, Phys. Lett. B 532 (2002) 209

In the first order

$$\sigma_{cc} = 2\pi \int b[1 - T^p(b)]d\mathbf{b}$$



proton density of the projectile

$$T^p(b) = \exp\left[-\left(\sigma_{pp} \int \rho_p^{\mathrm{targ}} \rho_p^{\mathrm{proj}} + \sigma_{np} \int \rho_n^{\mathrm{targ}} \rho_p^{\mathrm{proj}}\right)\right]$$

densities of the proton and neutron of the target

Triggered theoretical discussions

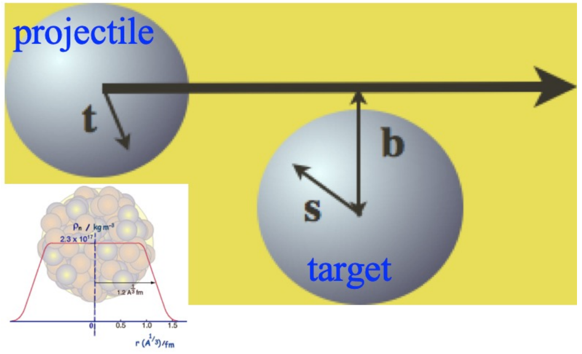
- Reaction mechanism: Glauber model + RMF/RHB density

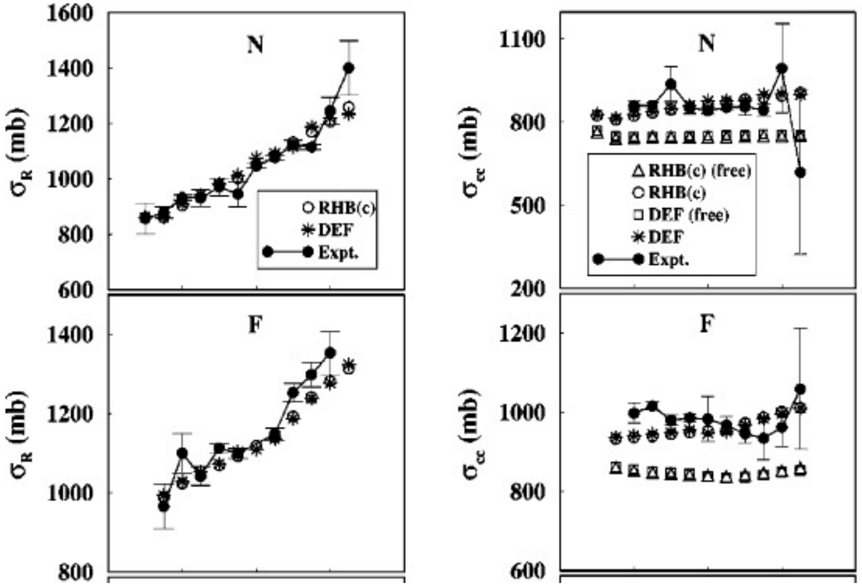
$$\sigma_R = 2\pi\int_0^\infty b[1-T^p(b)T^n(b)]db = 2\pi\int_0^\infty b[1-T^p(b)]db \;+2\pi\int_0^\infty b[T^p(b)\{1-T^n(b)\}]db$$

$$\sigma_{cc} = \sigma_{cc}^{free} + \mathcal{F}\sigma_{cc}^{I}.$$

$$\mathcal{F} = 0.8\frac{Z^2}{N^2} \quad \text{for} \quad N \geqslant Z$$

$$= 0.8 \quad \text{for} \quad N < Z,$$

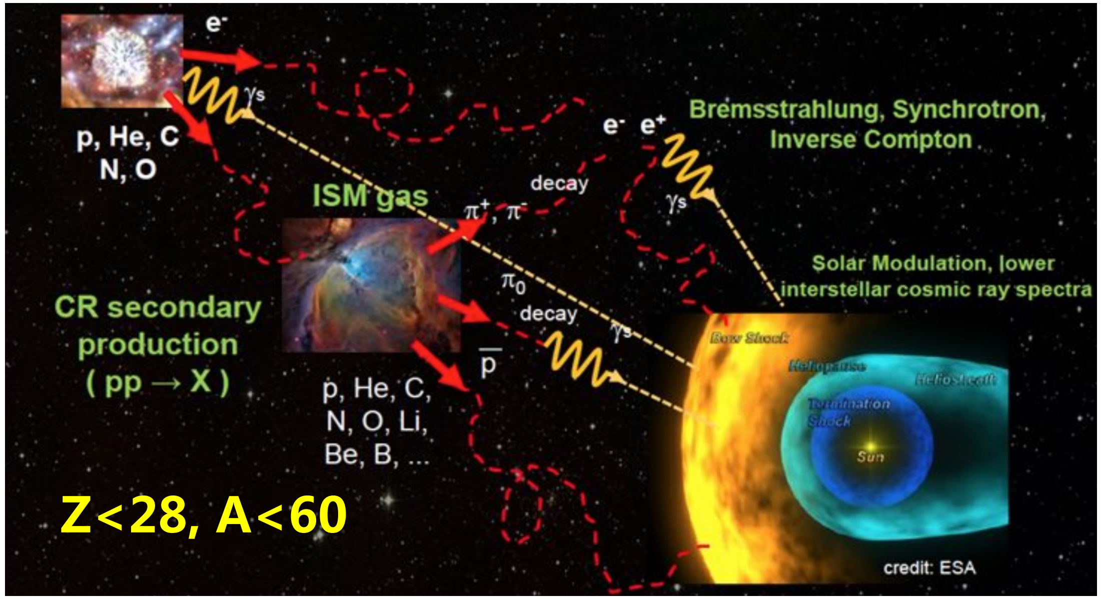


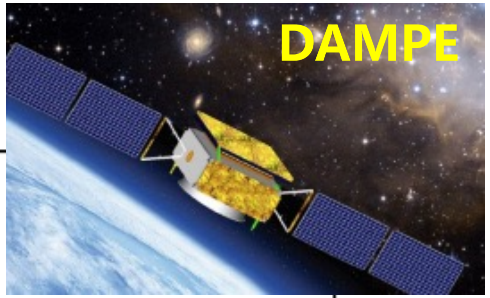


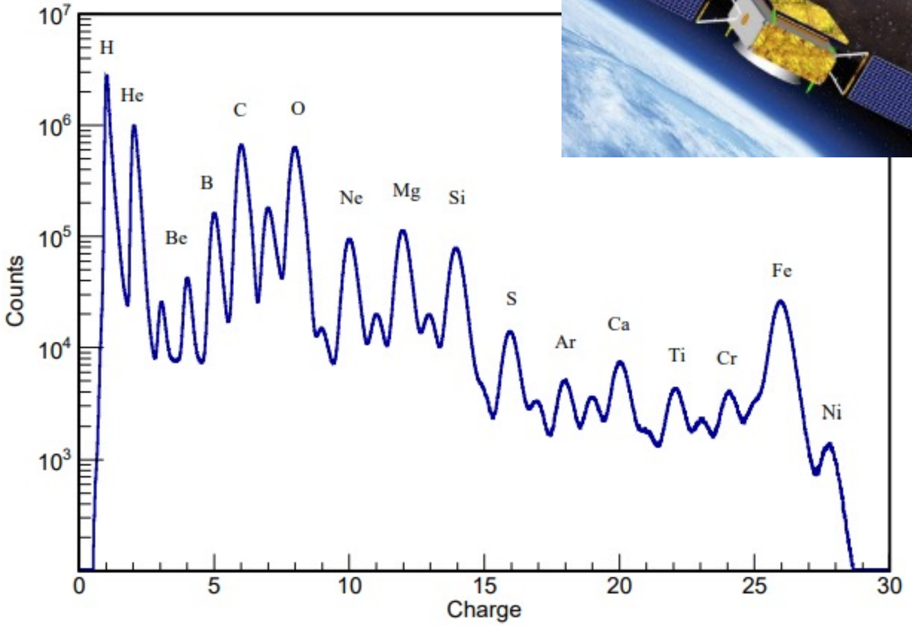
the neutron contributions to the σ_{CC} are about 10%

Bhagwat and Gambhir. PRC69 (2004) 014315

Pioneering experiments addressing the propagation of cosmic ray nuclei in galaxy





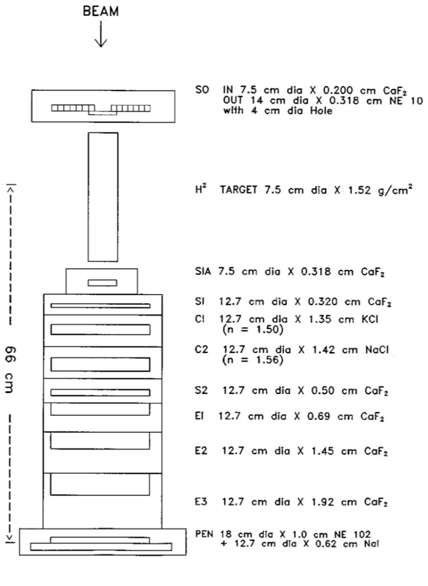


Cross sections of H-Fe in helium and hydrogen for energies from ~0.100 to ~10 GeV/nucleon

Dong *et al.*, Astropar. Phys. 105(2019)31

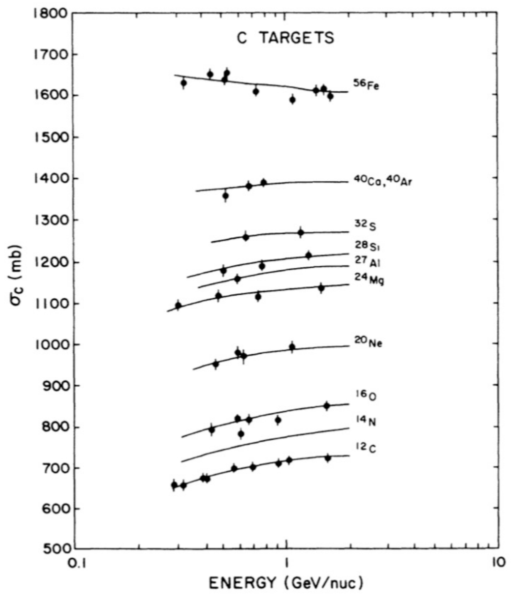
Pioneering experiments using stable beams

Z<28, A<60

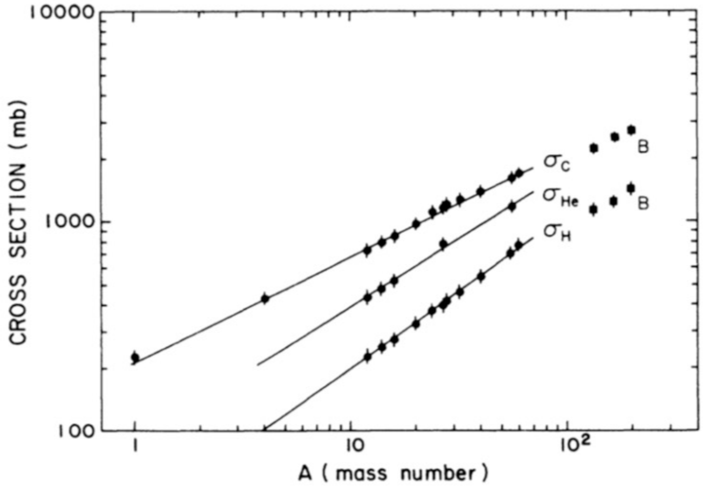


1988-1998@Saclay, Berkeley

Energy dependent



Taget, isotopic dependent



spallation cross sections of carbon, oxygen, and iron in helium and hydrogen, at beam energies from 540 to 1600 MeV/nucleon,

Ferrando *et al.*, PRC37(1988)1490; Webber *et al.*, PRC41(1990)520; Webber *et al.*, PRC58(1998)3539

One of the most systematic database

Link to nuclear structure

Combined analysis of s_I and s_{CC} can provide unique information on the difference in proton and neutron densities.

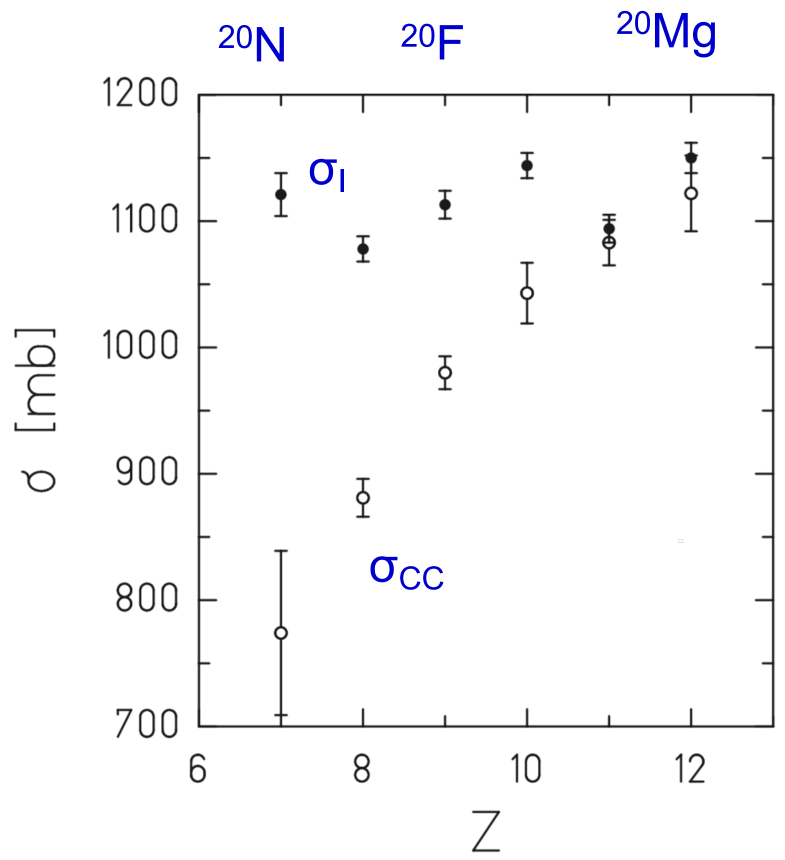
^{20}N-^{20}Mg@950AMeV + C; GSI (1988)

A=20 isobars

Projectile	σ_i [mb]	σ_{cc} [mb]	r_m [fm]	r_p^{max} [fm]
^{20}Mg	1150(12)	1122(30)	2.86(3)	3.18(9)
^{20}Na	1094(11)	1083(18)	2.69(3)	3.14(5)
^{20}Ne	1144(10)	1043(24)	2.84(3)	3.10(7)
^{20}F	1113(11)	980(13)	2.75(3)	2.98(4)
^{20}O	1078(10)	881(15)	2.64(3)	2.72(5)
^{20}N	1121(17)	774(65)	2.77(4)	2.39(20)

- R_m and R_p^{max} derived
- Existence of neutron skin in ^{20}N

$\sigma_I = \sigma_{CC} + \sigma_{DN}$

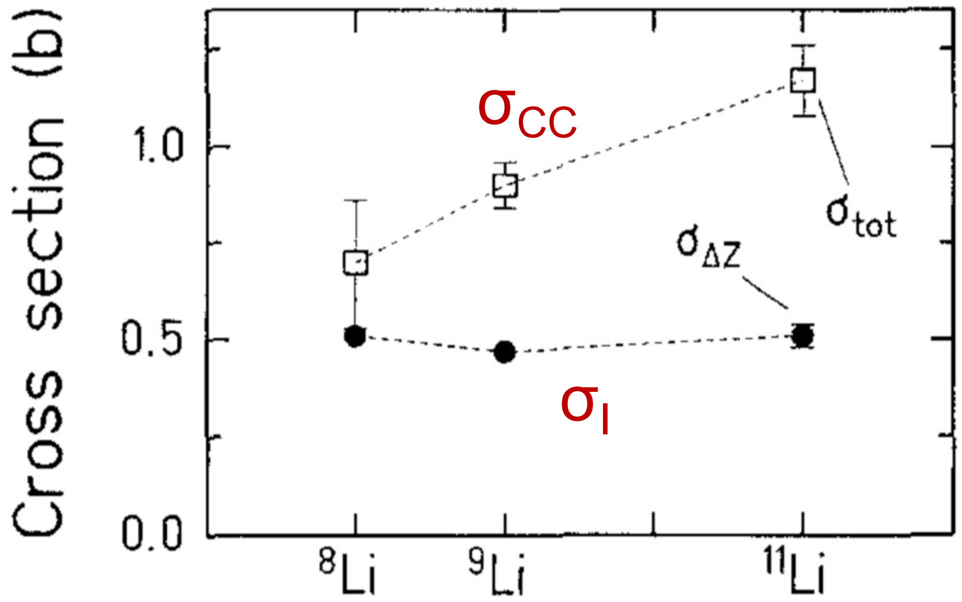


Bochakarev et al., Eur. Phys. J. A 1, 15–17 (1988)

σ_I and σ_{CC} measurements of $^{8-9,11}$Li

■ ^{8,9,11}Li @ 80 AMeV + different targets

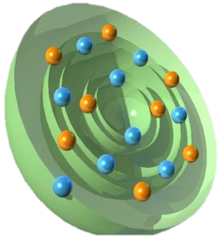
Blank *et al.*, Z. Phys. A 343 (1992) 375-379



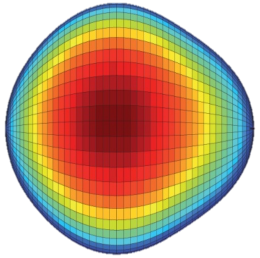
- σ_{CC} stays almost constant for the same isotopic chain
- The proton density distribution is almost the same for ^{8,9,11}Li and is not affected by the long tail in the neutron distribution established for ^{11}Li.

Nuclear size, nuclear extension in space, can be used to reveal structure

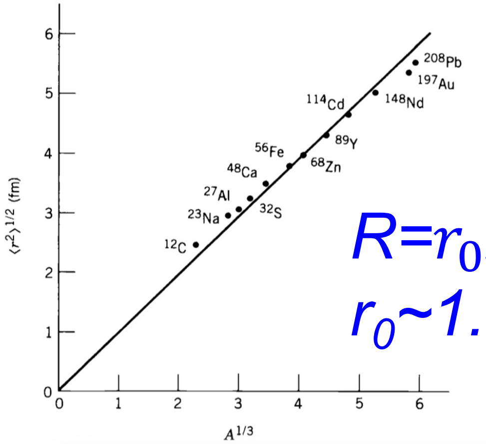
- ■ Bulk properties
- ■ Halo, skin
- ■ Nuclear theory
- ■ Shell, subshell



- ■ Deformation, shape transition
- ■ Pairing ，cluster

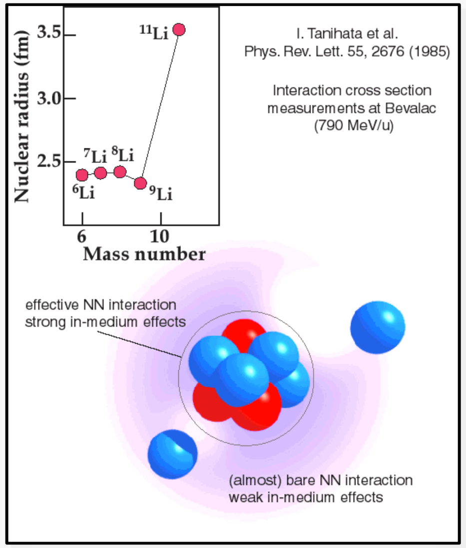


- ■ Equation of state



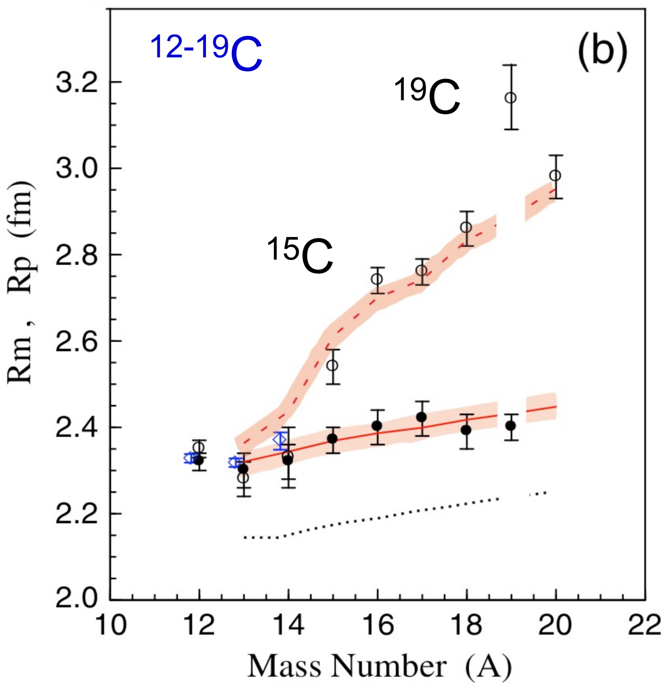
$R = r_0 A^{1/3}$

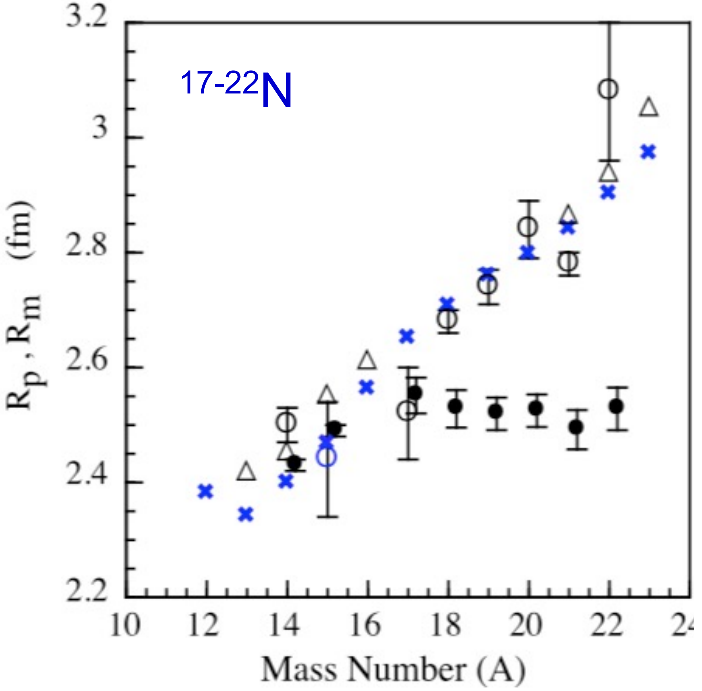
$r_0 \sim 1.2$ fm



Tanihata et al., Phys. Rev. Lett. 55 (1985) 2676
Hansen & Jonson, Europhys. Lett. 4(1987)409

Experiments at 900 MeV/u at GSI

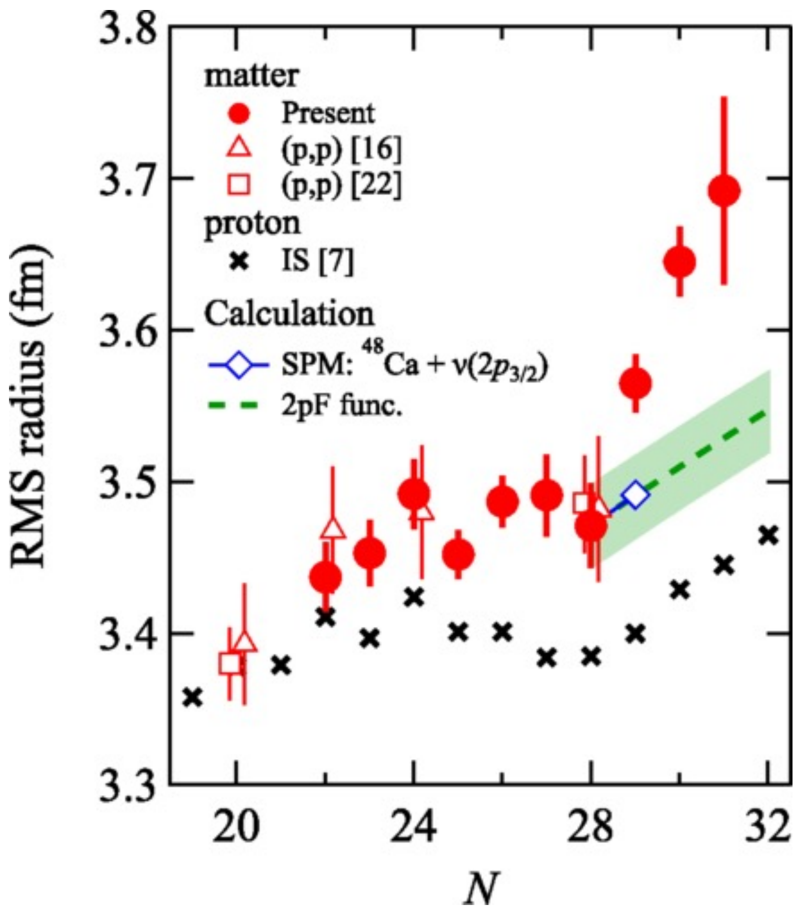




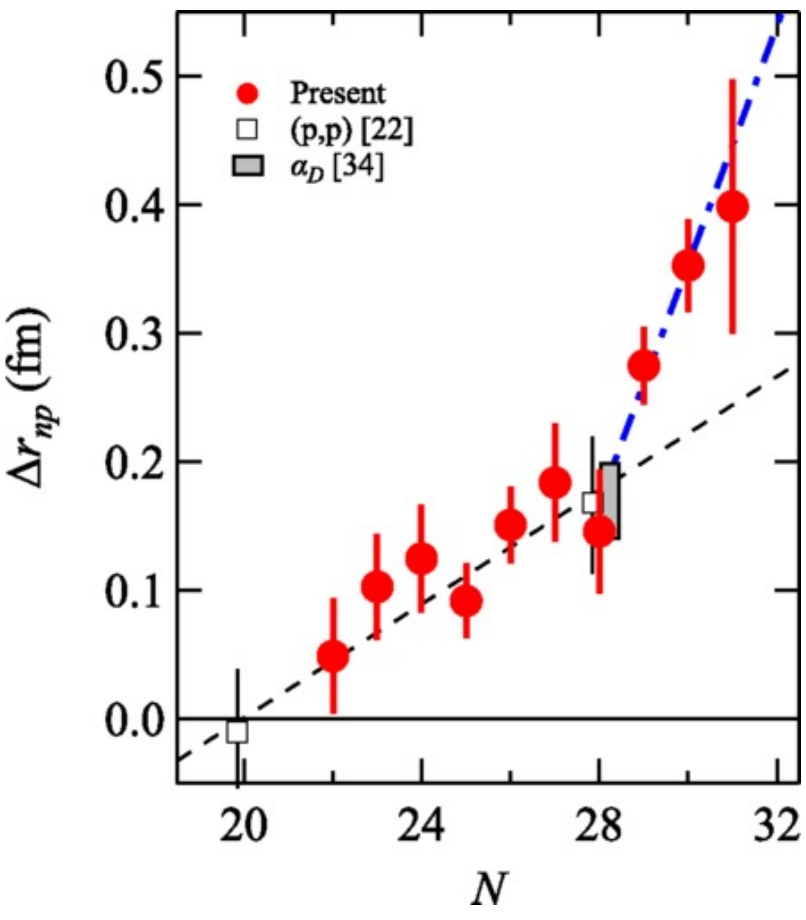
- Neutron surface: 0.2 fm (^{15}C) ~ 1fm (^{19}C)
- Halo radius in ^{19}C: 6.4(7) fm from core+neutron model: as large as ^{11}Li
- kink at N=14 for N isotopes? ^{22}Na neutron halo-like structure?

Kanungo *et al.*, PRL117, 102501(2016); Bagchi *et al.*, PLB790, 251(2019)

σ_I and σ_{CC} of Ca isotopes at RIKEN



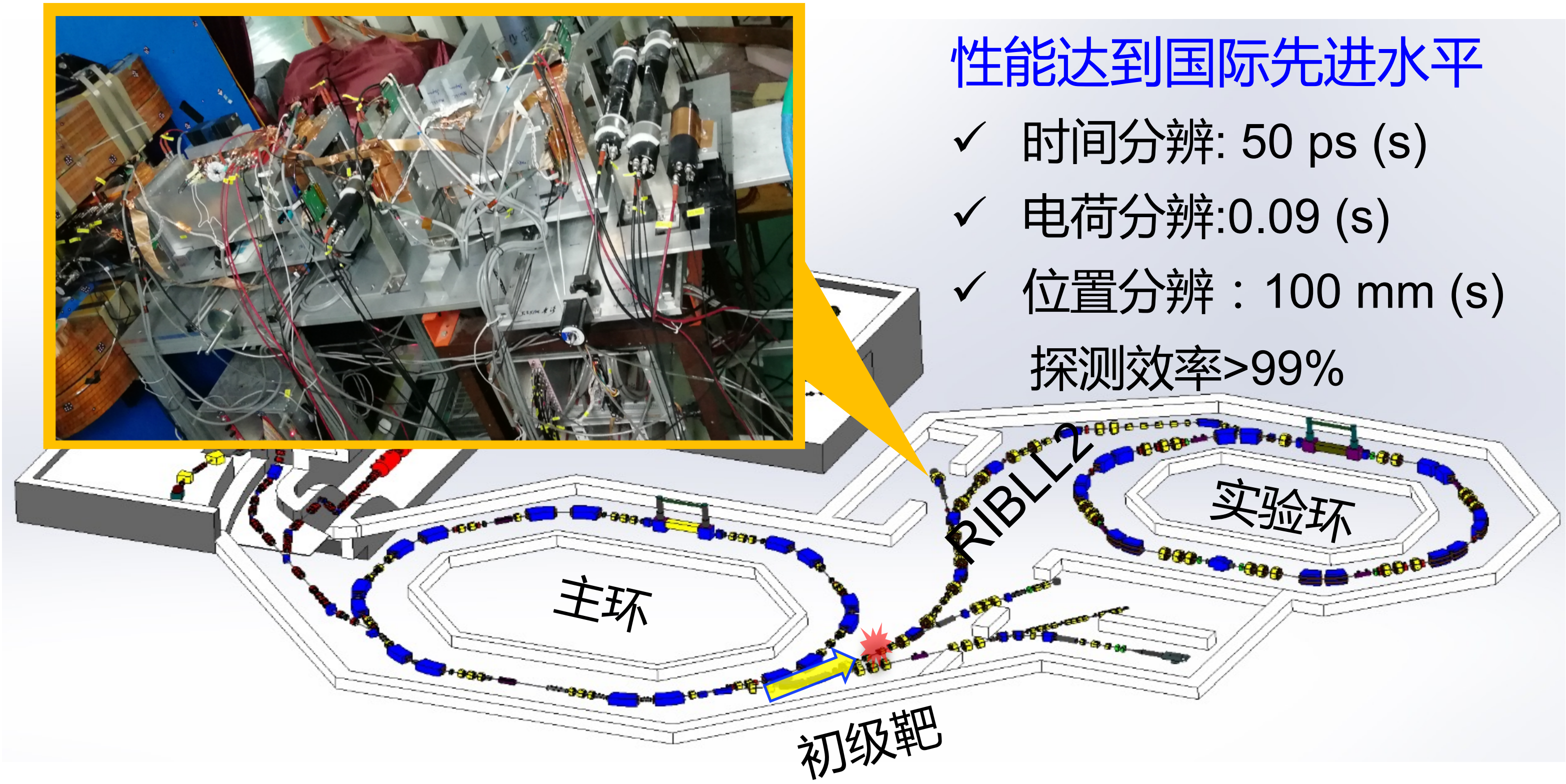
Ruiz *et al.* Nat. Phys. (2016)



M. Tanaka et al., PRL**124**(2020)102501

电荷改变截面实验平台(2013-2018)

兰州重离子加速器装置



性能达到国际先进水平

- ✓ 时间分辨: 50 ps (s)
- ✓ 电荷分辨:0.09 (s)
- ✓ 位置分辨：100 mm (s)

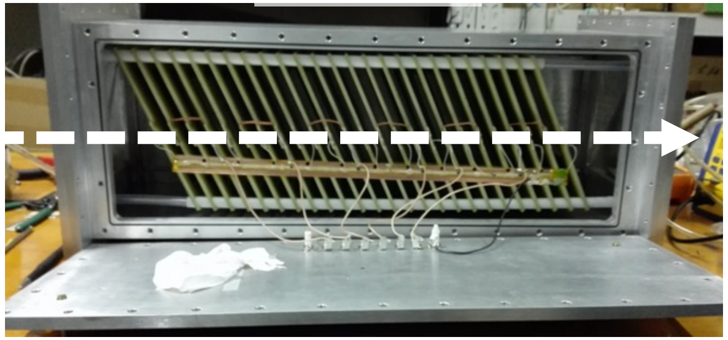
探测效率>99%

RIBLL2(兰州第二条次级束流线)：世界上少数几个可以提供相对论次级束的束流线 (≥300MeV/u)

BHS *et al.*, Sci. Bull. 63(2018)78; Zhao *et al.*, NIMA823(2016)41
Lin *et al.*, CPC41(2017)066001; Zhao *et al.*, NIMA 930(2019)95

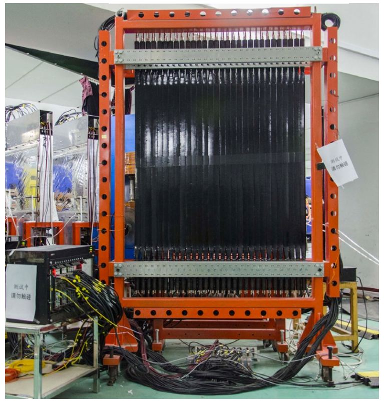
Detector development

MUSIC



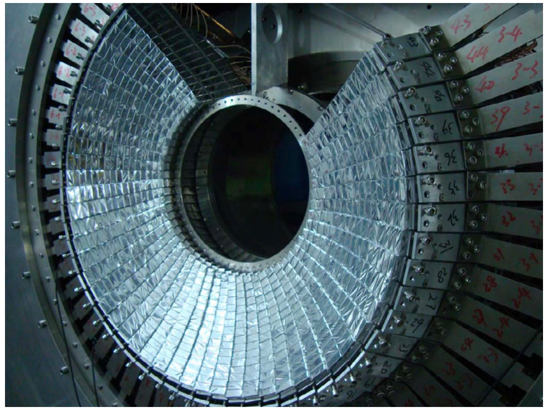
Zhang-NIMA795(2015)389
Zhao-NIMA930(2019)95

TOF wall



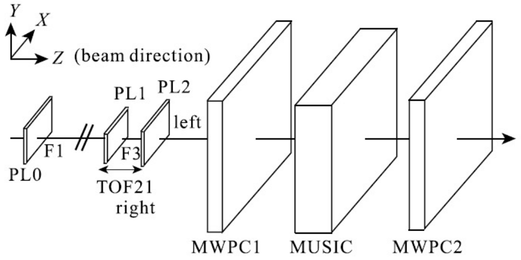
Y.Sun-NIMA893(2018)68

CsI(Tl) γ array



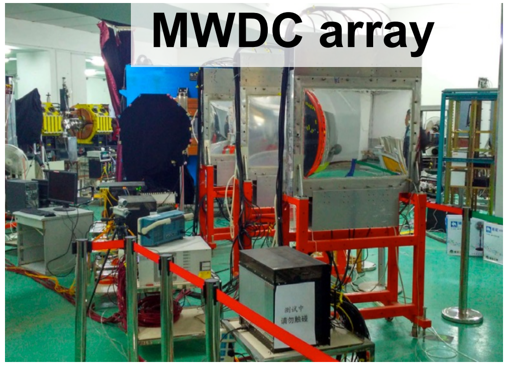
Yue-NIMB317(2013)653

TOF detector



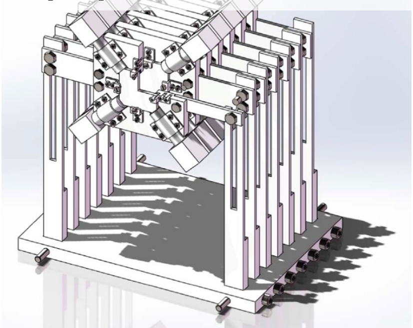
Zhao-NIMA823(2016)41
Lin-CPC41(2017)066001

MWDC array



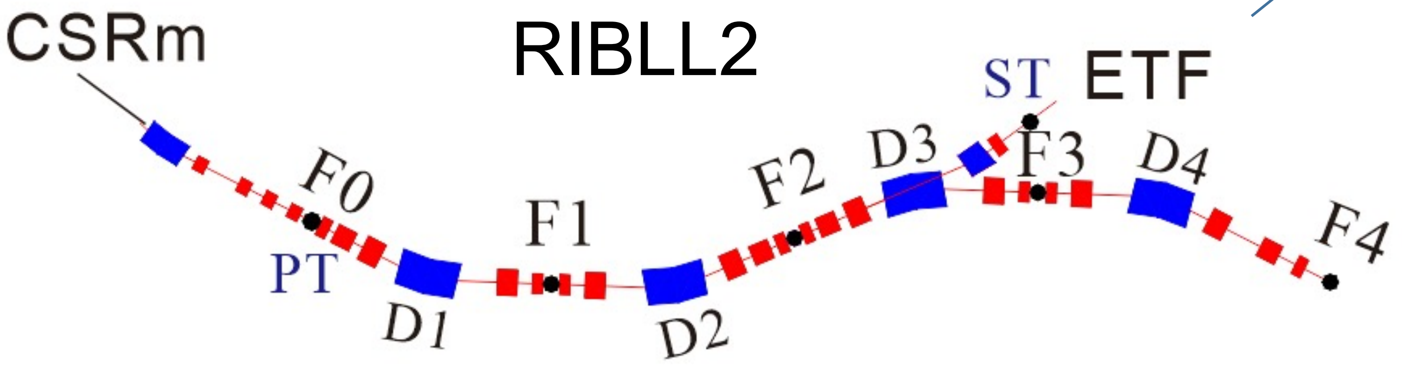
Y.Sun-NIMA894(2018)72;
NIMA985 (2021)164682

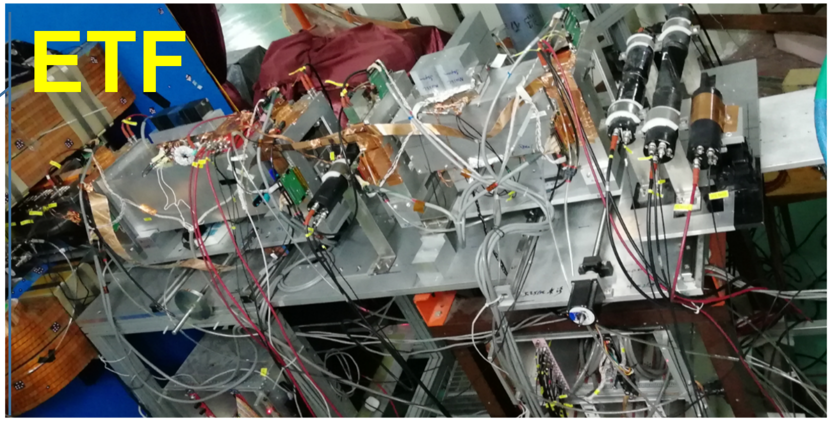
CsI(Tl) detector telescope

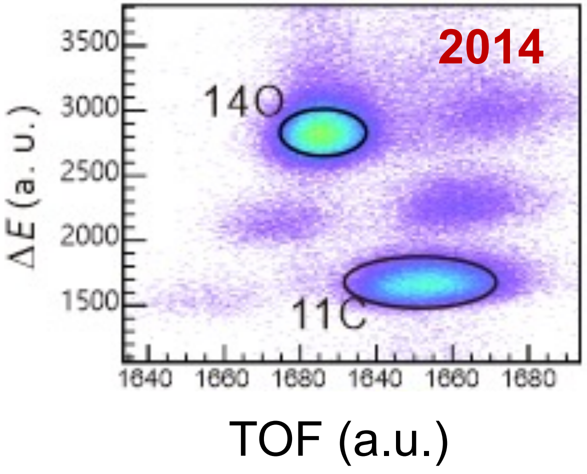


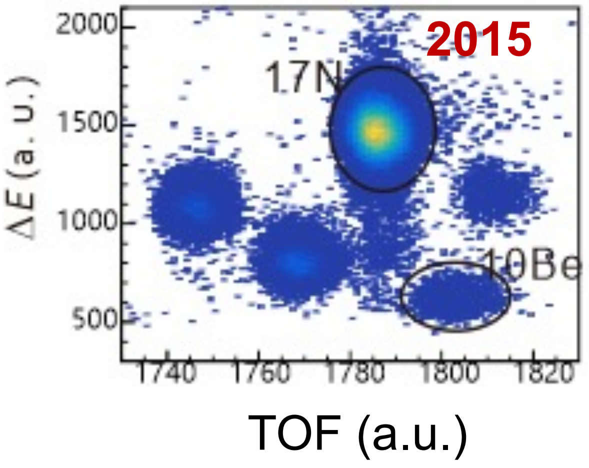
Yan-NIMA843(2017)5

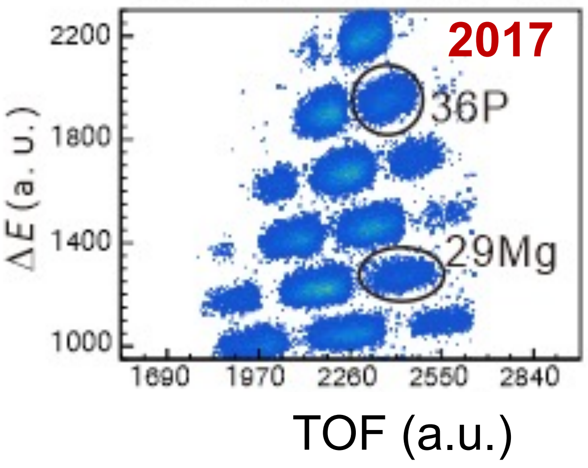
F1-ETF particle identification

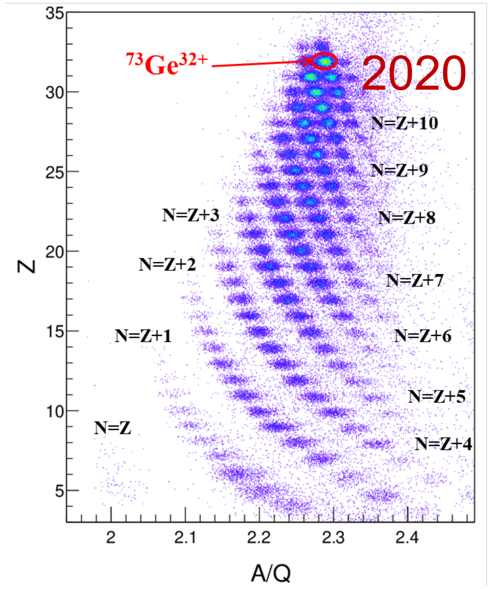








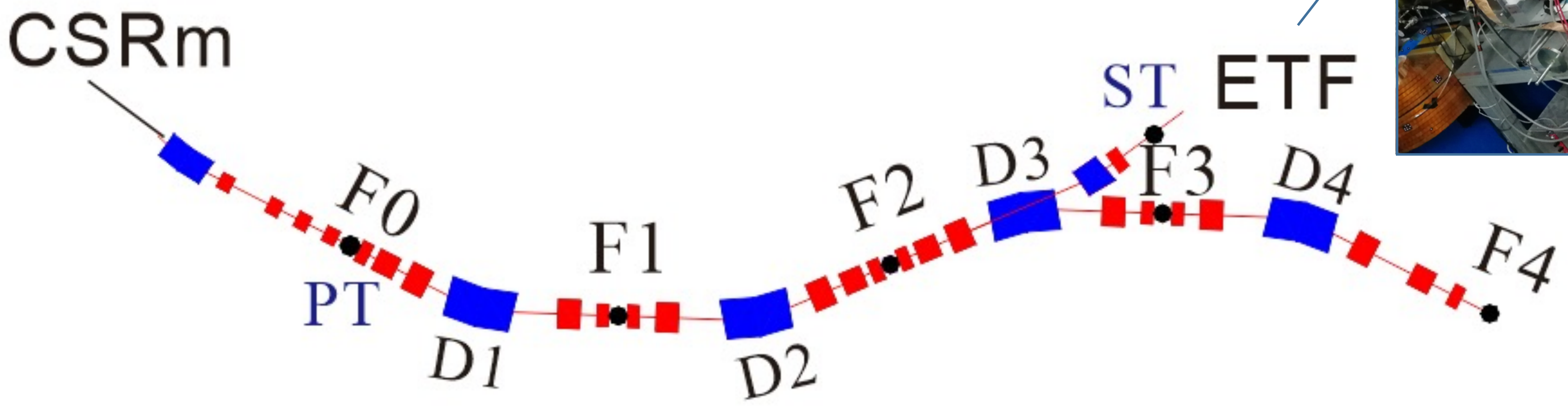


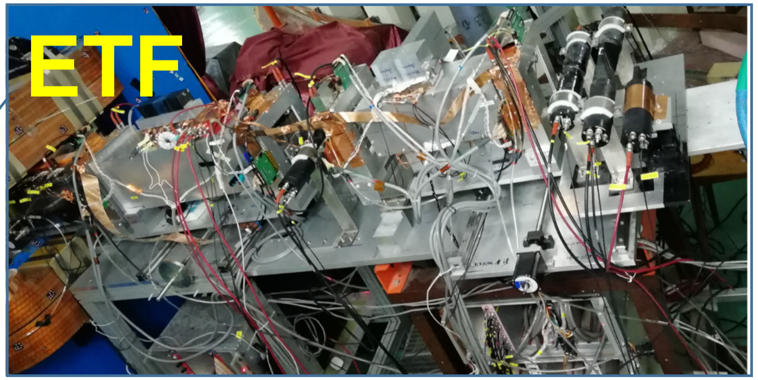


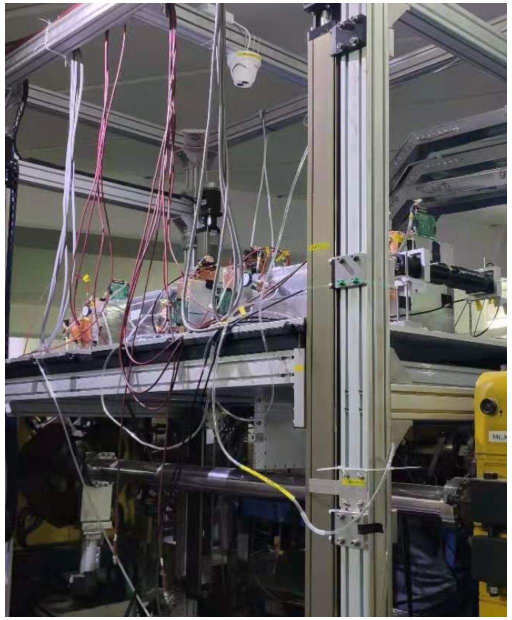
Increasing resolving power （light mass to intermediate mass range）

BHS et al., Sci. Bul. (2018); F. Fang et al., Nucl. Phys. Rev. (2021)

RIBLL2 upgrade and F4 (2017-)



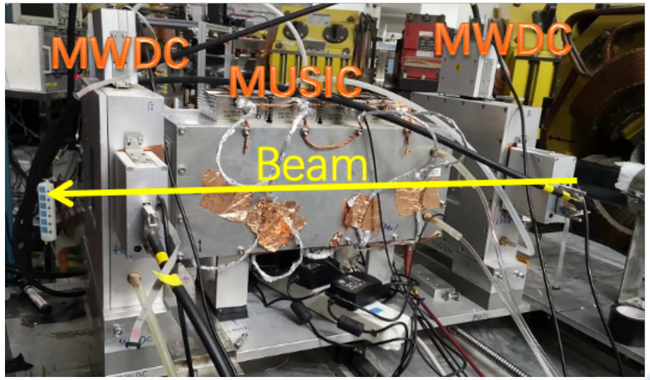


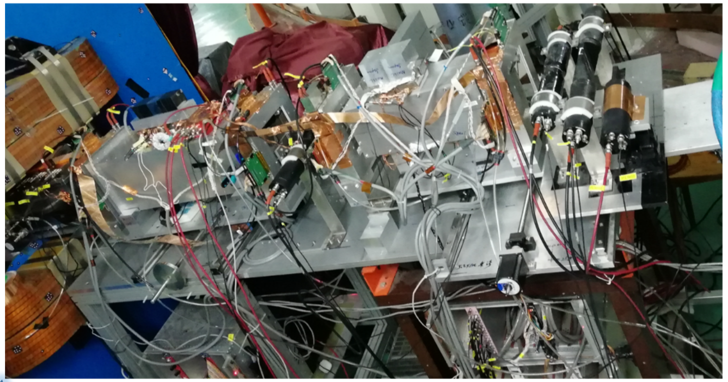


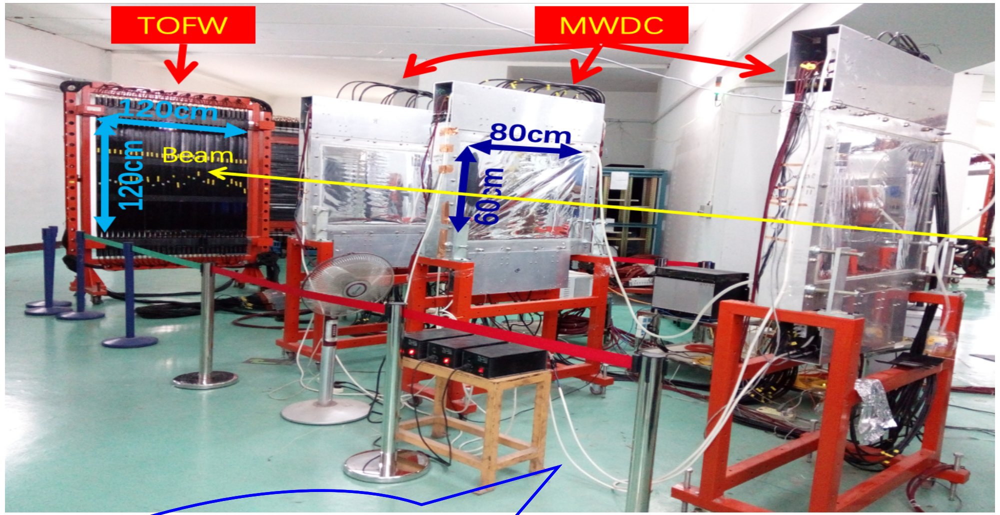
- Upgrade all the focal plans
- Install beam diagnosis system for primary beam and RIB beams
- Ion-optical optimization
- New F4 platform: increased TOF pathlength from 26m to 42 m

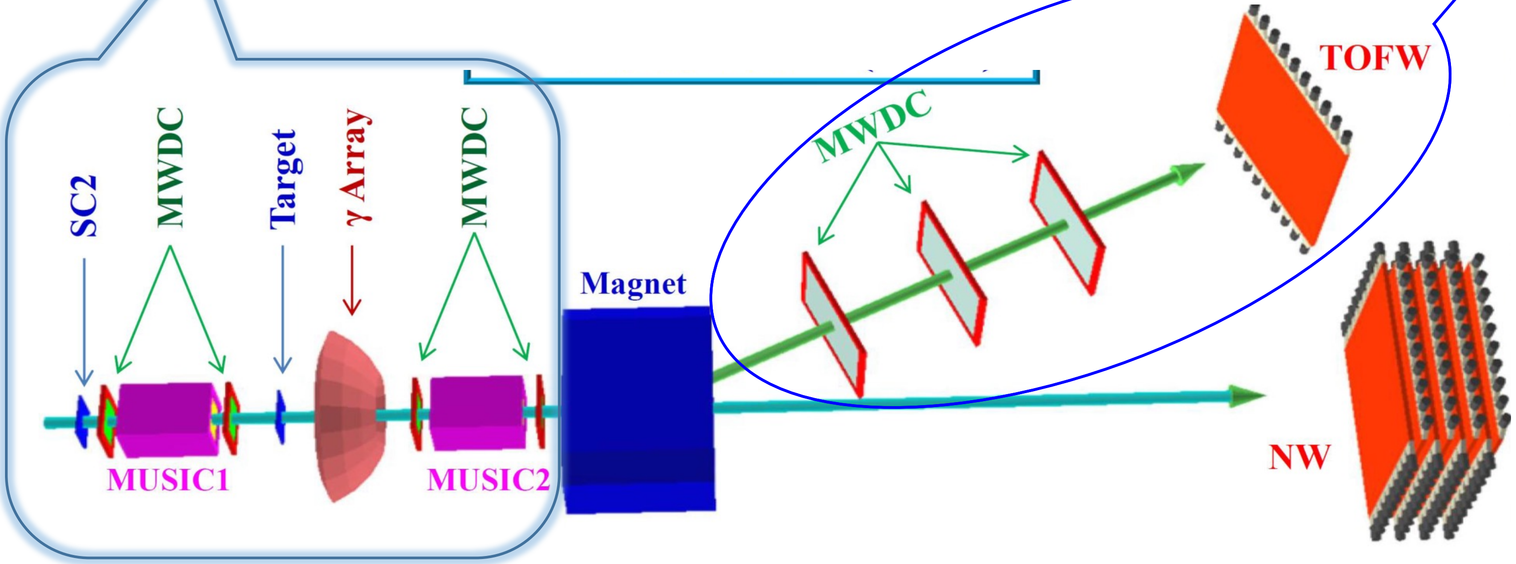
Courtesy: Yong Zheng, Xueheng Zhang, H. Ong

ETF: 2021





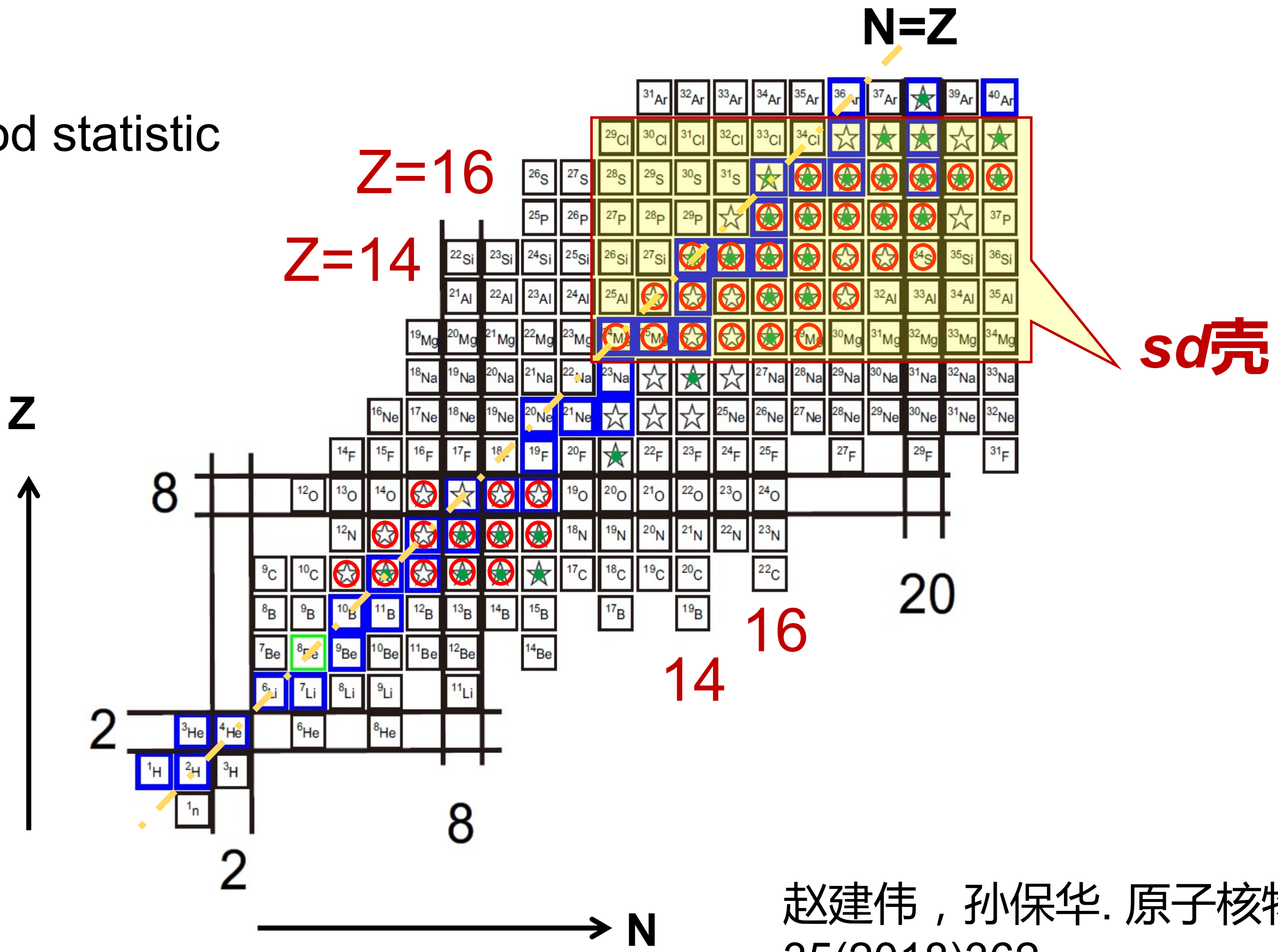




Y. Z. Sun, et al., *Nucl. Inst. Meth. A* 927 (2019) 390

CCCS measurements on C targets at ~ 300MeV/nucleon

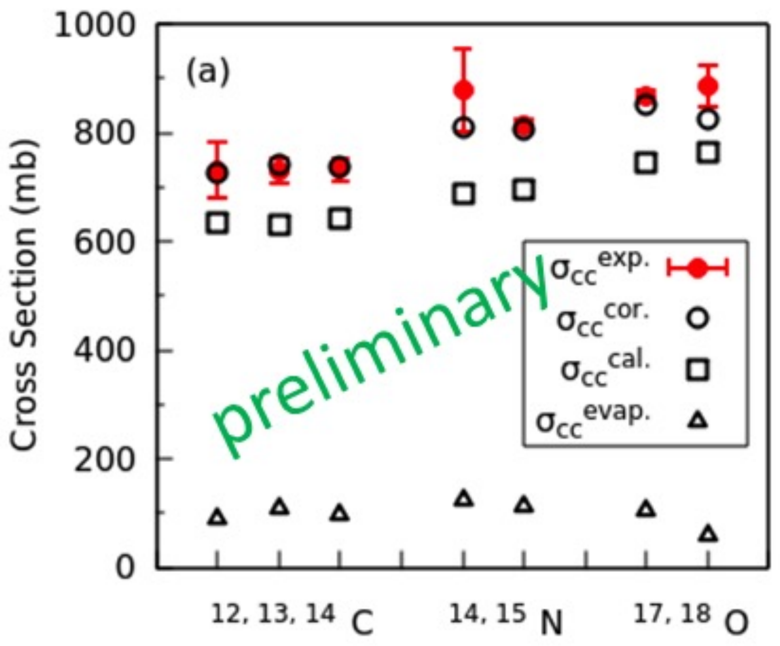
- ☆ ~60 nuclei
- ☆ ~10 nuclei with good statistic
- ☆ Preliminary results

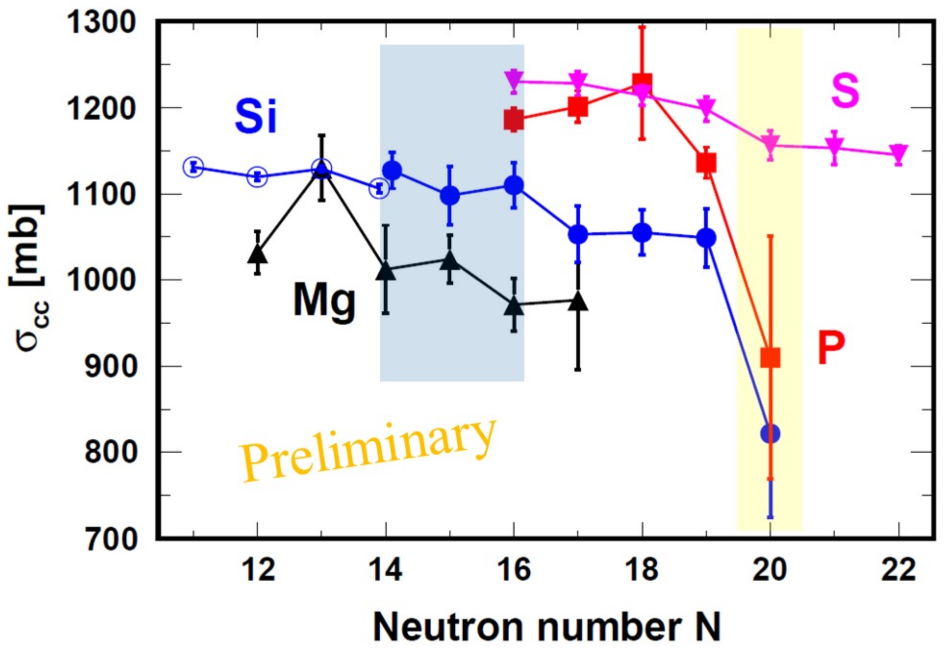


赵建伟，孙保华. 原子核物理评论, 35(2018)362

孙保华. 科学通报 **65**, 3886 (2020)

Preliminary results



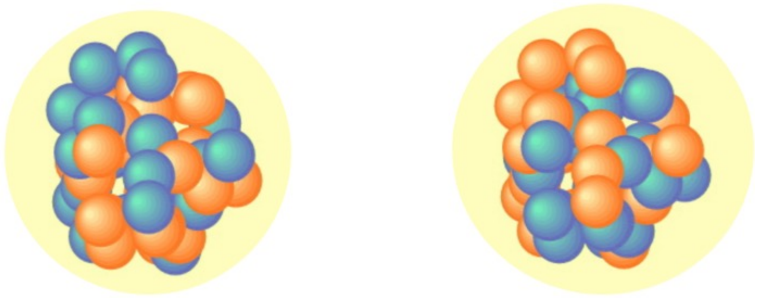


Reaction mechanism
(in preparation)

HIMAC-Data (empty) ,
$^{25-28}$Si: NPA961,142(2017)
Kink at N=20

Statistic to be improved in the coming experiment scheduled in this Autumn

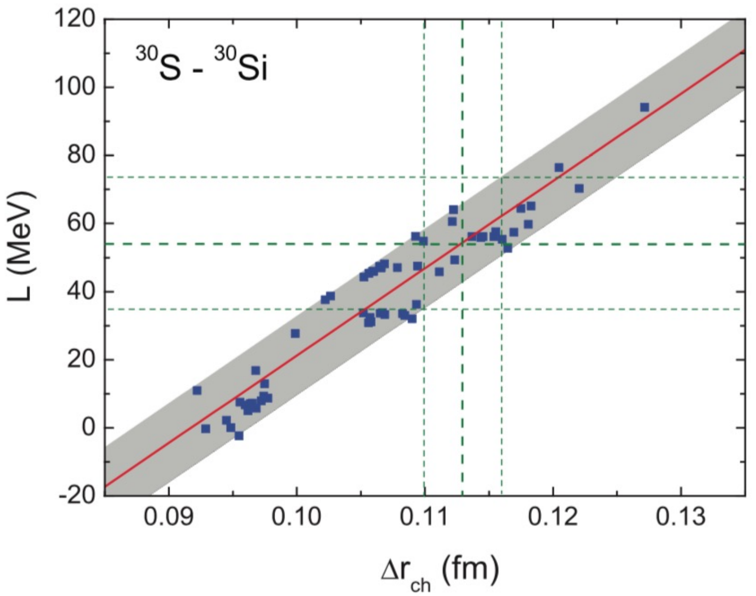
Mirror nuclei as a laboratory to probe EOS



$^{A}_{Z}\mathrm{X}_{N}$ $^{A}_{N}\mathrm{Y}_{Z}$

isospin symmetry

nearly identical properties

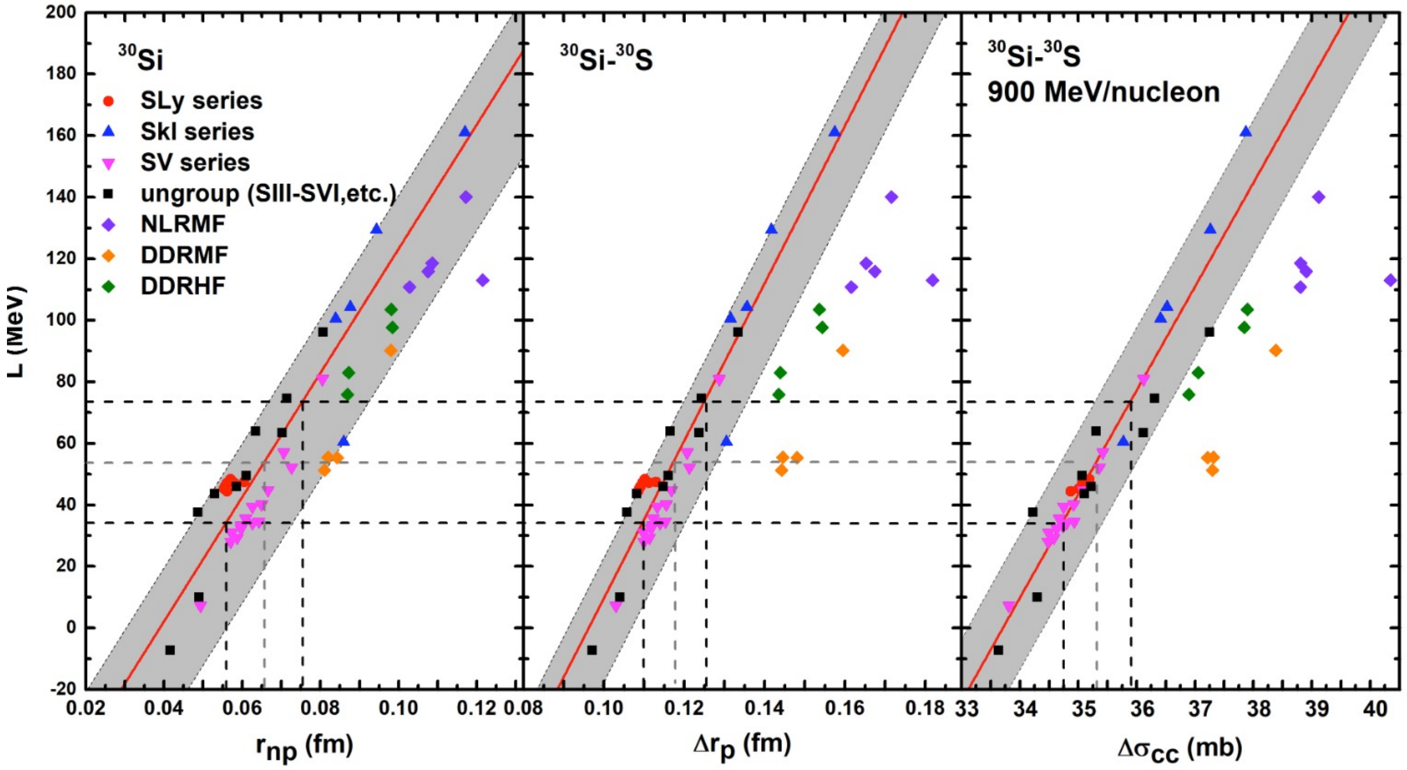


Wang & Li, PRC **88**, 011301(R) (2013)

The differences in the charge radii of mirror nuclei are shown to be proportional to the derivative of the symmetry energy *L* at nuclear matter saturation density.

Brown, PRL 119, 122502(2017)； Yang & Piekarewicz, PRC97,014314(2018)

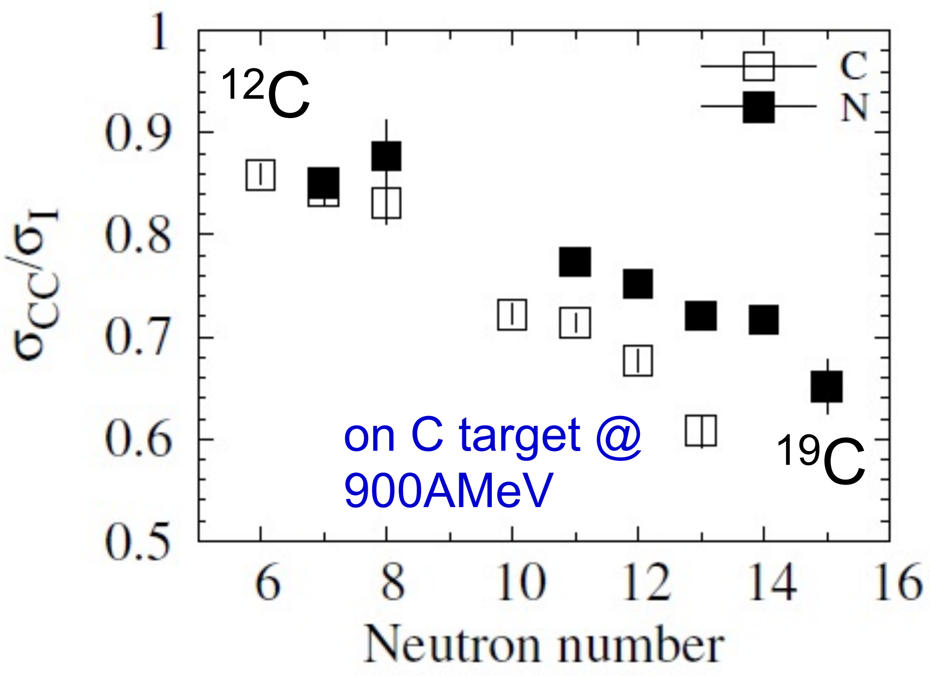
Constraining EOS by CCCS difference of mirror nuclei ?



- A linear correlation between cross section difference of mirror nuclei and L
- Model dependent: SHF vs. RMF

Xu，Li，BHS，Niu et al. in preparation

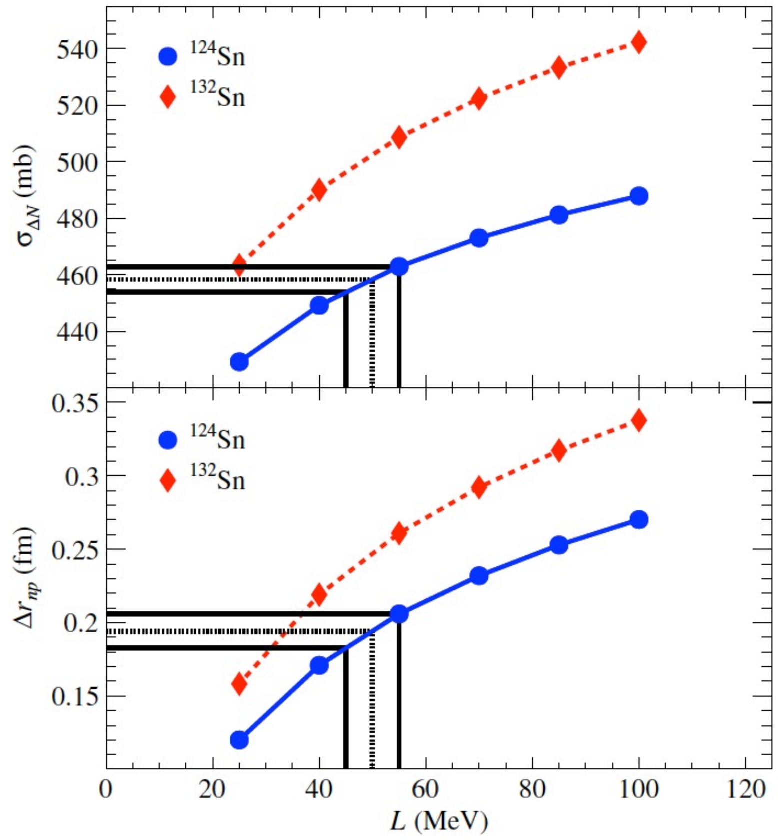
Simultaneous measurements of σ_I and σ_{CC} on the same target at the same energy



- contributions from the neutron removal reaction is increased with increasing neutron number
- Combining with the Glauber model analysis, it is possible to deduce both R_m and R_p, and thus neutron-skin thickness
- The neutron-skin thickness can put a strong constraint to nuclear models

Simultaneous measurements of σ_I and σ_{CC} for EOS studies

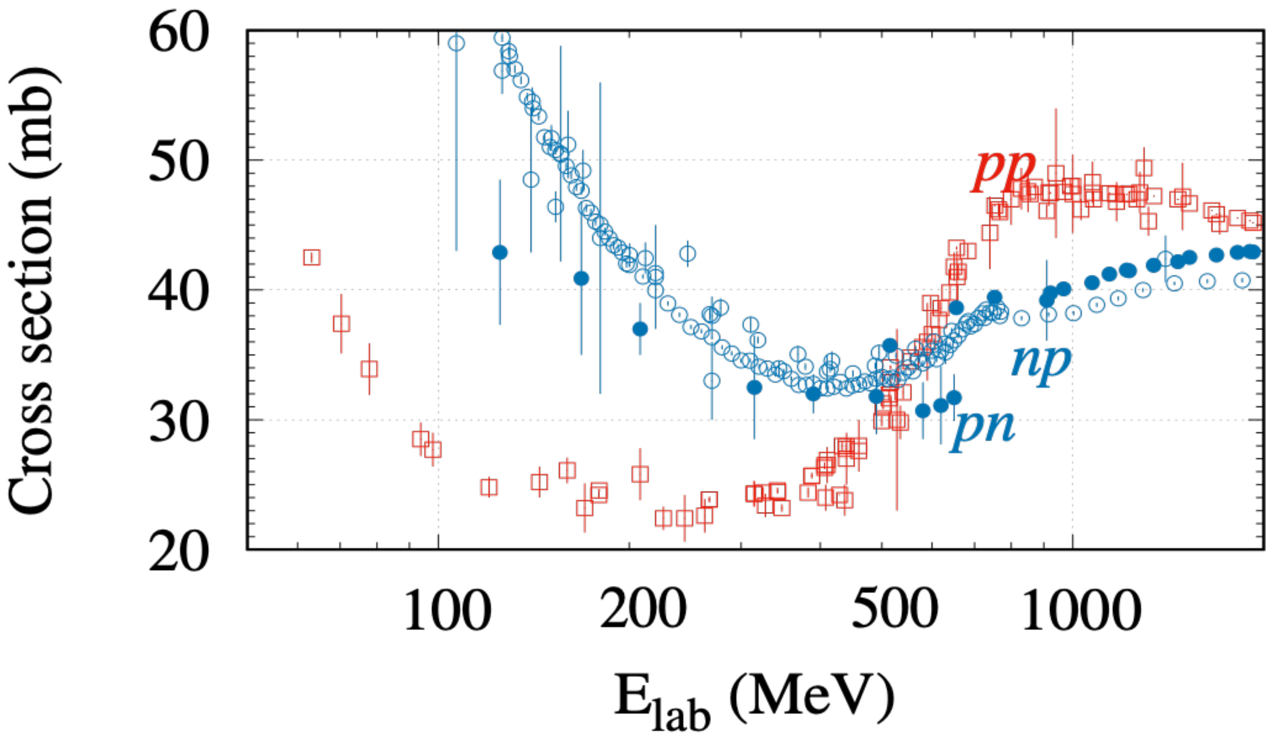
$\sigma_{\Delta N} = \sigma_I - \sigma_{CC}$

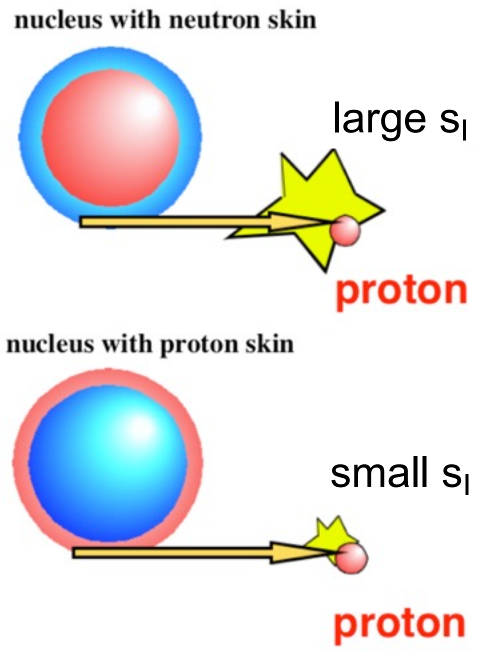


Aumann et al., PRL119, 262501(2017)
Bertulani and Valencia, PRC100, 015802(2019)

total neutron-removal cross section can be a sensitive probe to constraint EoS

Simultaneous measurements of σ_I and σ_{CC} on the H target at the same energy





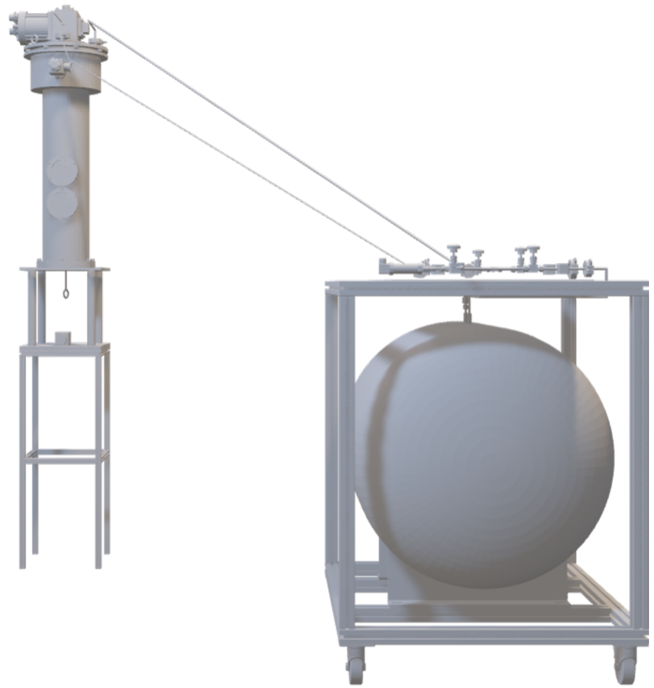
H target: best target to disentangle r_p and r_n, isospin effect; proton/deuteron target can be used to deduce neutron skin thickness

Horiuchi, Suzuki, Uesaka, Miwa, PRC102, 054601(2020)

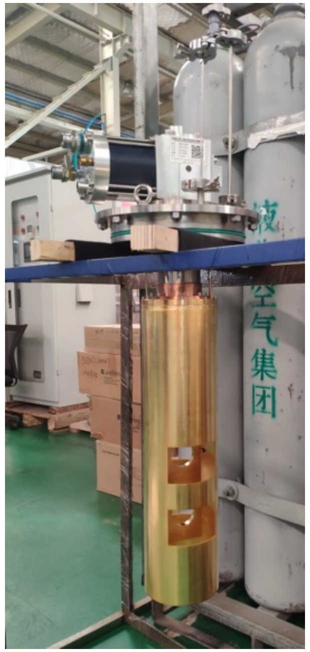
Solid hydrogen target R&D

- 完成了固态氢靶系统的研制：空间占用小、厚度和角度可调

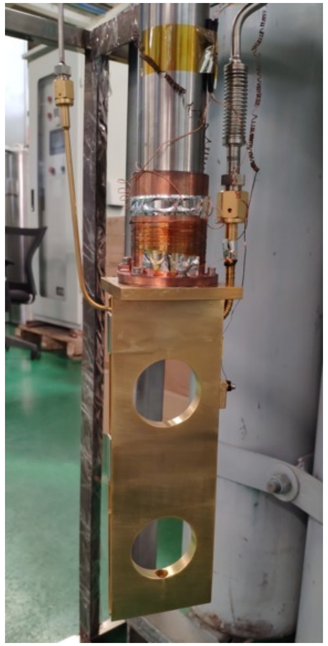
使用 G-M 制冷机作为冷源，通过多屏绝热与真空绝热减少对流和辐射传热。整个设计方案包含供气单元、冷冻单元、靶室单元以及控制单元等部分。



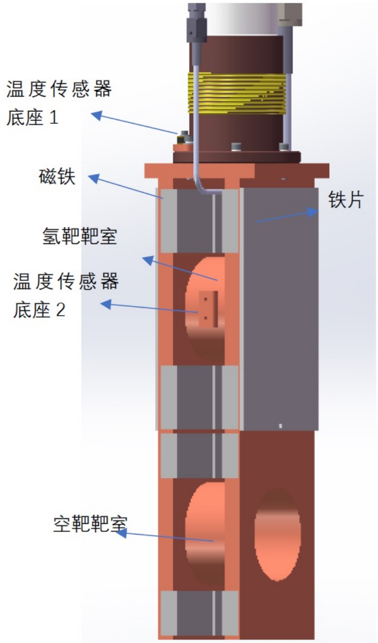
系统主体部分



无氧铜冷屏



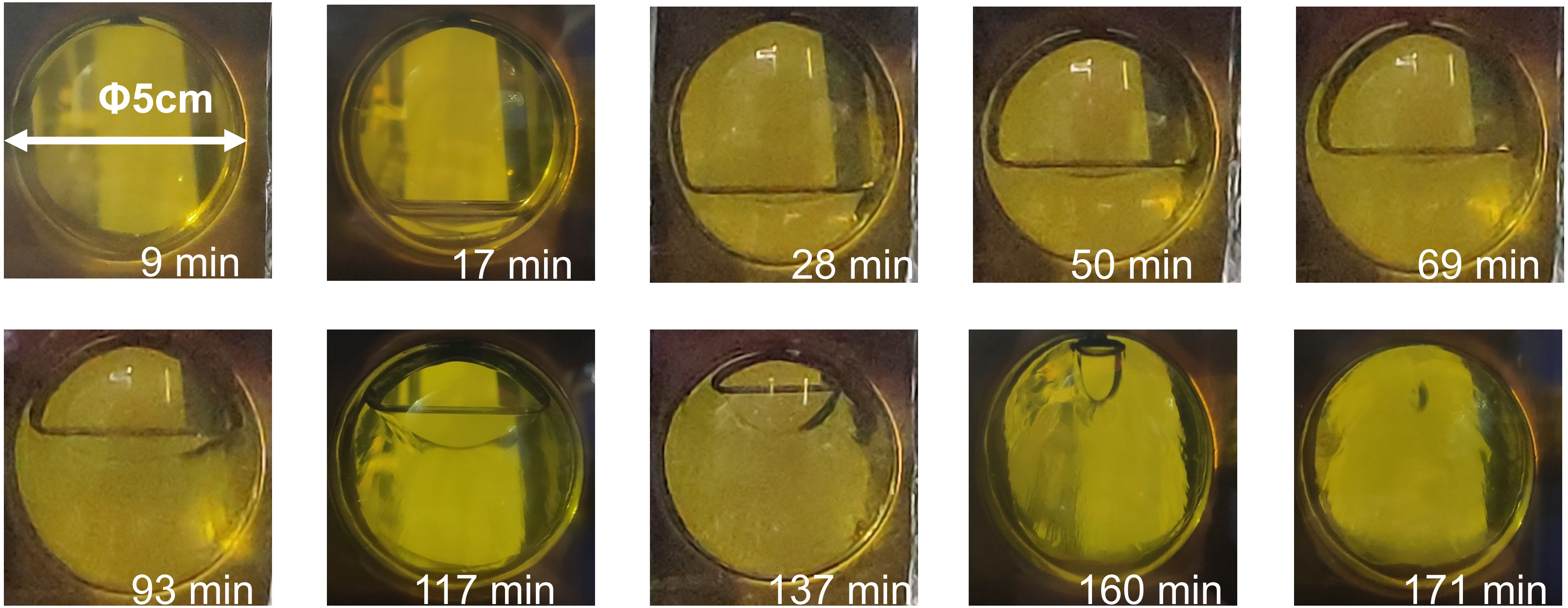
20mm-target cell



unit

R&D on Solid hydrogen target

Test with nitrogen, 2cm thick x Φ5cm

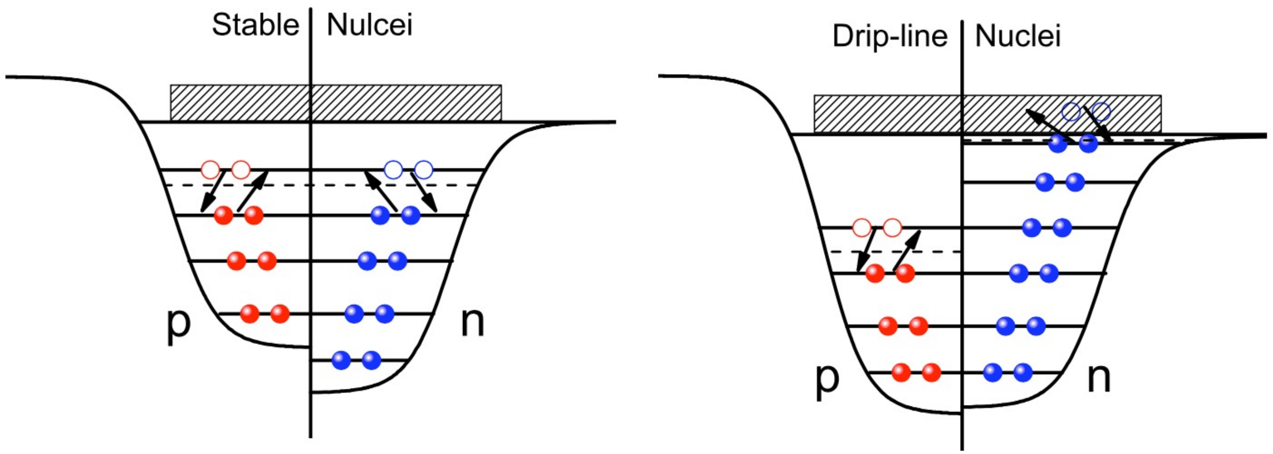


Test with hydrogen in preparation

Nucleon-removal cross sections:
-1n, -2n,
-p, -2p,
(p,2p)
etc.

单核子敲出反应

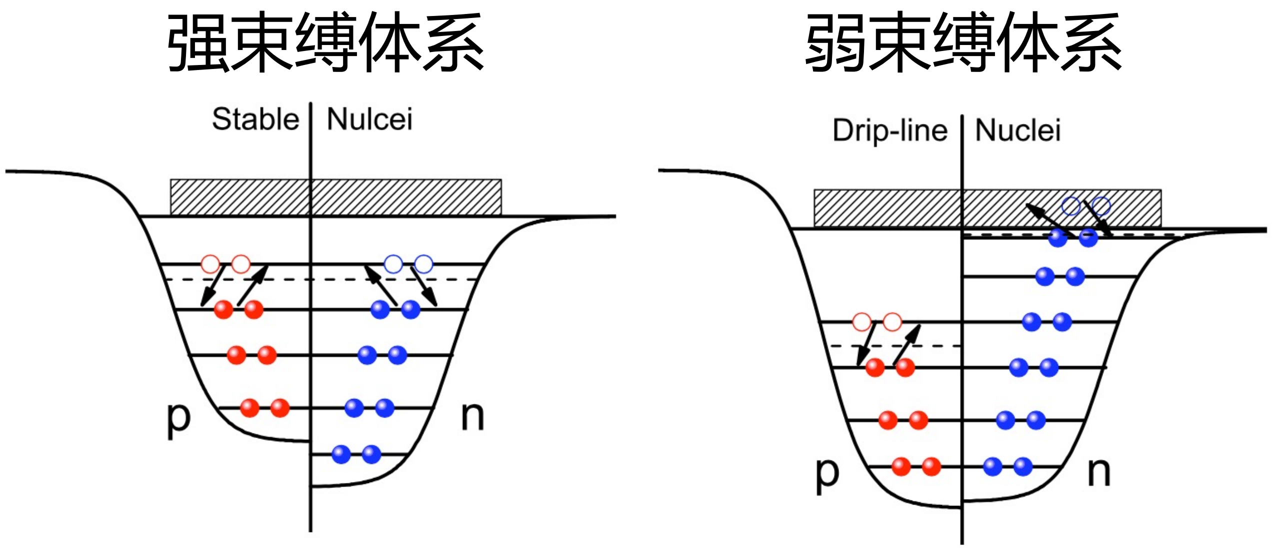
强束缚体系　　　　弱束缚体系



Courtesy：周善贵

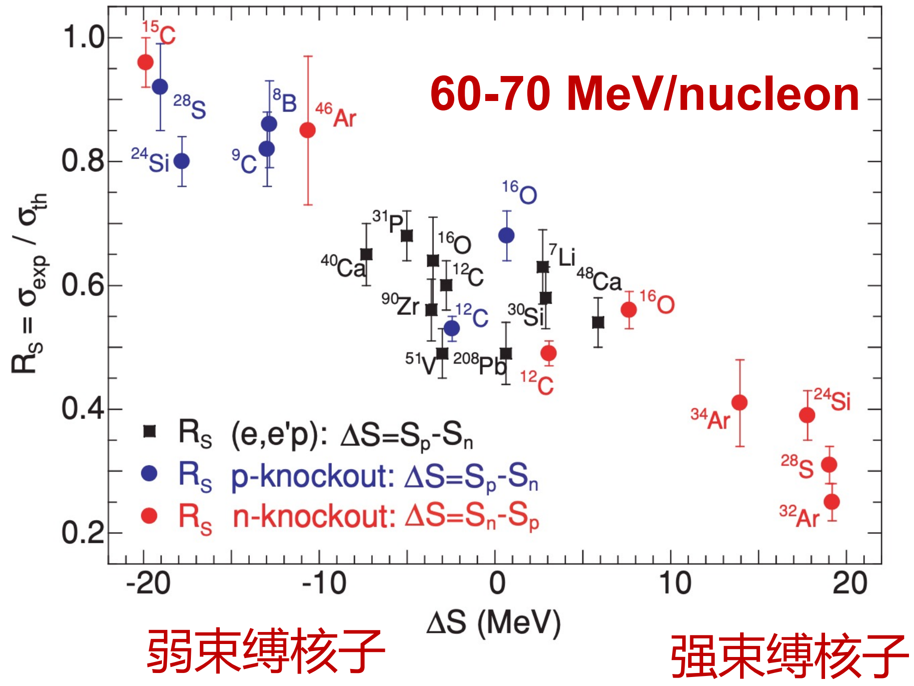
- 核子在某个轨道的占居几率，可通过在中高能区（>80Mev/核子）测量单核子敲出截面、结合Eiknoal模型分析得到，探索单粒子自由度和壳层结构的演化

单核子敲出反应



Courtesy：周善贵

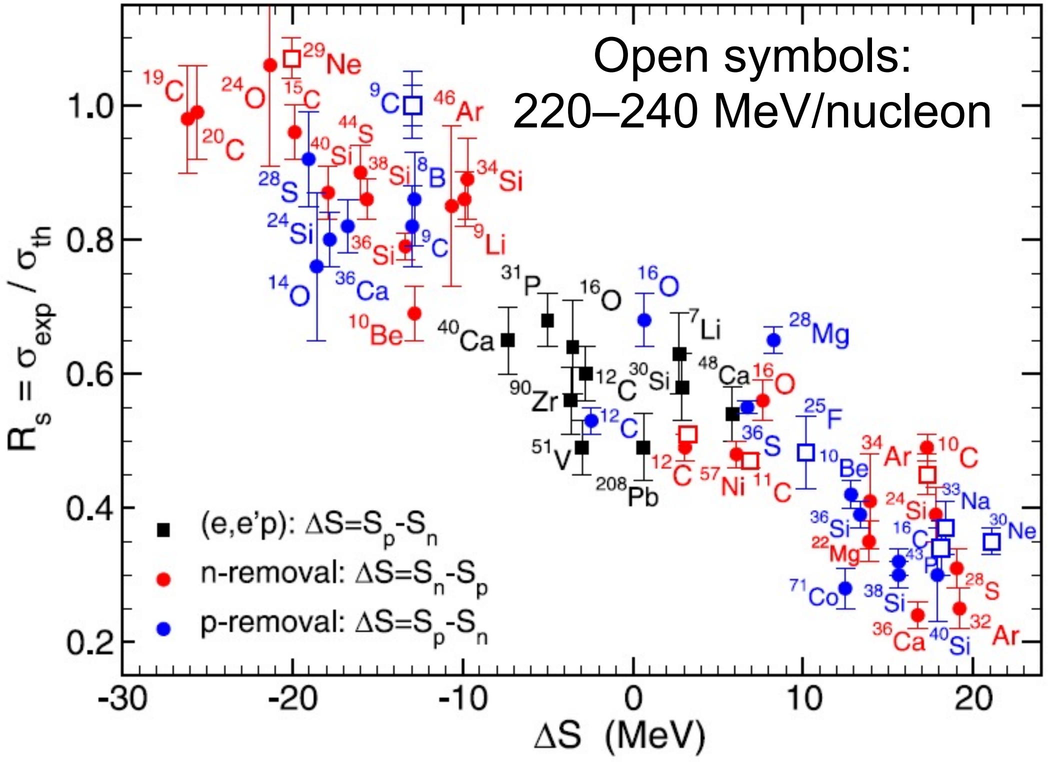
Gade et al., PRC77(2008)044306



- 核子在某个轨道的占居几率，可通过在中高能区（>80Mev/核子）测量单核子敲出截面、结合Eiknoal模型分析得到，探索单粒子自由度和壳层结构的演化
- 发现谱因子Rs与核子分离能之差ΔS间存在线性关系，吸引了大量的研究

？对于深束缚敲出，在<100MeV/nucleon束流情况下模型适用性

基于ETF的单核子敲出反应

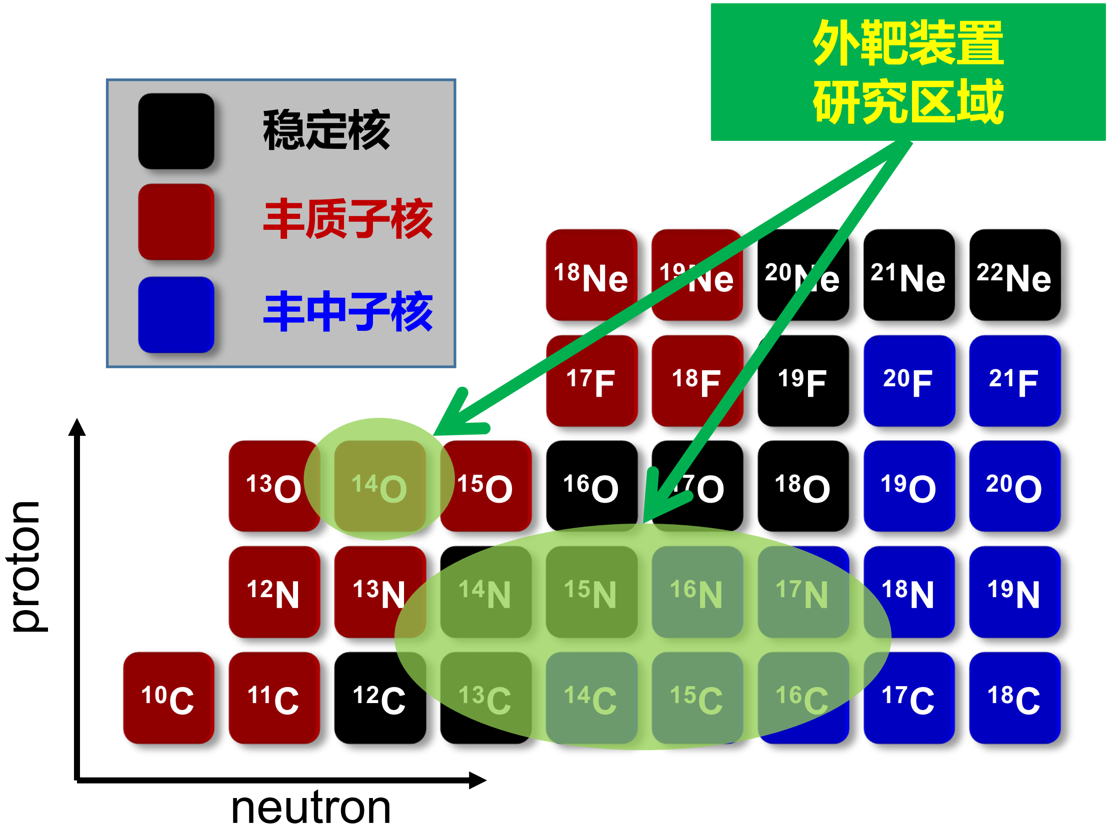


PHYSICAL REVIEW C **103**, 054610 (2021)

Updated systematics of intermediate-energy single-nucleon removal cross sections

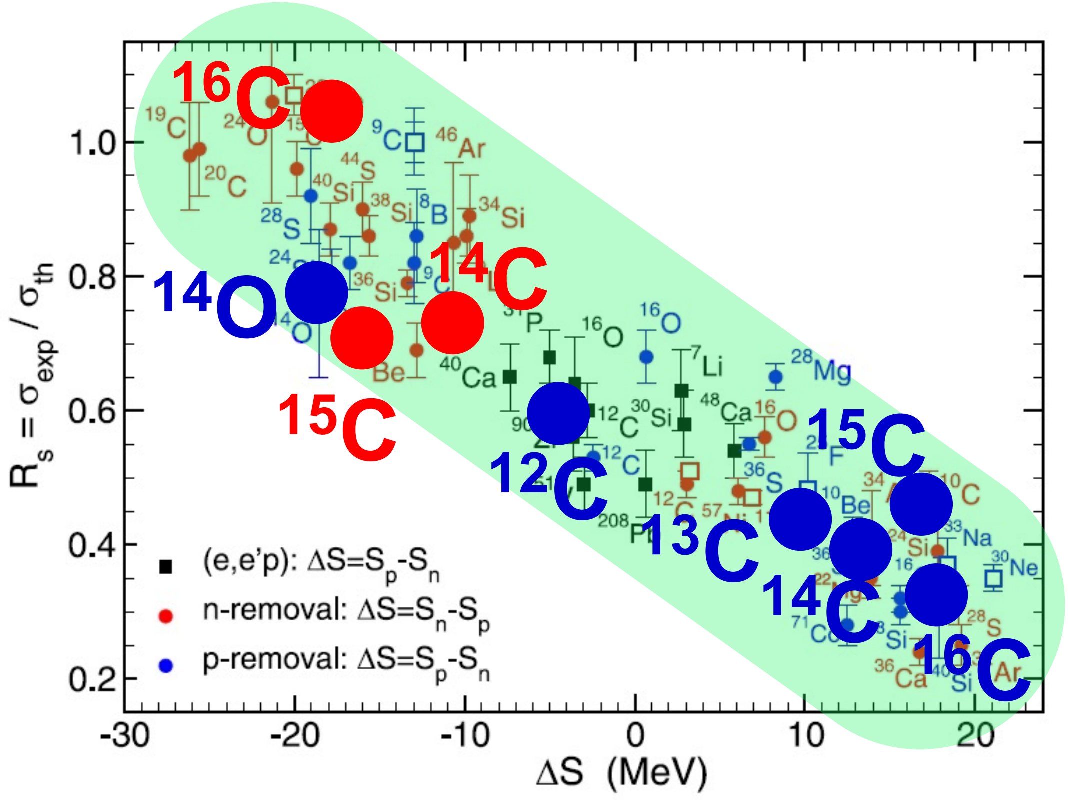
J. A. Tostevin[1] and A. Gade[2,3]

[1]Department of Physics, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom
[2]National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA
[3]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA



^{14}O (-p), *Phys. Rev. C* 90 (2014) 037601
^{16}C (-p), *Phys. Rev. C* 100 (2019) 044609
$^{14-16}$C (-n), *Phys. Rev. C* （2021）
$^{12-15}$C, $^{14-17}$N (-p), Data in analysis

基于ETF的单核子敲出反应



PHYSICAL REVIEW C **103**, 054610 (2021)

外靶结果：240 - 300 MeV/nucleon

Rs与ΔS间仍旧保持着线性关系

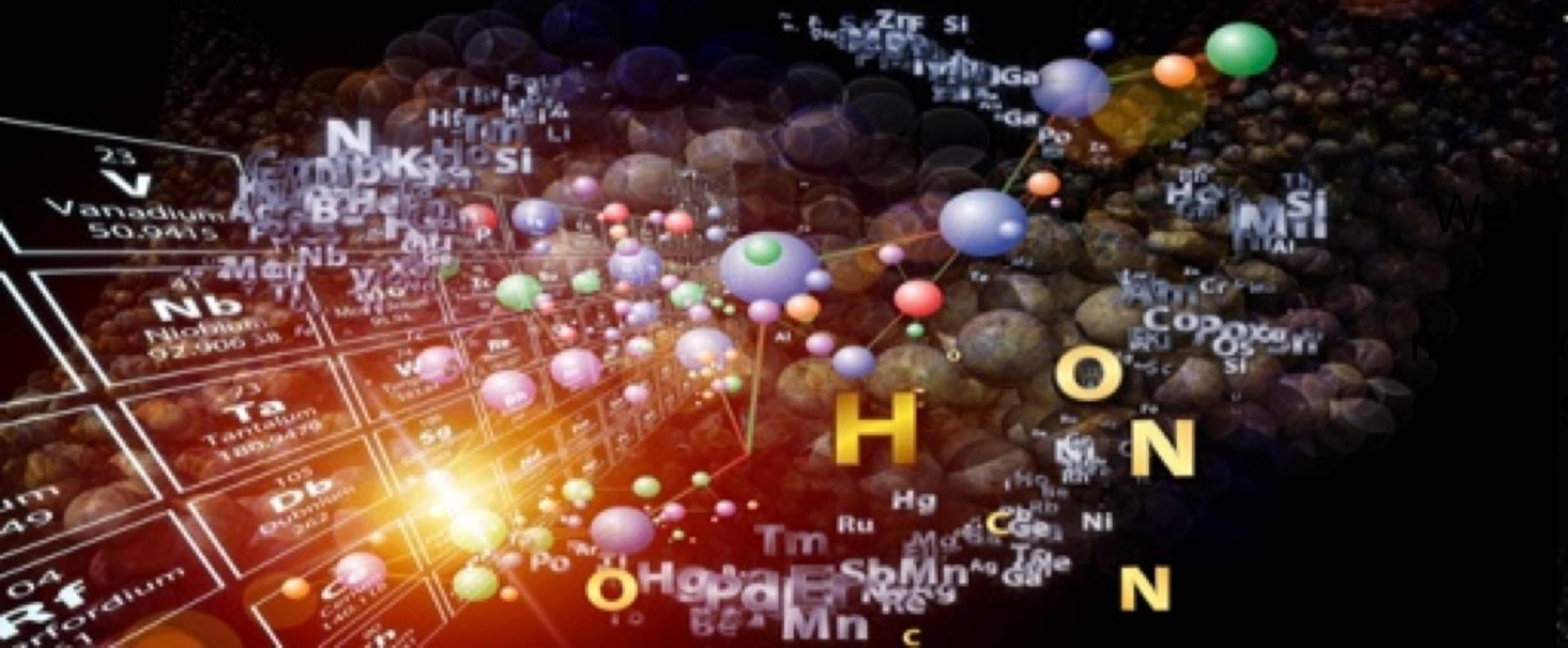
- 继续拓展敲出反应研究核区
- 开展(p, 2p)准自由敲出反应

Charge-exchange reaction

Isotopes, which are exposed to high temperatures and densities in a stellar plasma, may experience a dramatic change of their decay rates.

- High temperature (GK)
- High density (nuclear matter)

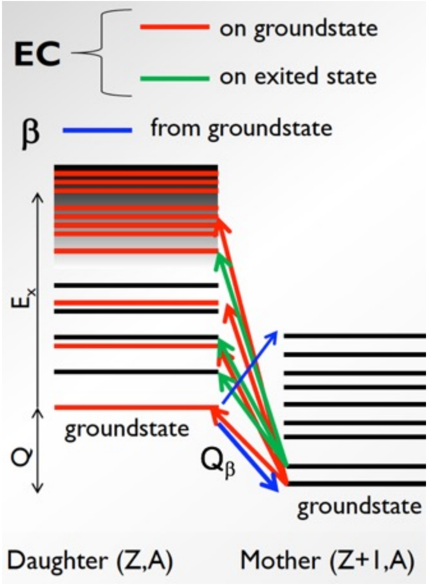
Source of energy and elements in cosmos



Stellar vs. Terrestrial

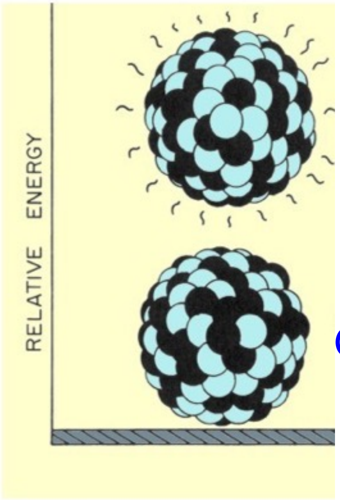
High temperature

- Highly-charged state (even fully-striped)
  electron capture, isomer (IC),
  bound-state β-decay, electron screening, …
- Thermal population of low-lying excited states



High intensity

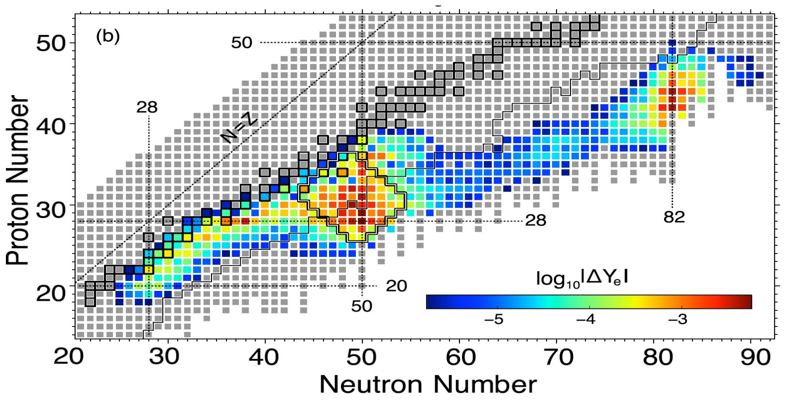
- “decay” beyond Q_β window
- Daughter nuclide vs. mother nuclide



Hot nuclide

Ground state

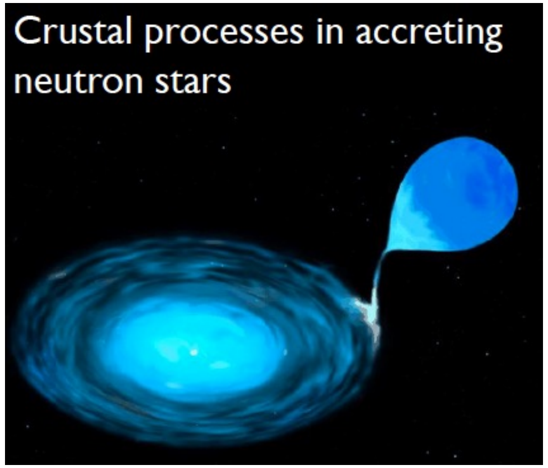
➢ Capture of free electrons in dense-matter scenarios

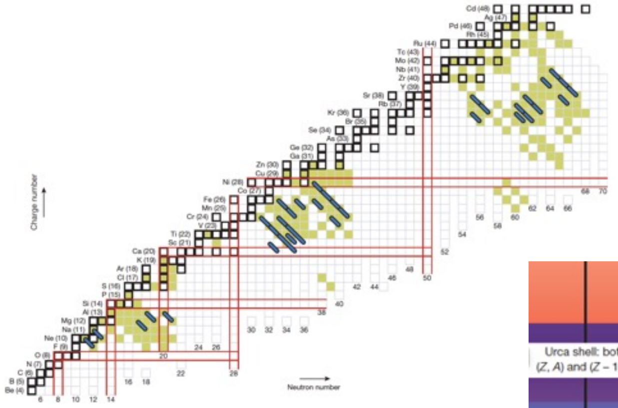


Sullivan et al. 2016

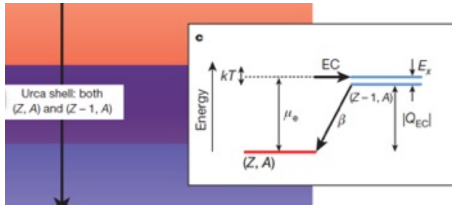
electron-capture on stable or n-rich nuclei

EC





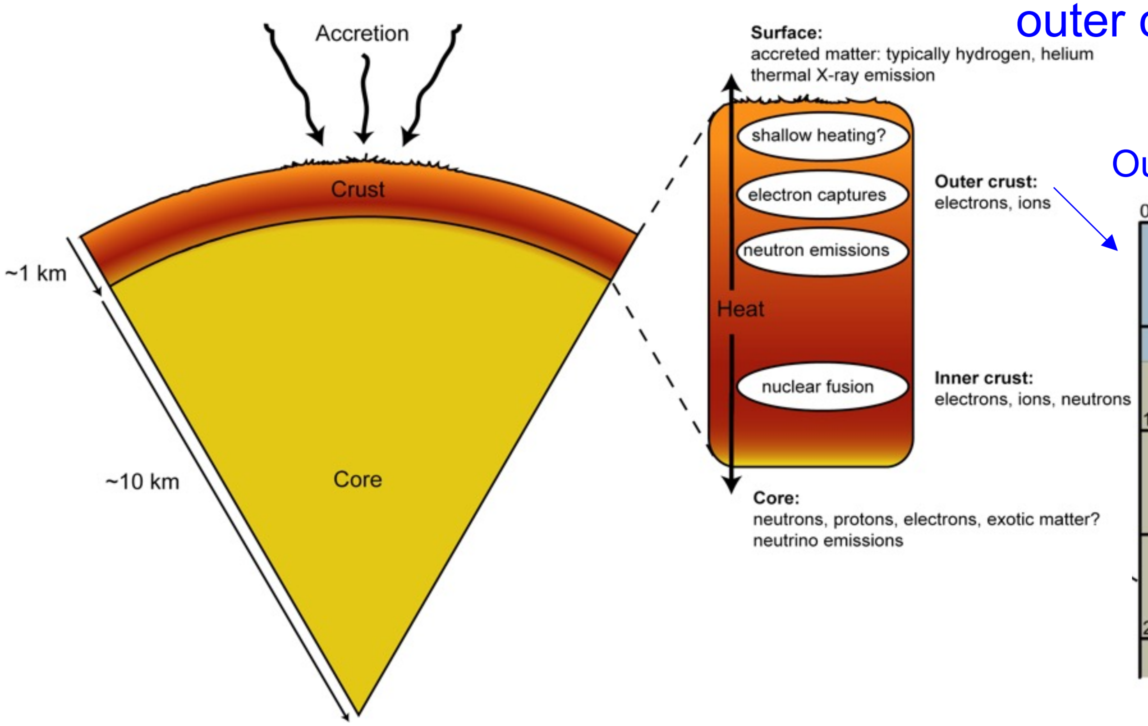
H Schatz *et al. Nature* *505*,**62(2014)**



Electron-capture reaction rates on n-rich medium-heavy nuclei (unstable nuclei) are an important ingredient for modeling the late evolution of stars that become core-collapse or thermonuclear supernovae, and neutron stars

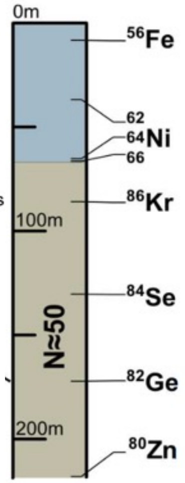
EC in neutron stars

Neutron stars are the remnants of core-collapse supernova explosions

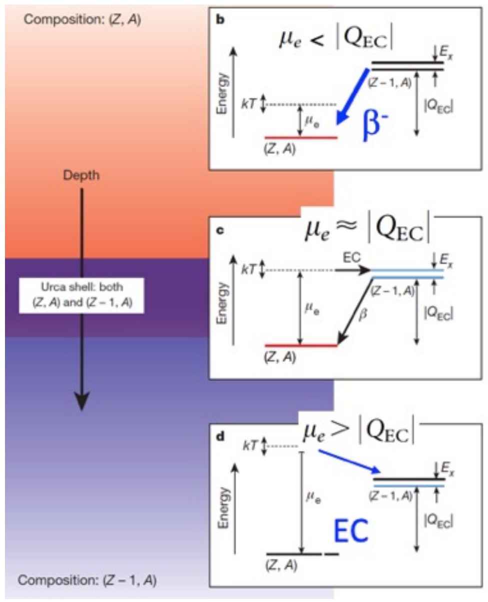


β-equilibrium reached in the outer crust

Outer crust

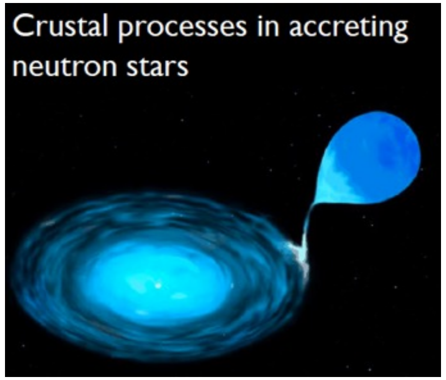


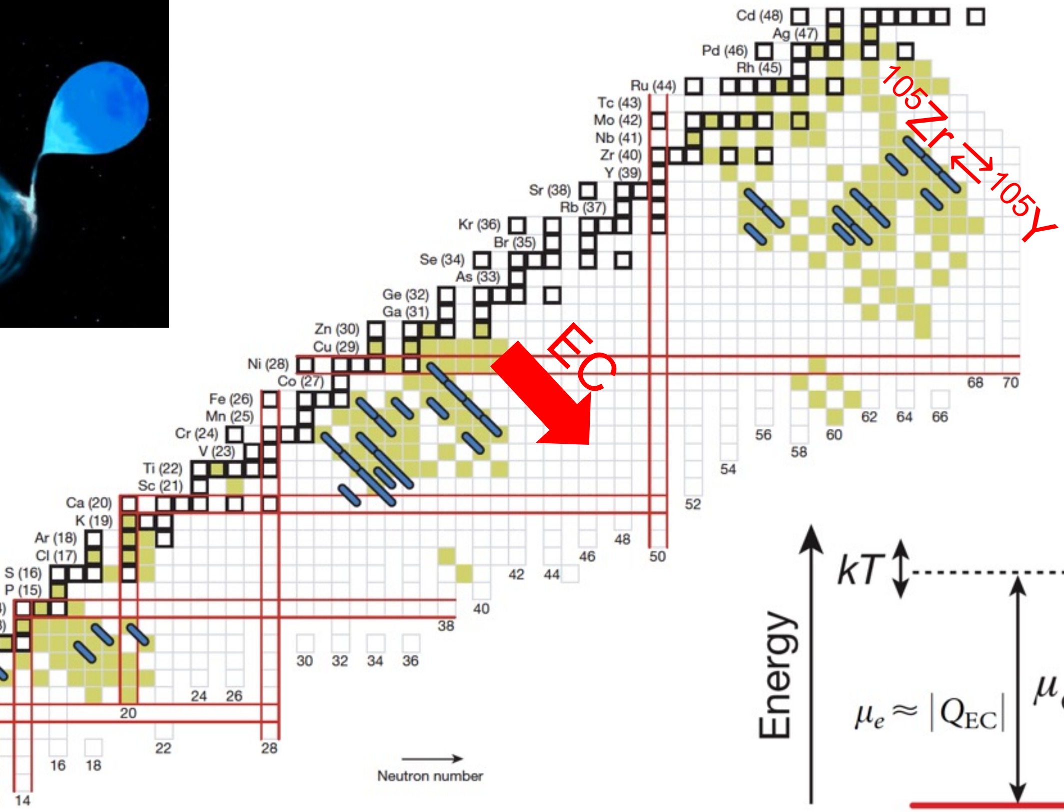
Schematic nuclear energy-level diagrams for an EC/β⁻-decay pair.



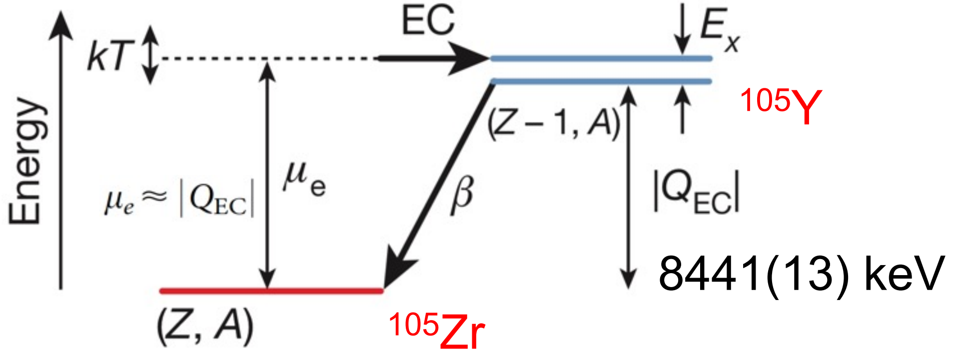
Strong neutrino cooling by cycles of electron capture and b- decay in neutron star crusts

Neutrino cooling by EC and beta decay





URCA cooling process



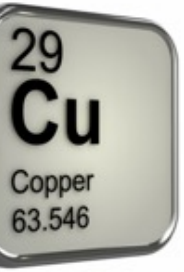
EC due to dense electron plasma

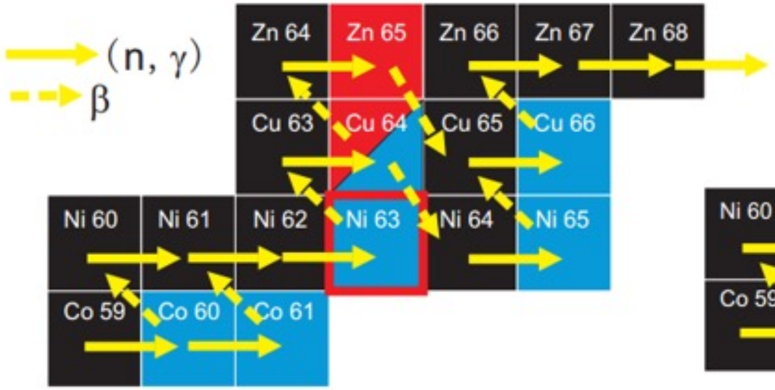
- No experimental B(GT+) of n-rich isotopes

H. Schatz *et al. Nature 505,* **62(2014)**

➢ Half-lives of “hot” atomic nuclei

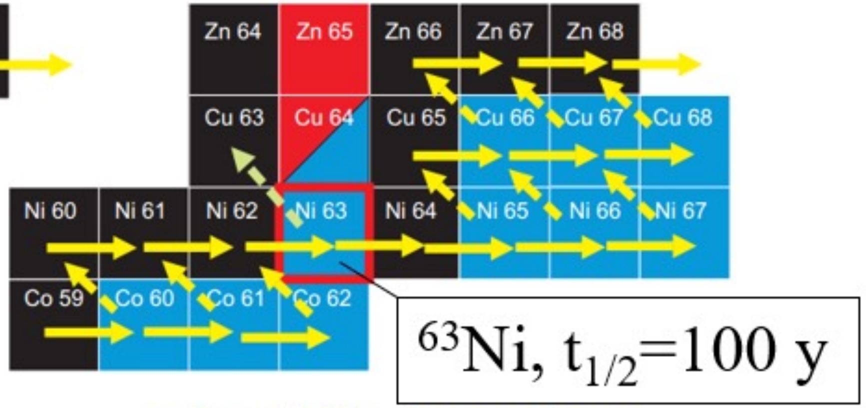
Origin of Cu elements





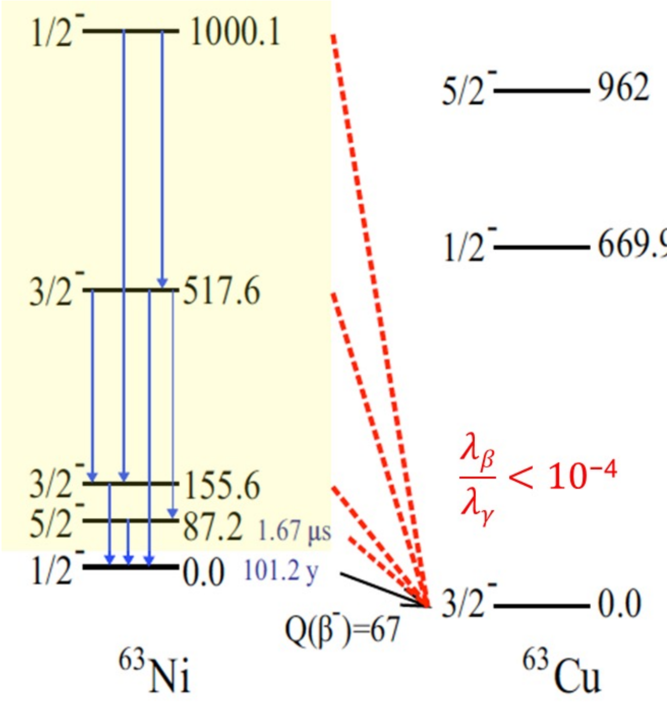
core He burning

T≈300 MK, n_n~$10^6 cm^{-3}$



shell C burning

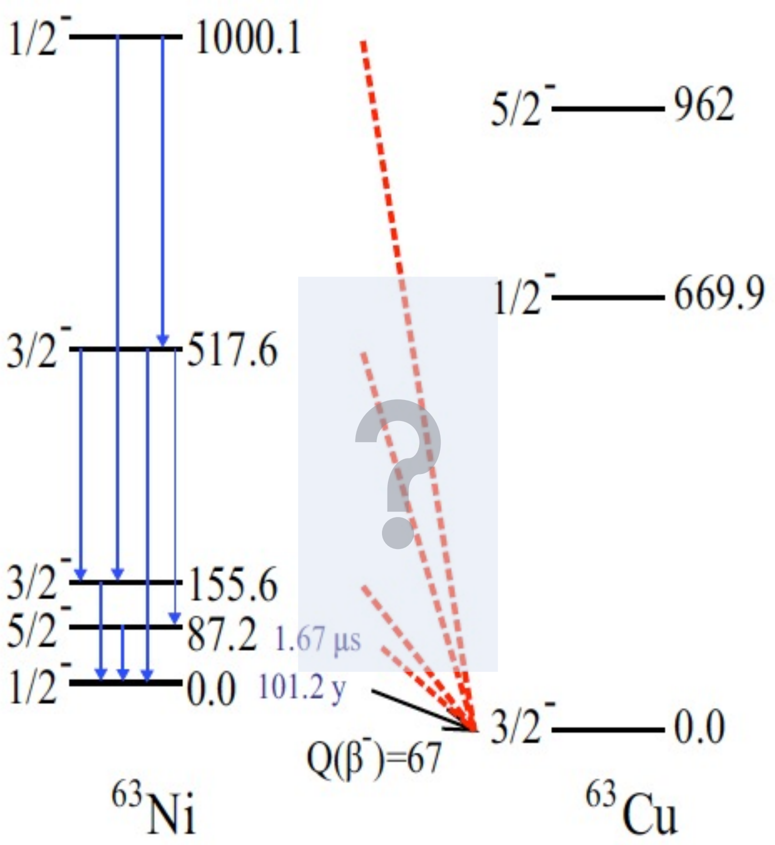
T≈ 1GK, n_n>$10^{11} cm^{-3}$

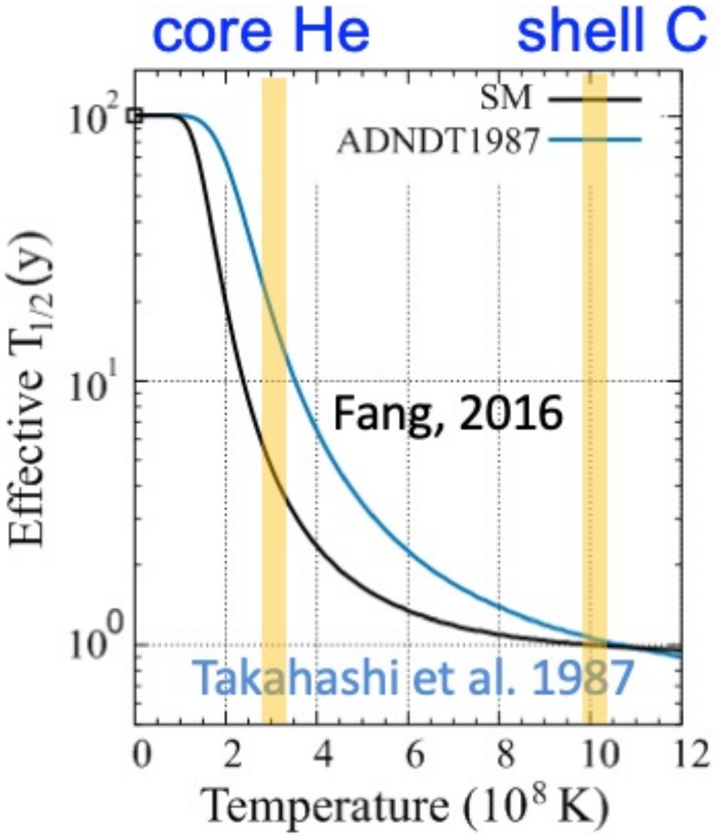


- ➢ The half-life of ^{63}Ni can be enhanced by up to two order of magnitudes in the weak slow-neutron capture process.
- ➢ Direct measurement: impossible

B.H. Sun, approved proposal E501 (RCNP)

Stellar half-life of ^{63}Ni and origin of ^{63}Cu

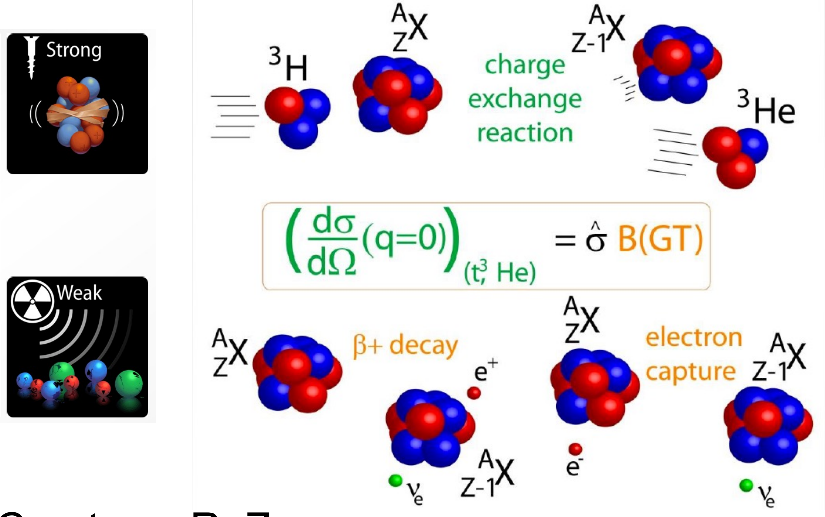




Various calculations show: reduced half-life by up to a factor of 20 at 300 MK, and two orders of magnitude at the C shell burning.

Experimental method: charge-exchange reaction

Charge-exchange reactions at intermediate beam energies has long been a powerful technique to study β-transition strength, especially can probe excitation regions, which are inaccessible to β-decay.



$$B(GT_+) = \sum_{i,f} \frac{n_i^p n_f^h}{(2j_i+1)(2j_f+1)} \left|\langle f|\vec{\sigma}\tau_+|i\rangle\right|^2$$

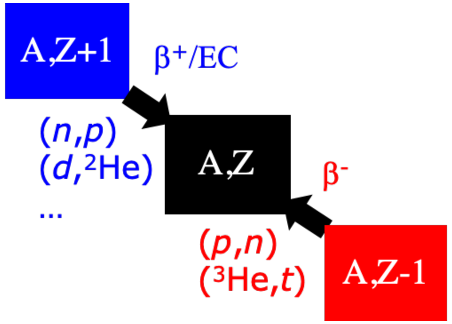
β-decay weak

$$\frac{d\sigma}{d\Omega}(q=0) = \left[\frac{\mu}{2\pi\hbar}\right]^2 \frac{k_f}{k_i} N_D |V_{\sigma\tau}|^2 \left|\left\langle f\left|\sum_k \sigma_k \tau_k\right|i\right\rangle\right|^2$$

charge-exchange strong

$\hat{\sigma}$: unit cross section

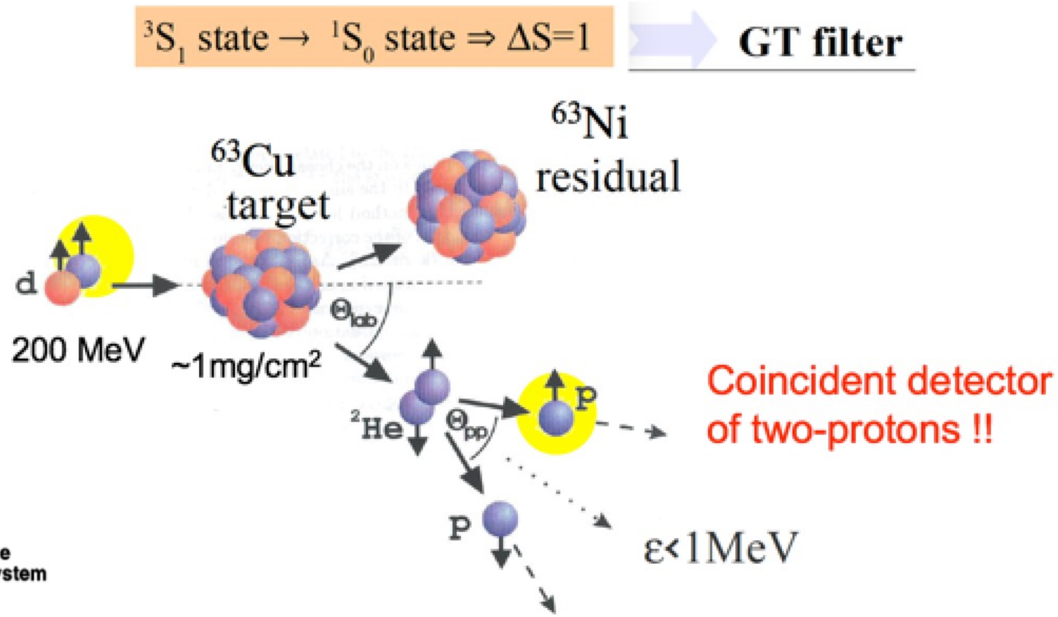
Taddeucci et al. NPA 469, 125 (1987)

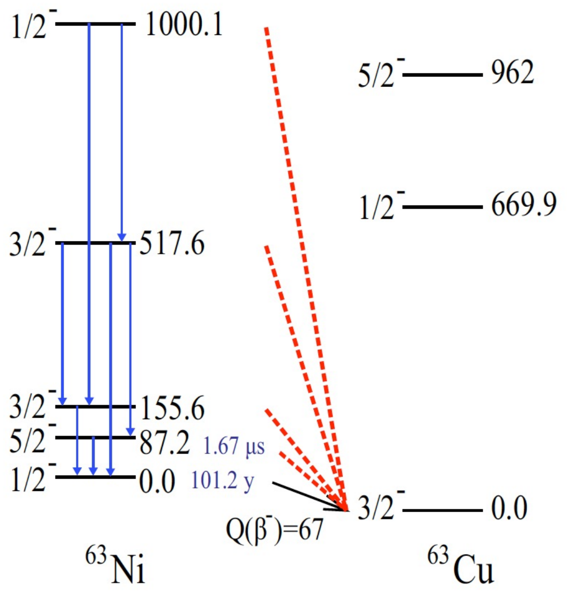


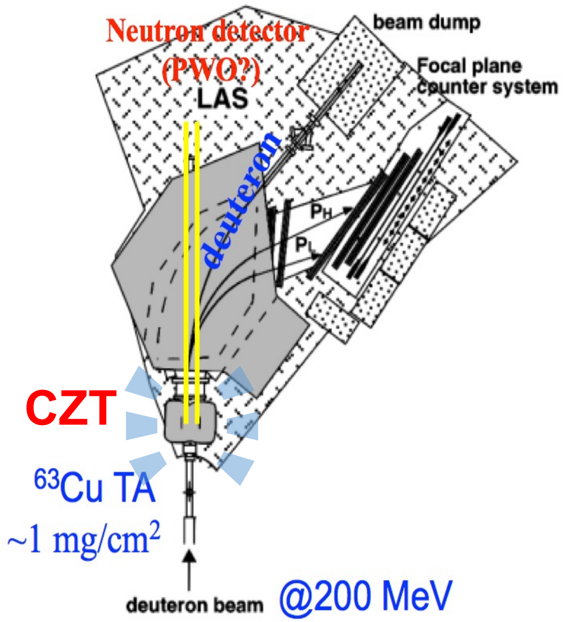
Courtesy: R. Zegers

- Charge-exchange reactions connect the same initial and final states as in a weak interactions and are mediated through similar spin and isospin transfer operator
- Proportionality holds at ~10% level for allowed GT/F transitions
- Applied to a variety of charge-exchange probes: (*p*,*n*)/(*n*,*p*), (*d*,^{2}He), (^{3}He,*t*)/(*t*,^{3}He) etc.

(d, ^{2}He) Charge-exchange reaction at > 100 MeV/u







Experimentally almost pure $^1S_0$ state can be selected by limiting the relative energy of the di-proton system to less than 1 MeV.

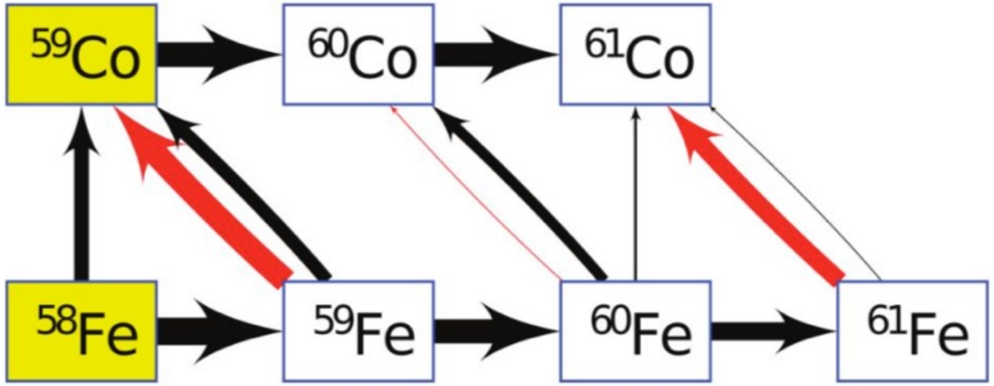
Breakup >> charge exchange!

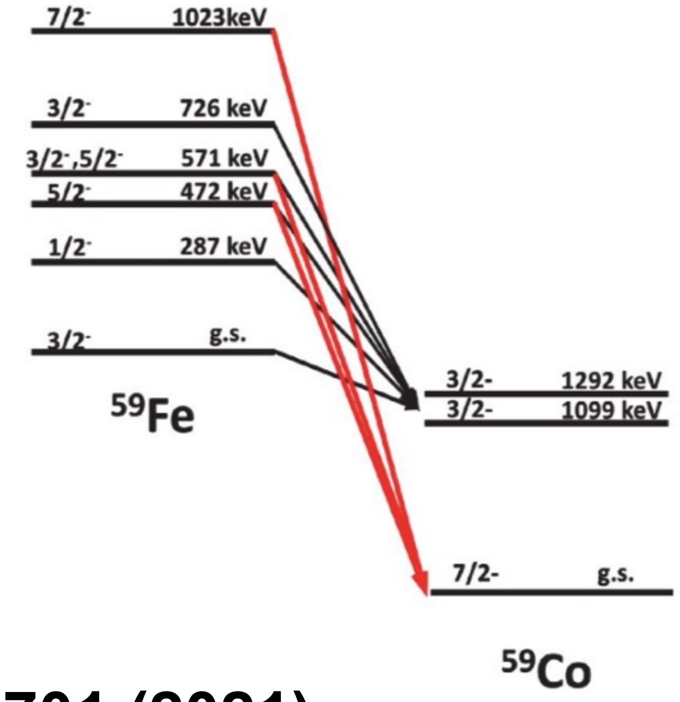
Approval RCNP proposal (2017)

Another example: decay of ^{59}Fe

B.S. Gao et al., IMP-NSCL-BUAA,
approved NSCL proposal (2018); done in Feb. 2020 at NSCL

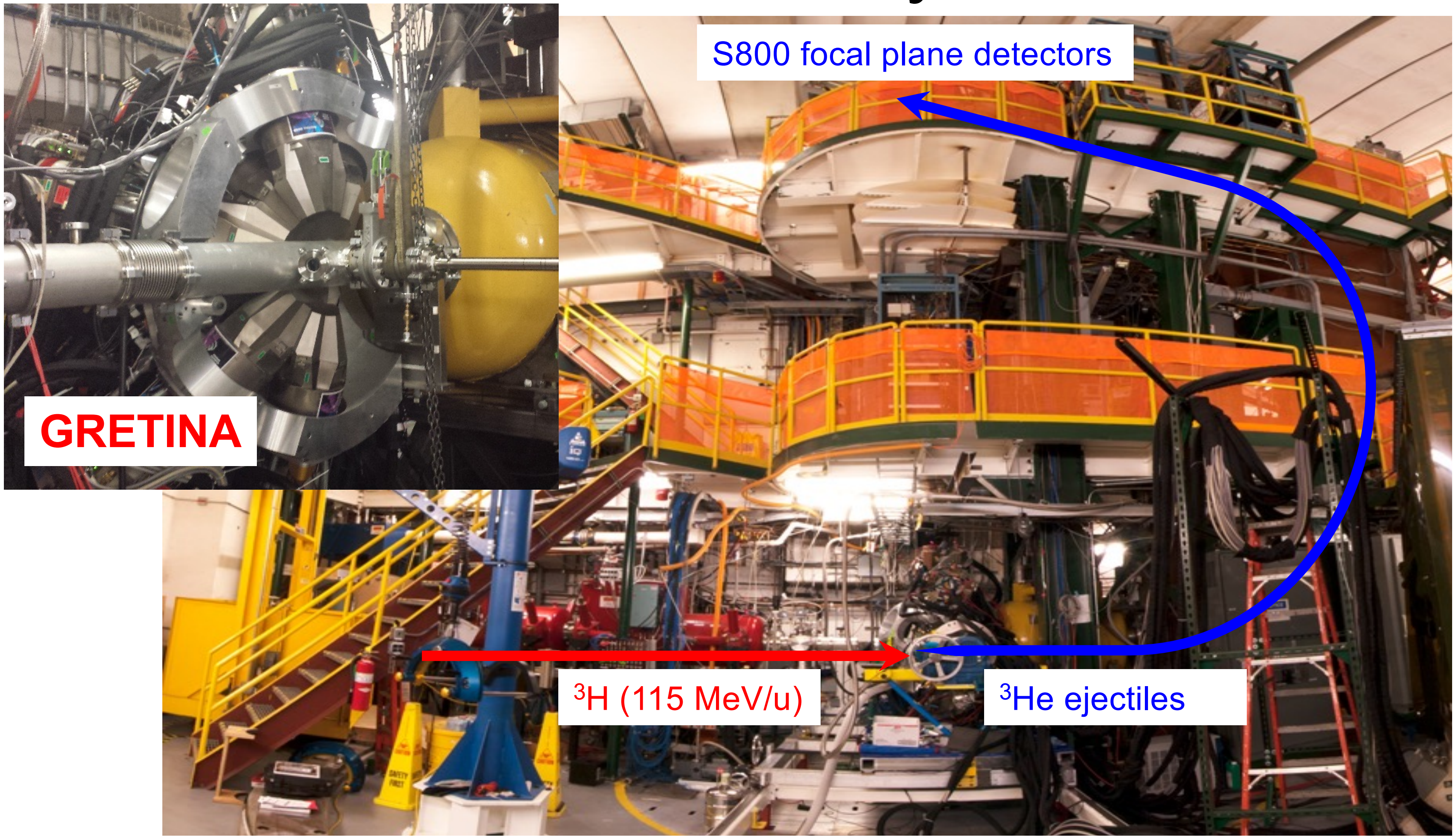
^{59}Co(t,^{3}He)^{59}Fe → decay from excited states of ^{59}Fe



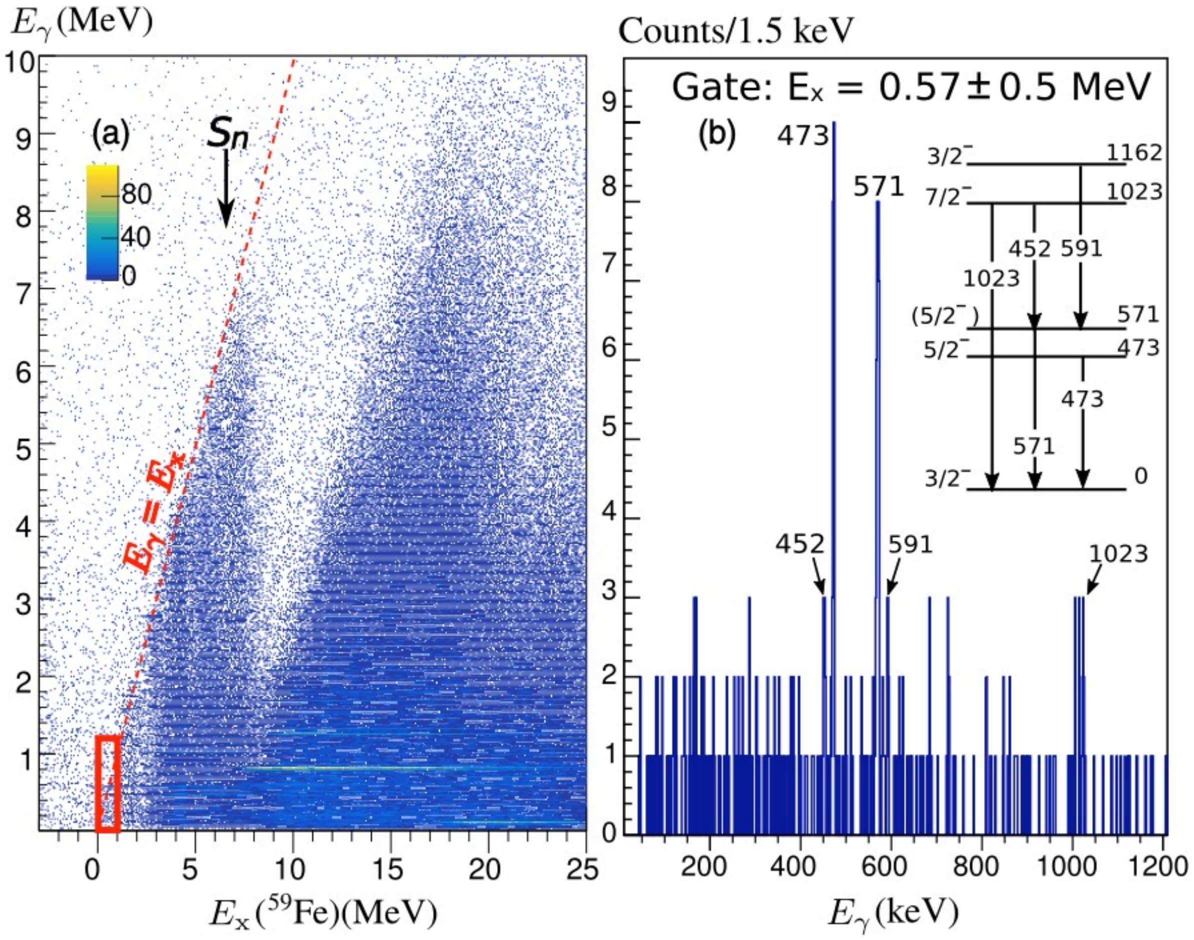


Gao et al., PRL 126, 152701 (2021)

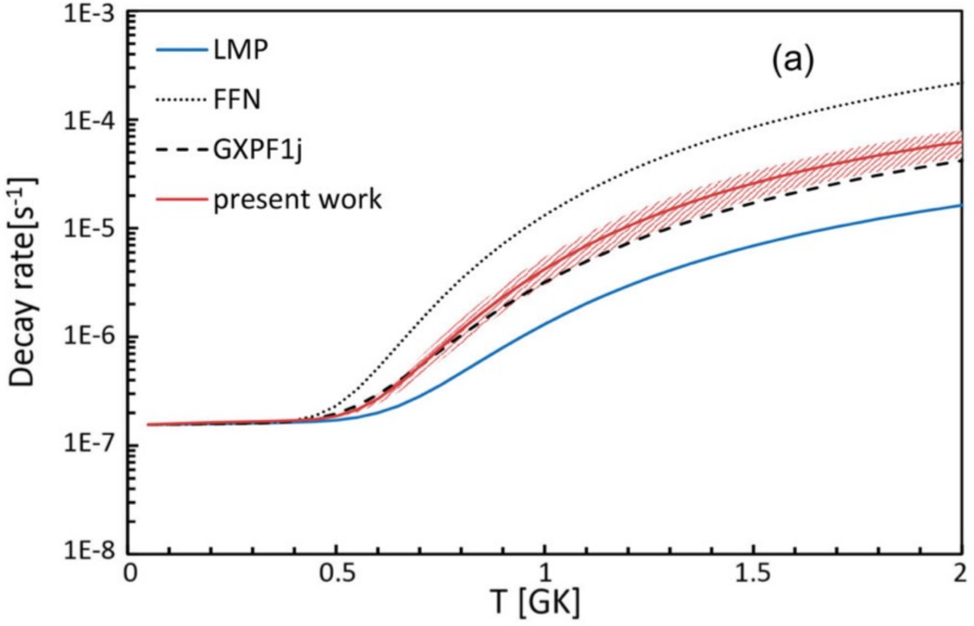
The stellar beta-decay rate of ^{59}Fe



$^{59}Co(t,^{3}He)^{59}Fe$, + γ-rays of ^{59}Fe



$$\left(\frac{d\sigma}{d\Omega}\right)_{q=0} = \hat{\sigma}B(\text{GT})$$

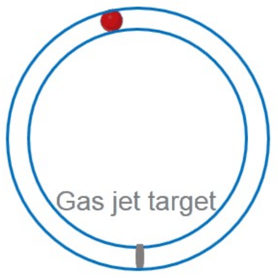


Gao et al., PRL 126, 152701 (2021)

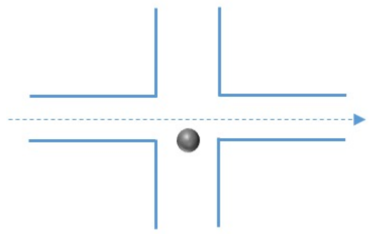
Stored RIB beams for most rare cases

Luminosities in storage rings are superior by orders of magnitude compared to experiments with fixed-target experiments.

Ring

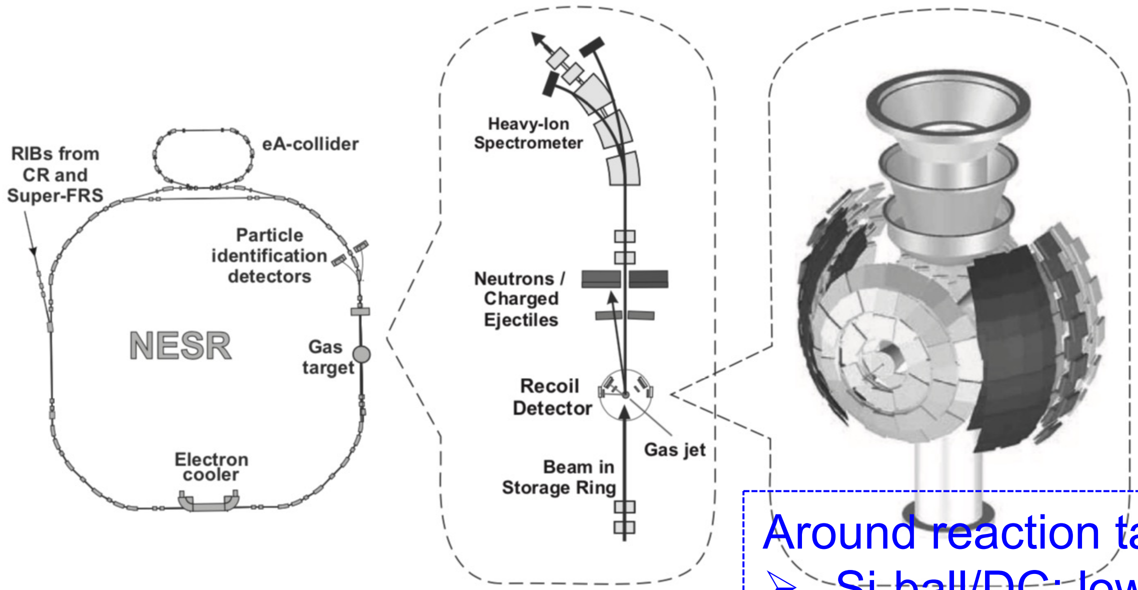


Gas jet target



EXL project @ FAIR

Heavy-ion spectrometer



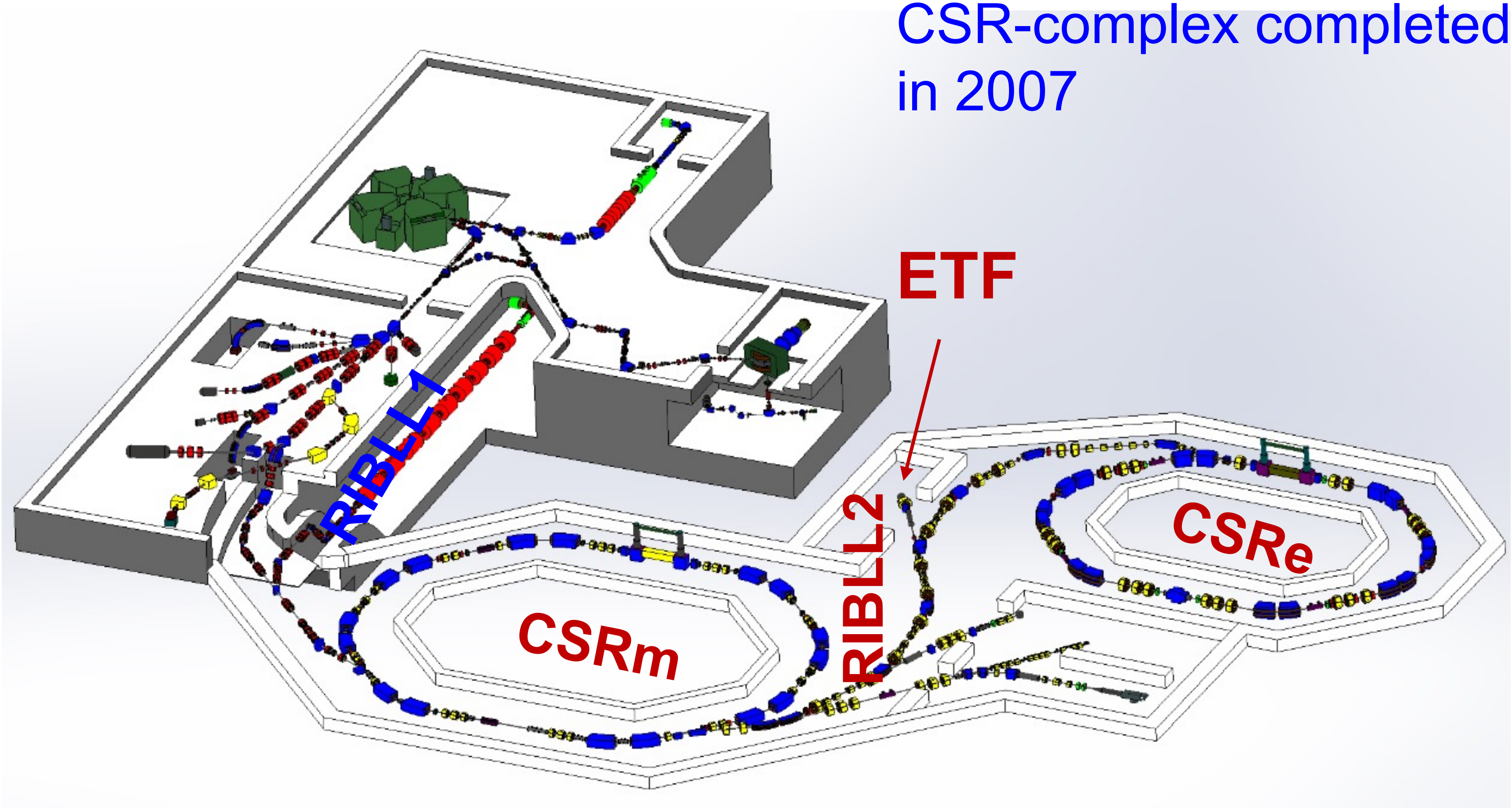
Identified beam
or fast cooling (down to <1s)

Around reaction target for recoil particles:

- Si-ball/DC: low-energy proton, tritium
- low-neutron detector (n)
- γ-ray detector

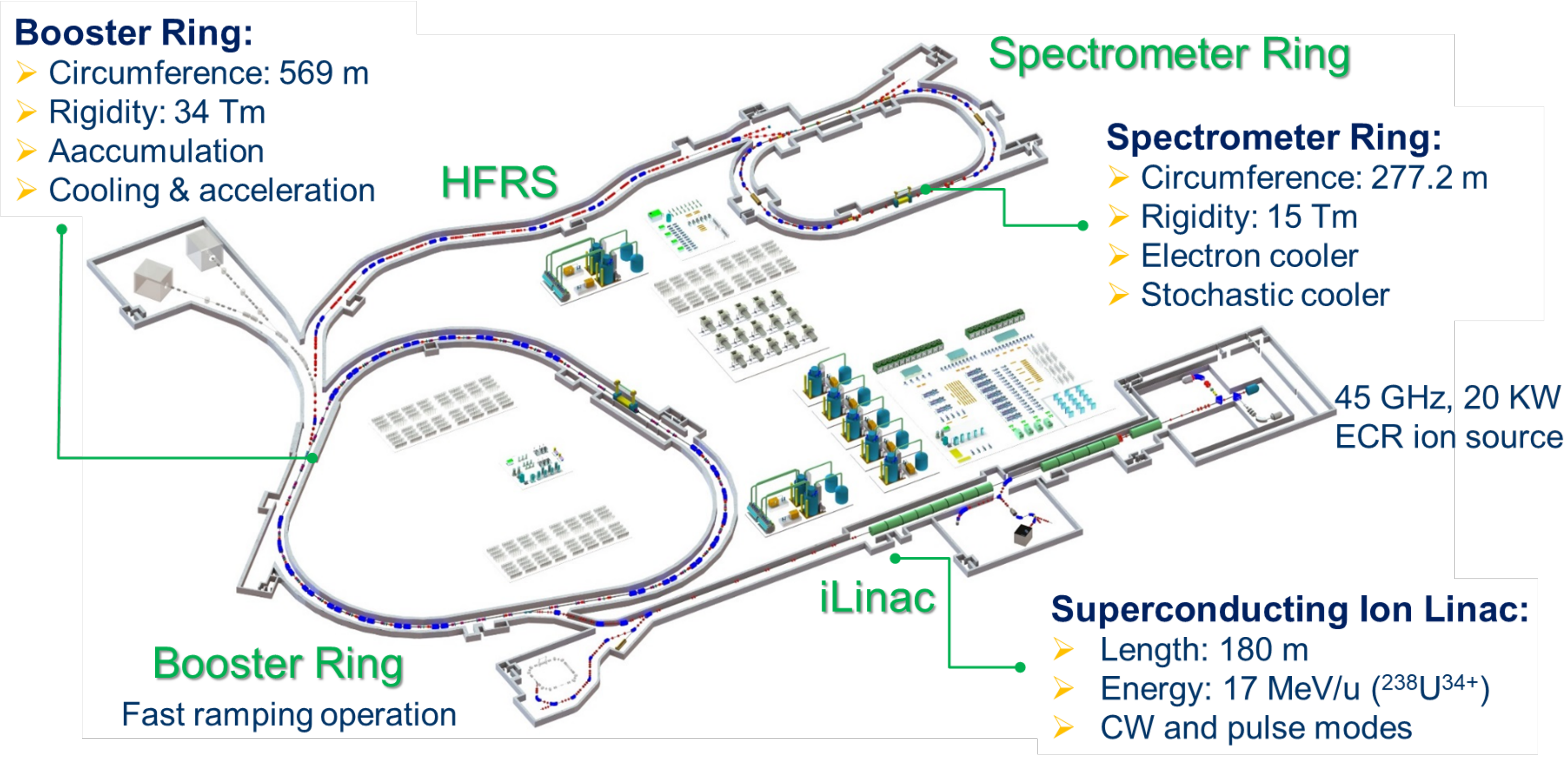
High energy reaction study in China

HIRFL-CSR facility at Lanzhou



J.W. Xia et al. Nucl. Instrum. Meth. A 488 (2002) 11

High intensity heavy-ion Accelerator Facility (HIAF)

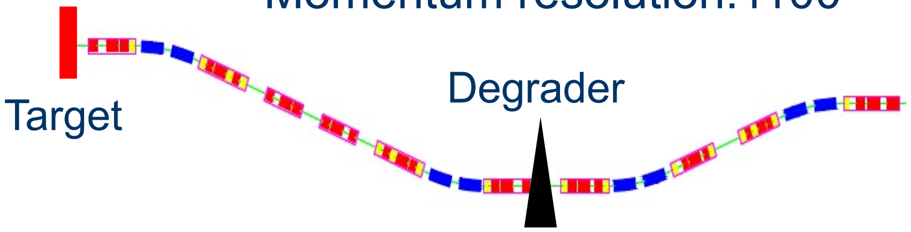


*Funding:*1.67 billion CNY for instrument + construction

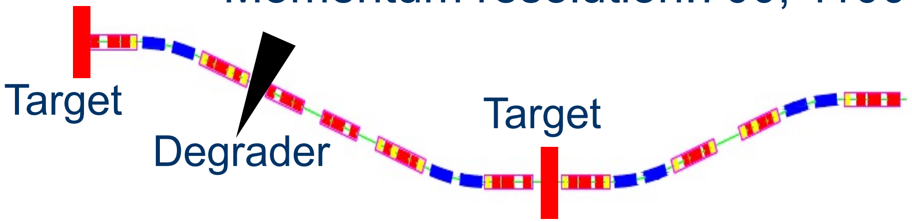
Structure and Performance of HFRS

Main-Separator: Separator + Spectrometer

Achromatic Mode
Momentum resolution:1100



Dispersive Mode
Momentum resolution:700, 1100



The peculiarities of the HFRS:

- A maximum Bρ=25 Tm, and thus high-energy secondary beams available
- High separation power, and fully stripped ions of all elements available
- Versatile spectrometer modes by different combinations of separator sections

Bρ=25Tm
Unique Experiments

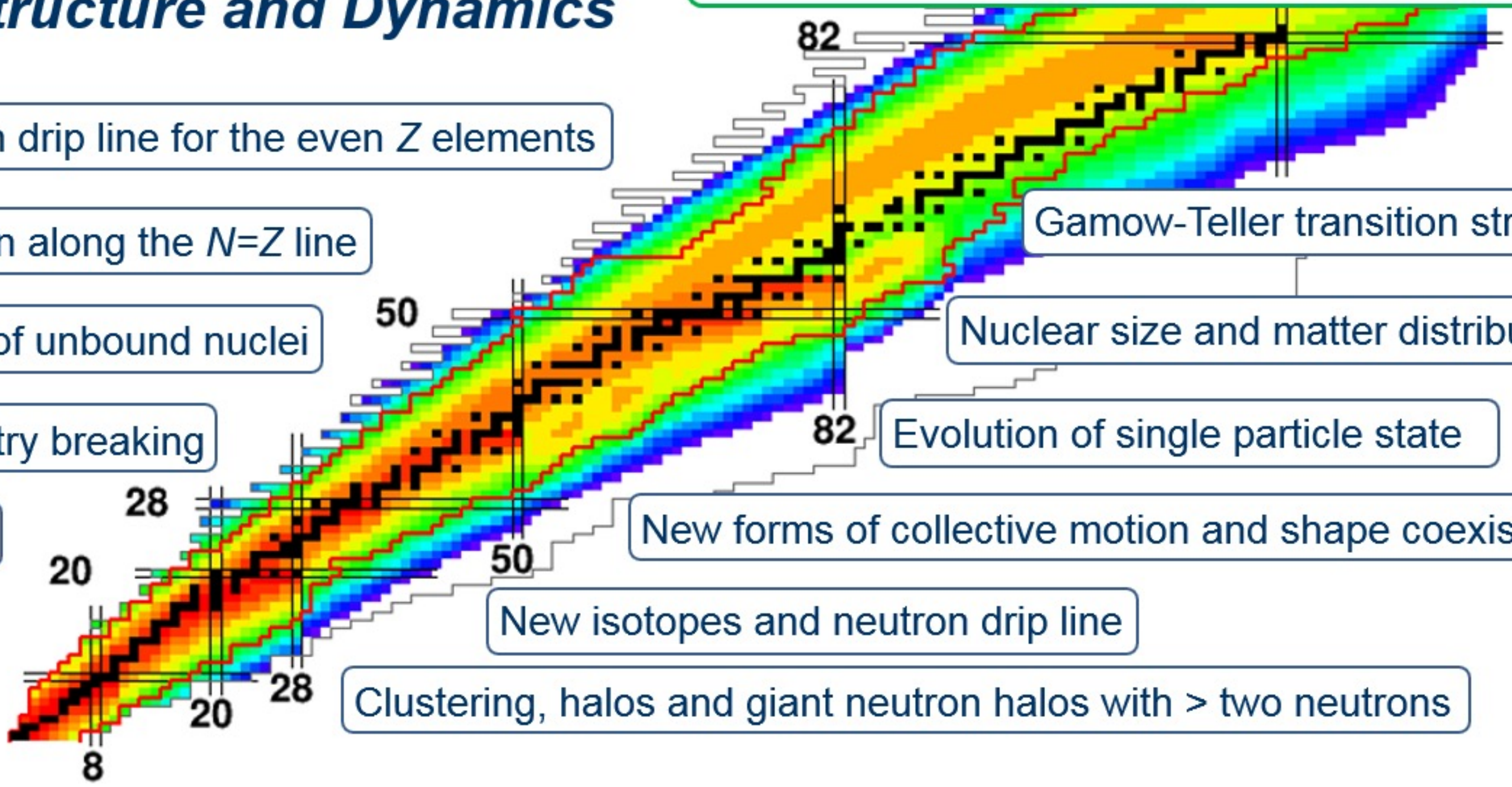
- Synthesis of neutron rich hypernuclei
- Nucleon excitations (Δ resonance and N*) in nuclei
- Giant resonance of neutron rich nuclei
- Spectroscopy of meson-nucleus bound system

Physics @HFRS

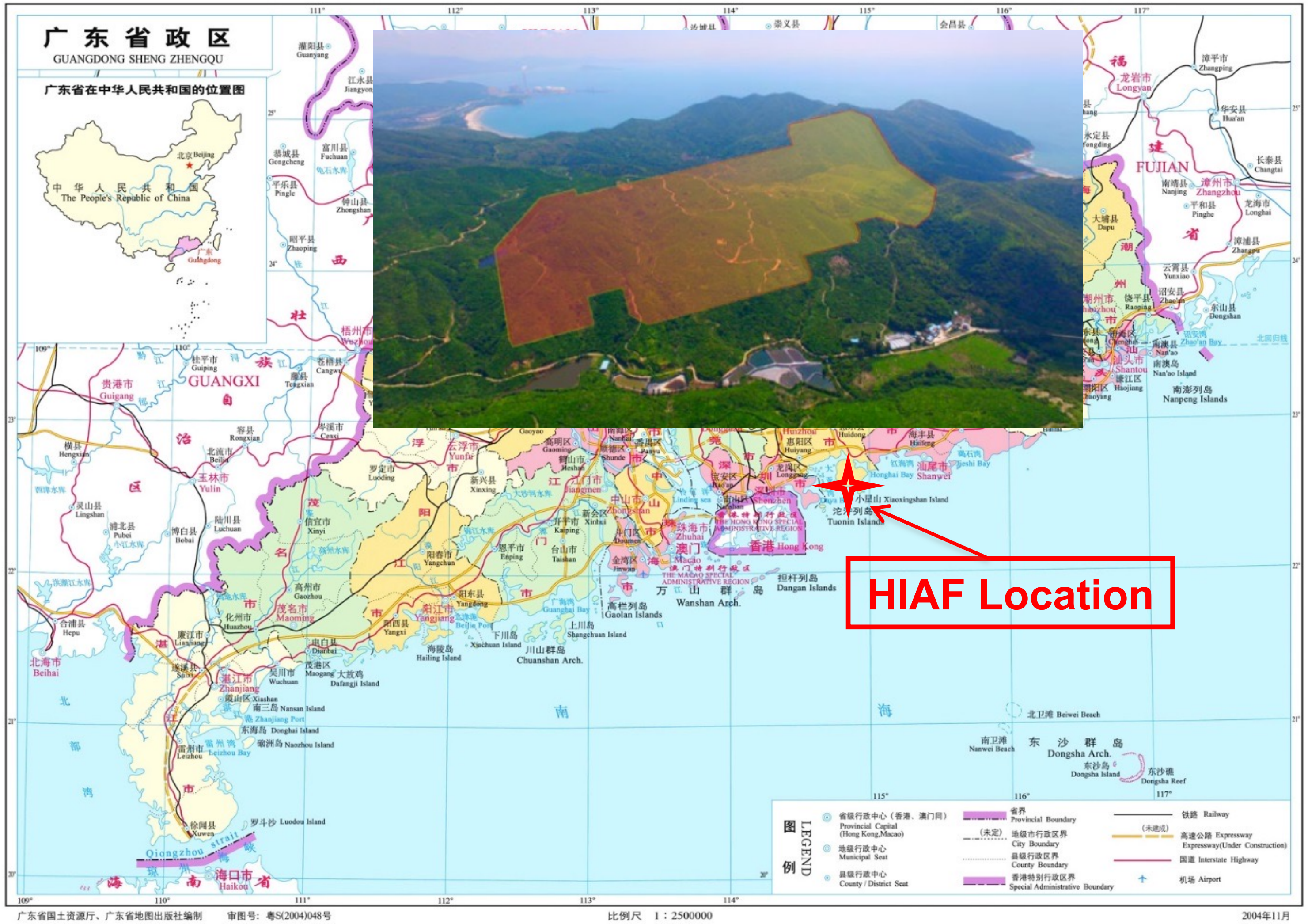
White paper on physics at HFRS is in preparation!

To explore the hitherto unknown territories and find new phenomena

Nuclear Structure and Dynamics

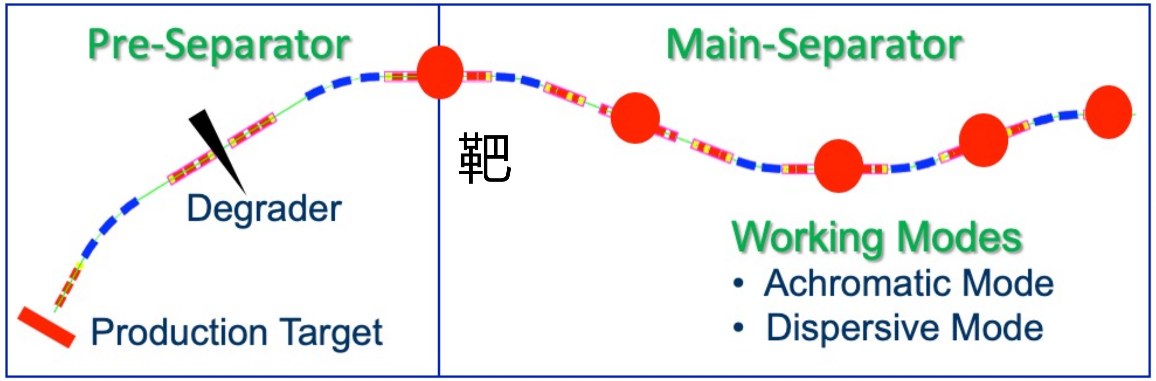


Facility Location



Construction Progress

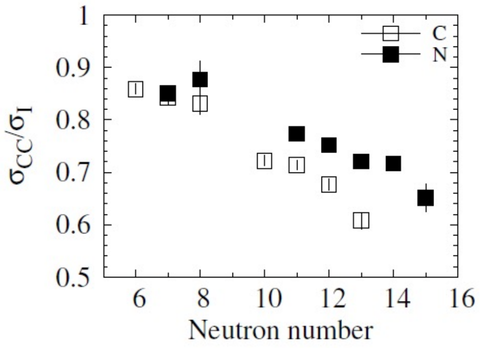
We have a dream at HFRS…

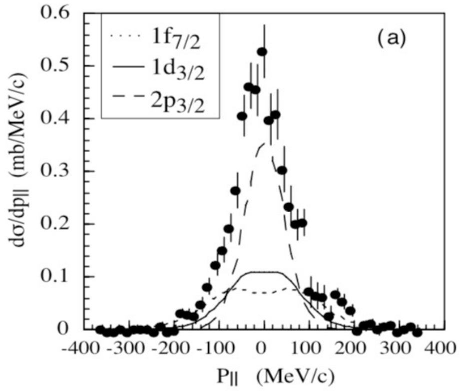


- Secondary target
- Tertiary target
- Degrader stations
- Detector systems
- Experimental areas

Separator + Spectrometer

- Charge-changing cross section：$\sigma_{CC} \rightarrow R_p$
- Interaction cross section：$\sigma_I \rightarrow R_m$
- Charge-exchange reaction：Cex → B(GT)
- Knockout reaction：spectroscopic factor
- Decay station
- …





Full data sampling
From analog to digital sampling

Summary

Studying atomic nuclei require us to use different “probe”from different aspect. Together, they help us to gain a “close-to-truth” imagine of atomic nuclei.

Nuclear structure can be investigated with nuclear reactions.

There are lots of exciting fields in front of you… and China should play an important/leading role in your generation…

- Possibility to calculate reaction cross sections from transportation method?

  AMD etc.

Acknowledgement

All the Beihang-IMP CCCS collaborators.
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谢谢！

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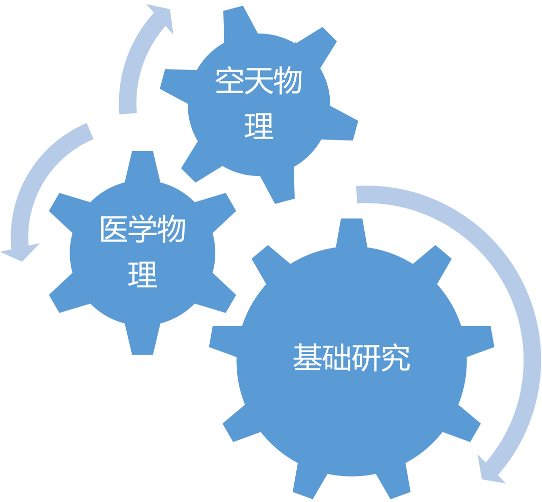
欢迎博士后！

10 硕士/博士



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