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Los Alamos NATIONAL LABORATORY

# New $^{16}O$ Evaluation Based on R-Matrix Analysis of the $^{17}O$ System

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# Outline

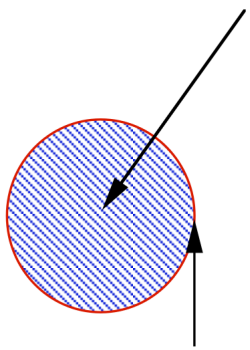
- Reminder of R-matrix properties, EDA code
- Status of the $^{17}O$ system analysis and $^{16}O$ evaluation
  - Low-energy scattering cross sections
  - $^{13}C(\alpha,n)$ and $^{16}O(n,\alpha_0)$ cross sections
  - Fits, data renormalizations, etc.
  - Extension of the evaluation to higher energies
- Summary and conclusions

# R-matrix Formalism

INTERIOR (Many-Body) REGION
(Microscopic Calculations)

$$\underbrace{H + \mathcal{L}_B}$$

compact, hermitian operator with real, discrete spectrum; eigenfunctions in Hilbert space



SURFACE

$$|\psi^+) = (H + \mathcal{L}_B - E)^{-1} \mathcal{L}_B |\psi^+)$$

$$\mathcal{L}_B = \sum_c |c)(c| \left( \frac{\partial}{\partial r_c} r_c - B_c \right),$$

$$(\mathbf{r}_c|c) = \frac{\hbar}{\sqrt{2\mu_c a_c}} \frac{\delta(r_c - a_c)}{r_c} [(\phi_{s_1}^{\mu_1} \otimes \phi_{s_2}^{\mu_2})_s^{\mu} \otimes Y_l^m(\hat{\mathbf{r}}_c)]_J^M$$

$$R_{c'c} = (c'|(H + \mathcal{L}_B - E)^{-1}|c) = \sum_\lambda \frac{(c'|\lambda)(\lambda|c)}{E_\lambda - E}$$

ASYMPTOTIC REGION
(S-matrix, phase shifts, etc.)

$$(r_{c'}|\psi_c^+\rangle = -I_{c'}(r_{c'})\delta_{c'c} + O_{c'}(r_{c'})S_{c'c}$$

or equivalently,

$$(r_{c'}|\psi_c^+\rangle = F_{c'}(r_{c'})\delta_{c'c} + O_{c'}(r_{c'})T_{c'c}$$

Measurements

# R-Matrix Theory Enforces Basic Properties of Scattering Theory

1) Unitarity ($\boldsymbol{S}\boldsymbol{S}^{\dagger} = \boldsymbol{S}^{\dagger}\boldsymbol{S} = 1$): enforced by $\boldsymbol{R_B}$ being real and symmetric ($H+\mathcal{L}_B$ hermitian).

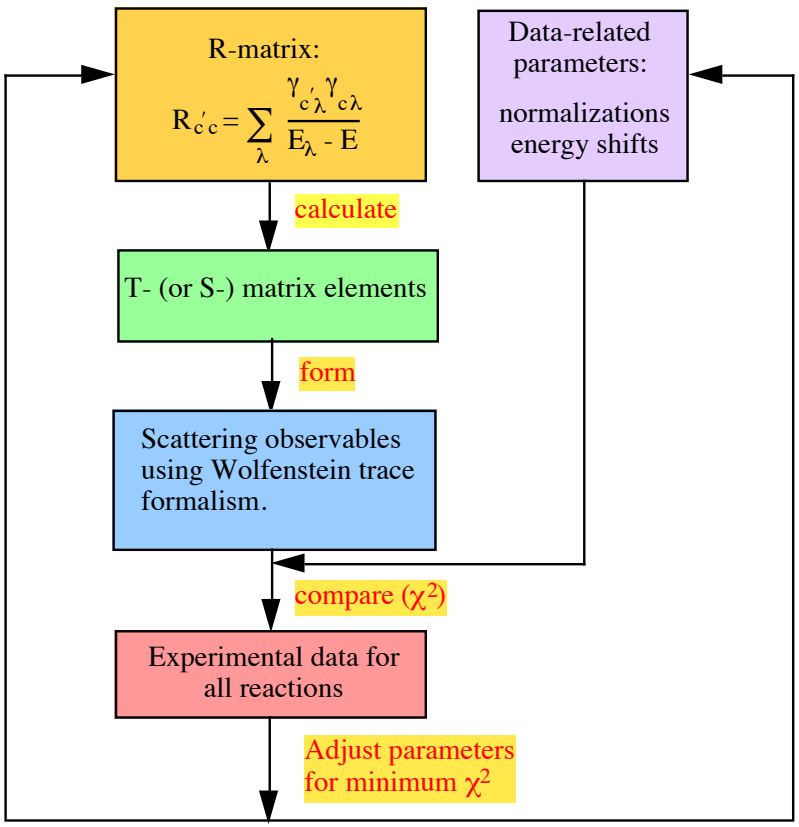
2) Reciprocity (TRI): enforced by the symmetry of $\boldsymbol{R_B}$ and all asymptotic matrices (such as $\boldsymbol{S}$) derived from it.

3) Causality: no poles of $\boldsymbol{S}$ in upper-half $k$-plane. Poles of $\boldsymbol{R_L}$ are all in the lower half-plane, at $k = k_0$ and $-k_0^*$.

Note that the MLBW approximation violates *all* of these basic principles.

# Scheme and Properties of the EDA Code

## Energy Dependent Analysis Code




- Accommodates general (spins, masses, charges) two-body channels
- Uses relativistic kinematics and R-matrix formulation
- Calculates general scattering observables for 2 ➔2 processes
- Has rather general data-handling capabilities (but not as general as, e.g., SAMMY)
- Uses modified variable-metric algorithm that gives parameter covariances at a solution

# R-Matrix Analysis of Reactions in the $^{17}O$ System

| channel | $a_c$ (fm) | $l_{max}$ |
|---|---|---|
| $n+^{16}O$ | 4.4 | 4 |
| $\alpha+^{13}C$ | 5.4 | 5 |

| Reaction | Energies (MeV) | # data points | Data types |
|---|---|---|---|
| $^{16}O(n,n)^{16}O$ | $E_n = 0 – 7$ | 2540 | $\sigma_T$, $\sigma(\theta)$, $P_n(\theta)$ |
| $^{16}O(n,\alpha)^{13}C$ | $E_n = 2.35 – 5$ | 672 | $\sigma_{int}$, $\sigma(\theta)$, $A_n(\theta)$ |
| $^{13}C(\alpha,n)^{16}O$ | $E_\alpha = 0 – 5.4$ | 870 | $\sigma_{int}$ |
| $^{13}C(\alpha,\alpha)^{13}C$ | $E_\alpha = 2 – 5.7$ | 1168 | $\sigma(\theta)$ |
| total | | 5250 | 8 |

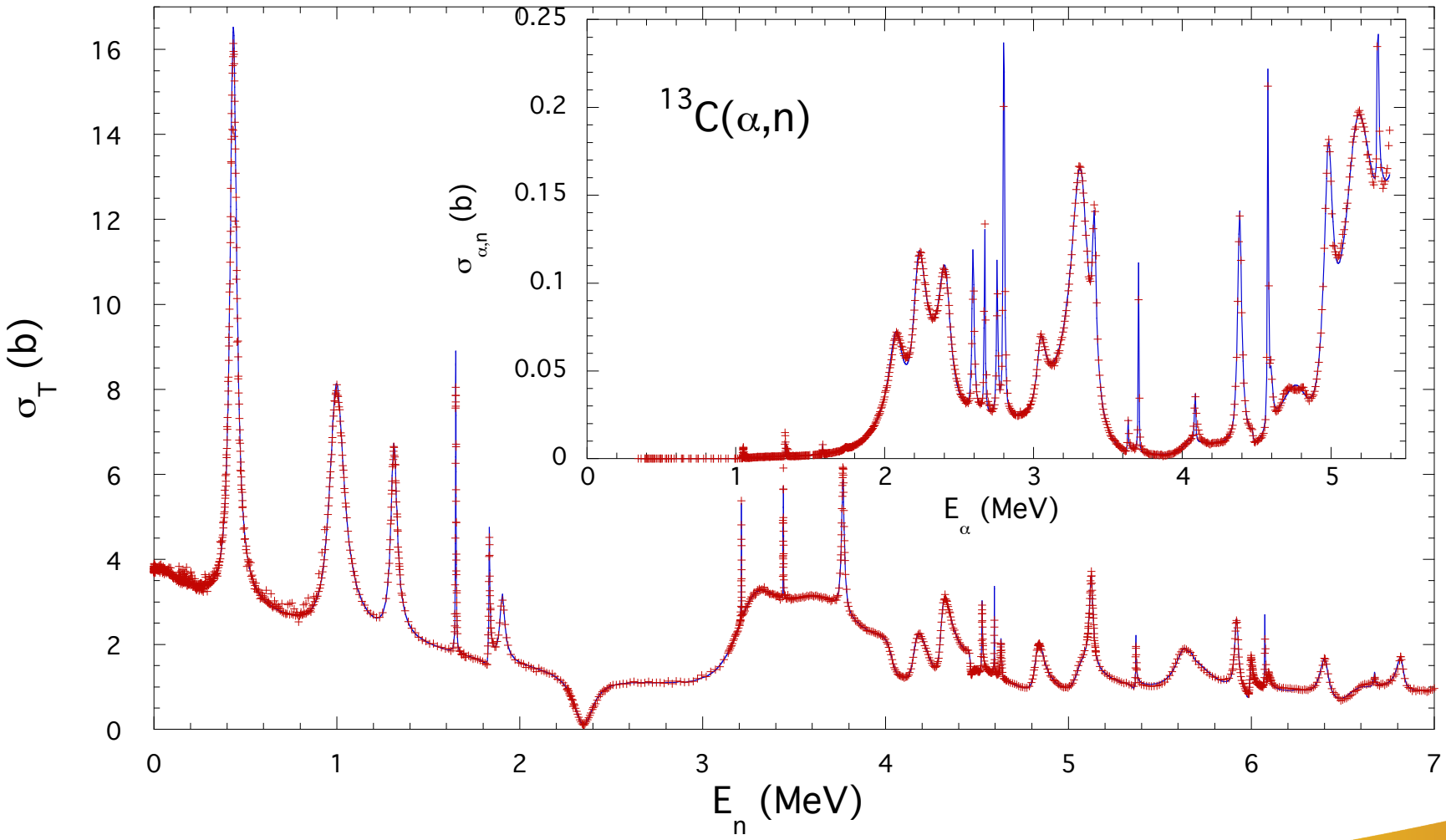
$\chi^2$ per degree of freedom = 1.68

# Total Cross Section Data

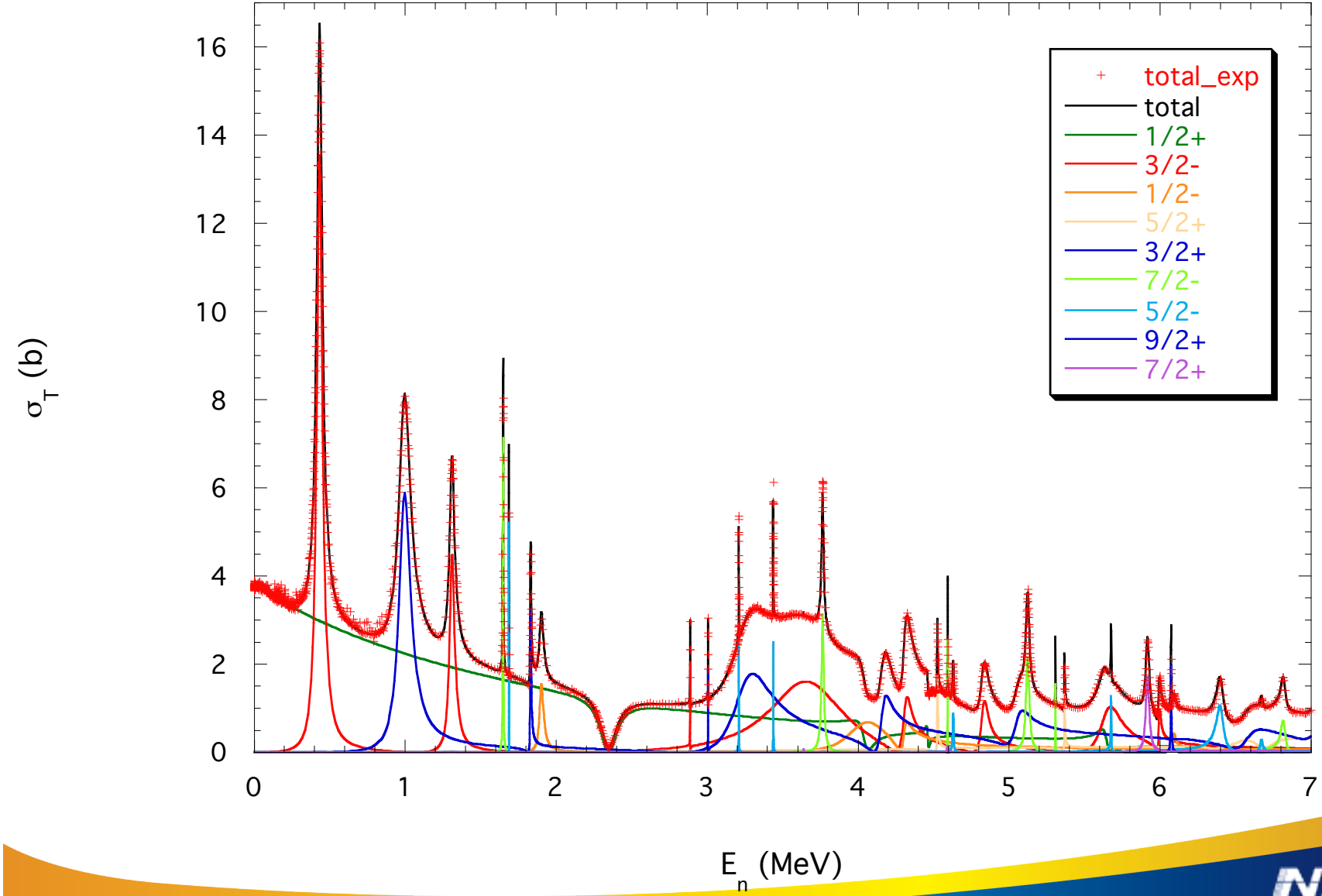
| Authors (n,n): | Energy Range | Energy Shift | Normalization |
|---|---|---|---|
| Schneider | 0.0253 eV | 0 | 1.0 (fixed) |
| Dilg,Koester,Block | 0.13 – 23.5 keV | 0 | 1.0 (fixed) |
| Ohkubo (corr. for H) | 0.8 – 935 keV | 0 | 0.9989 |
| Johnson & Fowler (including LOX) | 49 – 3139 keV | 0 | 0.9799 |
| Cierjacks et al. | 3.143 – 7.0 MeV | 0 | 1.0378 |

| Authors ($\alpha$,n): | Energy Range | Energy Shift | Normalization |
|---|---|---|---|
| Drotleff et al. | 346 – 1389 keV | 0 | 1.0 (fixed) |
| Heil et al. | 416–899 keV | 0 | 1.0 (fixed) |
| Kellogg | 445–1045 keV | 0 | 1.506 |
| Bair and Haas | 0.997–5.402 MeV | -4 keV | 0.9410 |

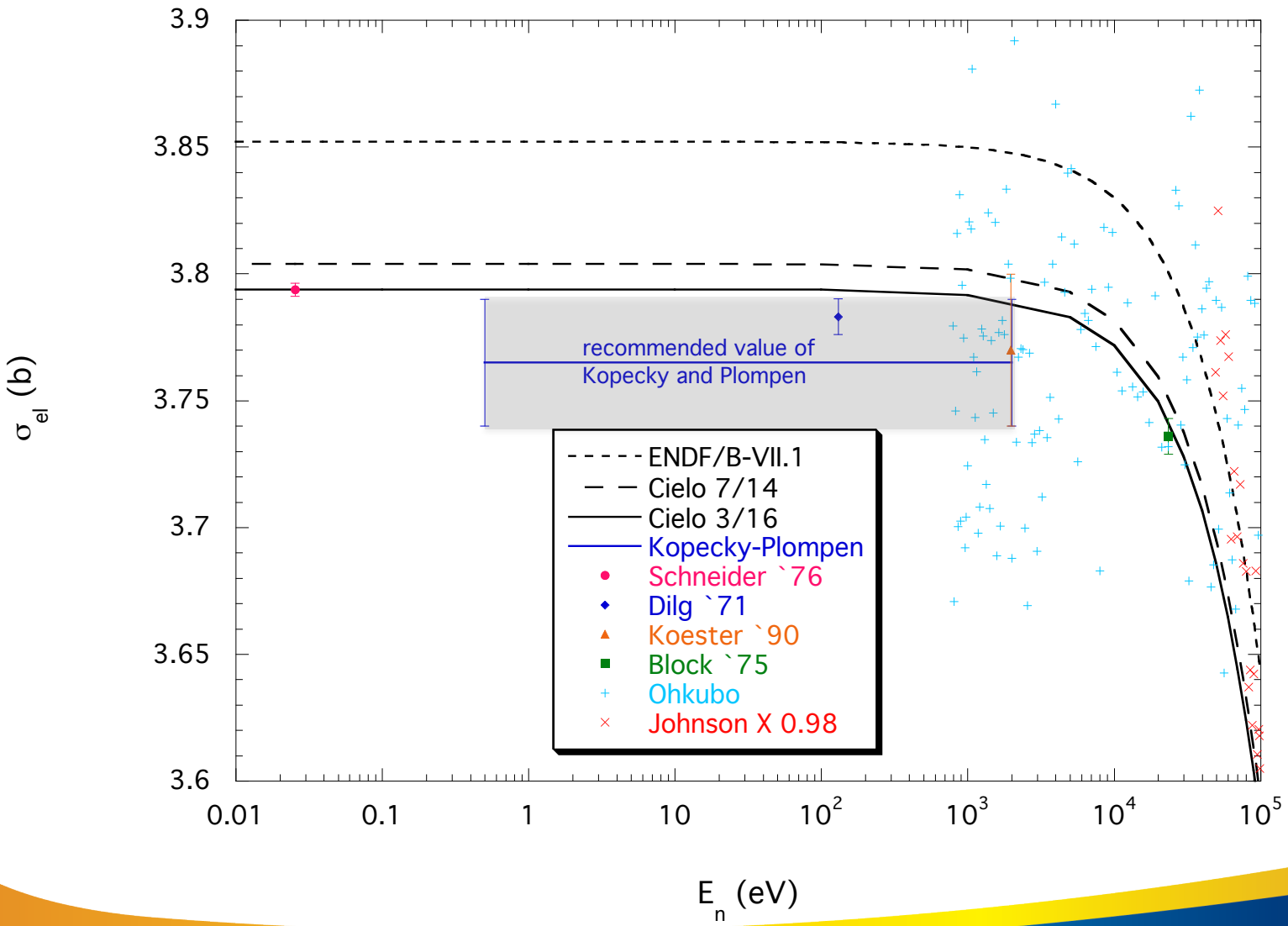
# Integrated (total) Cross Sections



# n+$^{16}$O Total Cross Section



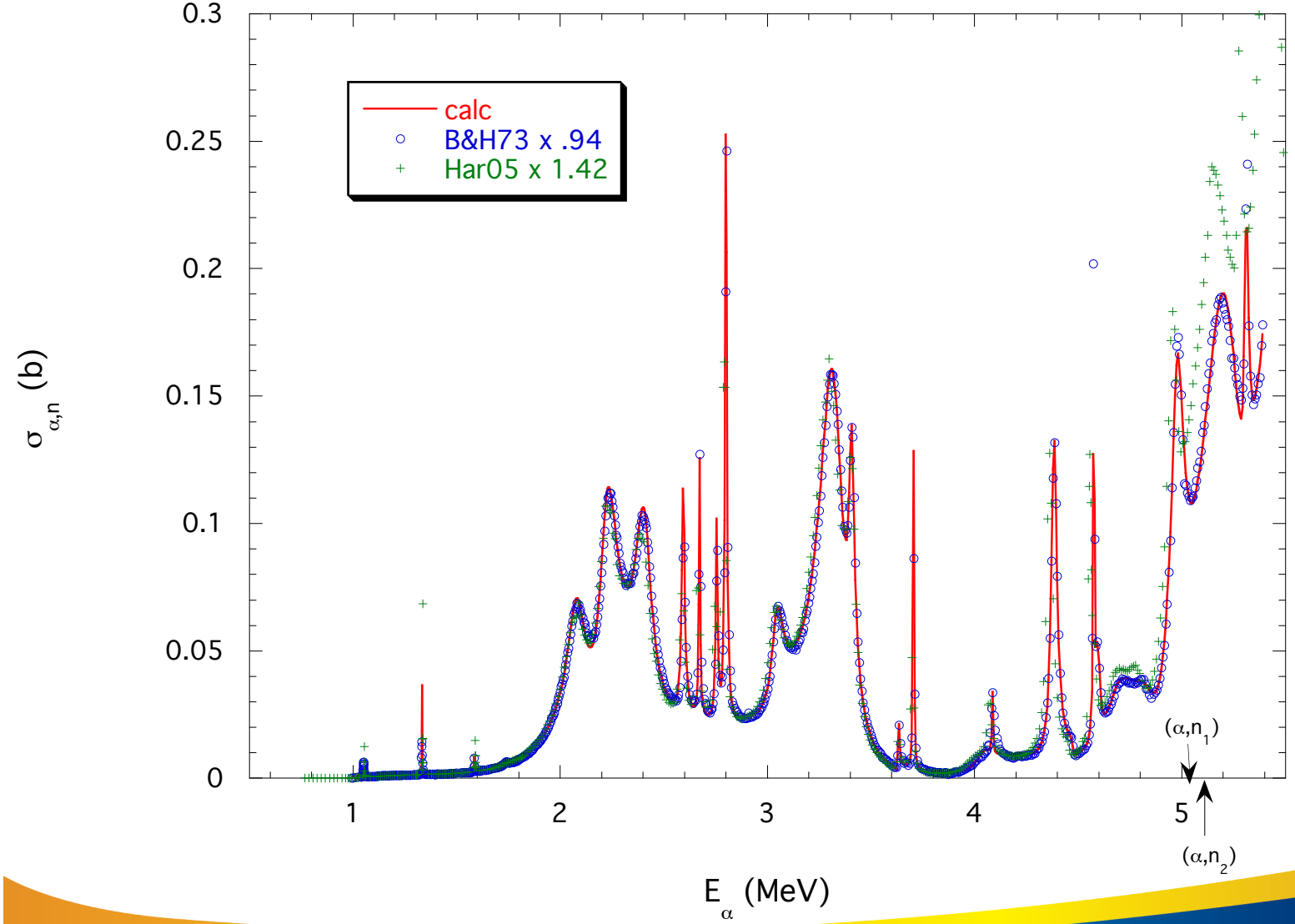
# n+$^{16}$O Elastic Scattering Cross Section



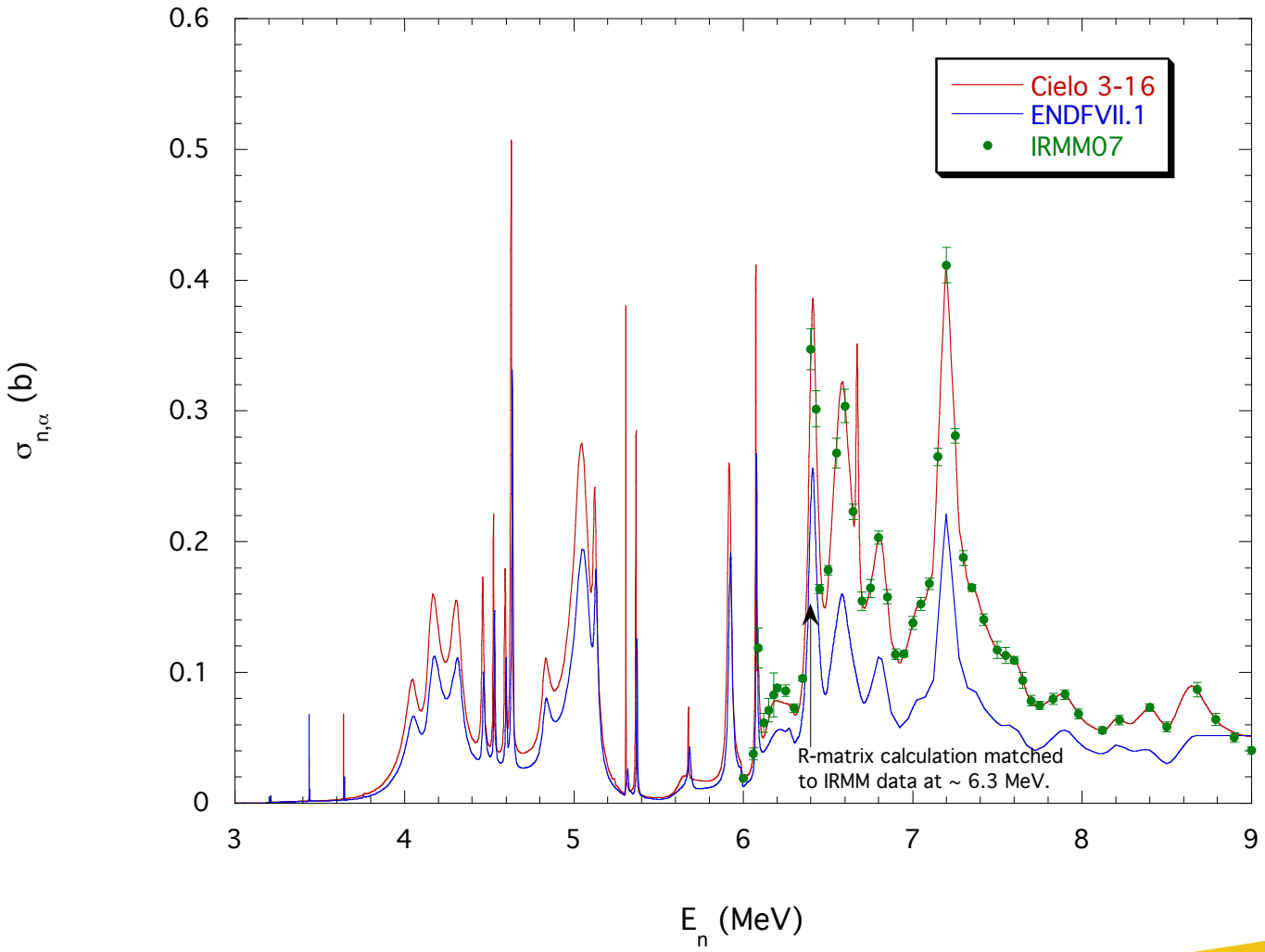
# Giorginis' Analysis of ($\alpha$,n) Measurements

- Considered two measurements, Bair and Haas (B&H73) and Harissopulos *et al*. (Har05).
- Determined a preliminary cross-section scale for B&H73 based on the integral of the thick-target yield over the narrow resonance at 1.056 MeV that agrees with the published scale of Har05.
- Then applied a correction common to both data sets related to characterization of the $^{13}C$ target that gives the cross-section scales 0.95×B&H73 and ~1.42×Har05.
- Considers the relative shape of the B&H73 measurement to be the most accurate since it had the thinnest target.

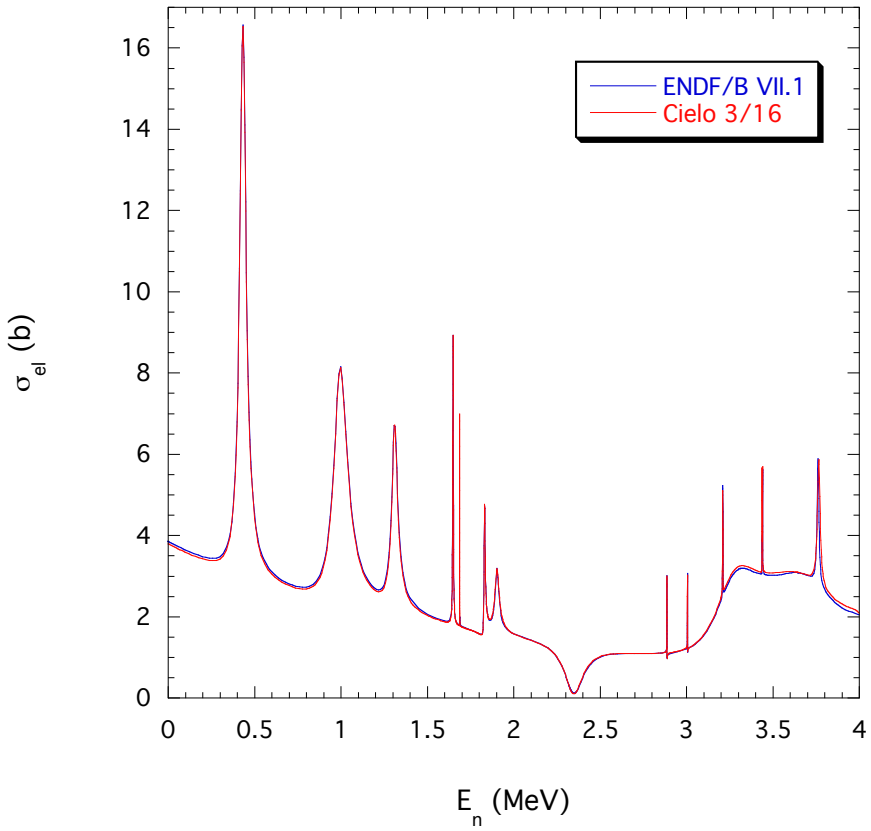
# $^{13}C(\alpha,n)^{16}O$ Cross Section

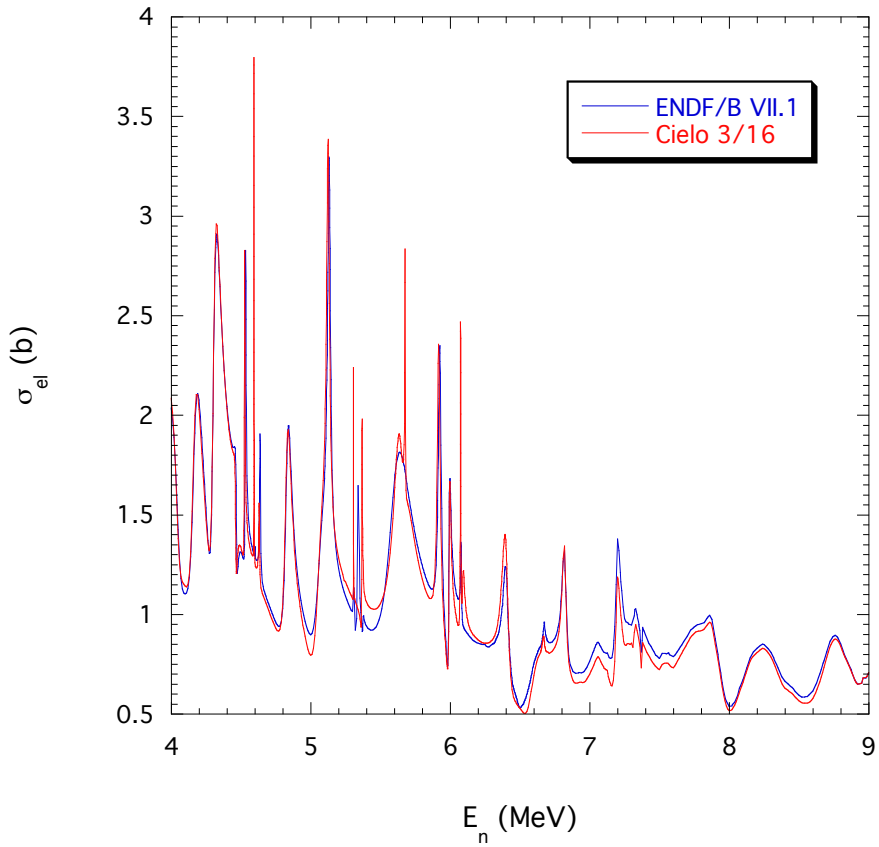


# $^{16}O(n,\alpha_0)^{13}C$ Cross Section

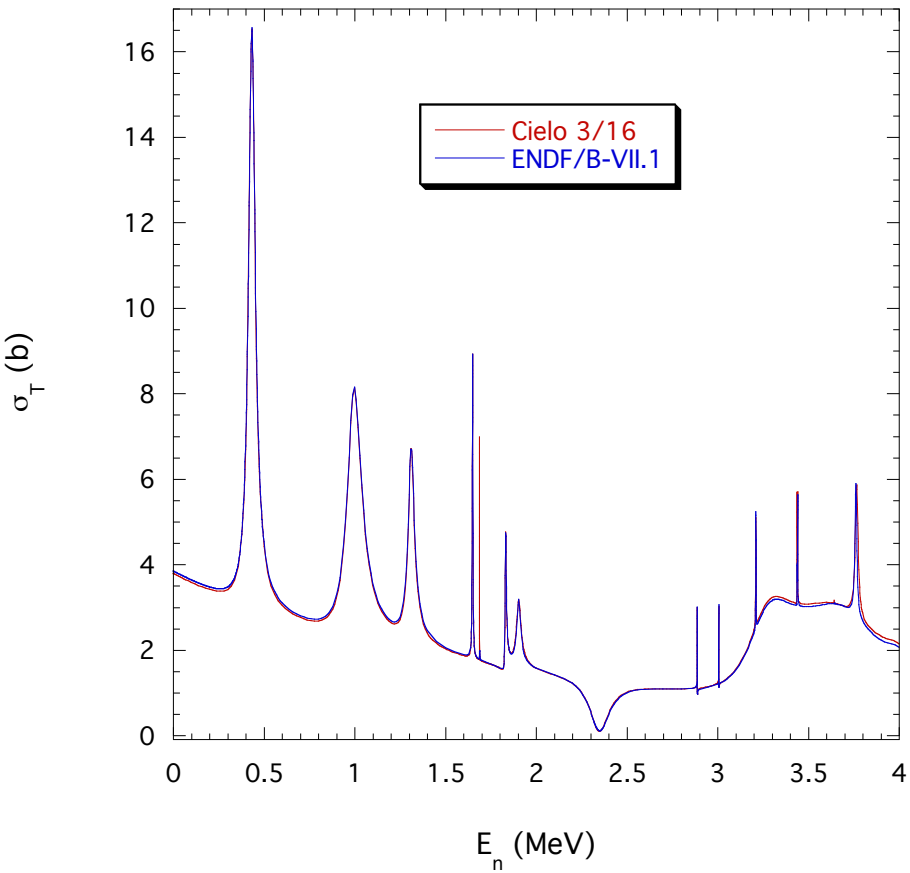


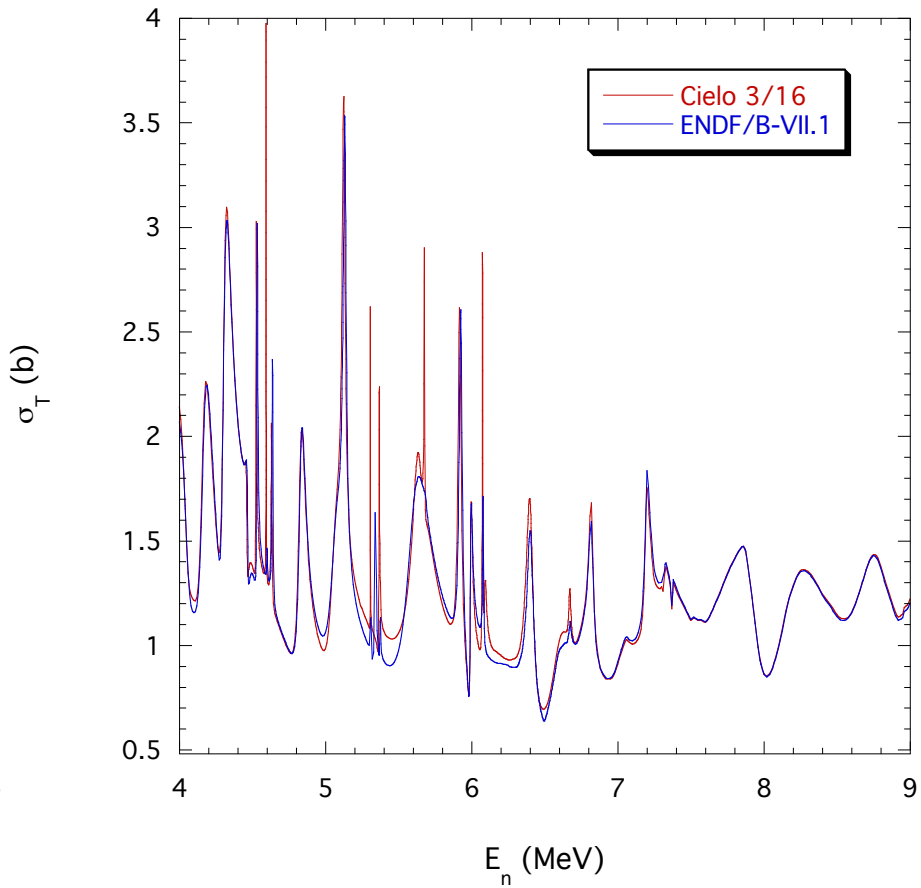
# n+$^{16}$O Elastic Cross Section



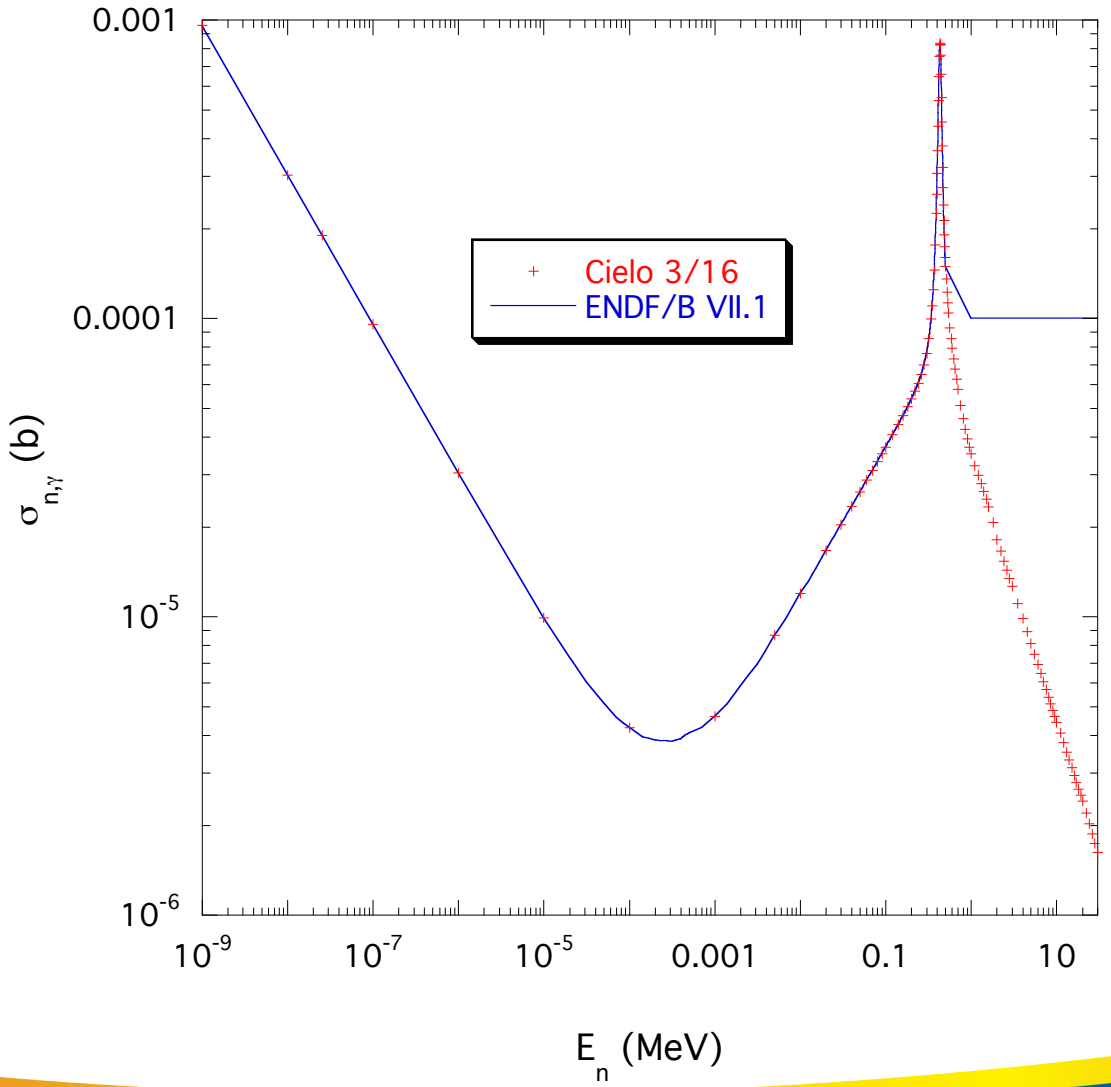



# n+$^{16}$O Total Cross Section



# Capture Cross Section



# Summary and Conclusions

- R-matrix descriptions are constrained by fundamental properties (unitarity, causality, TRI) of nuclear reaction theory.
- EDA analysis of the $^{17}O$ system includes data from all possible reactions, giving results that are highly constrained by the properties above (especially unitarity).
- The low-energy n+$^{16}O$ scattering cross sections are now in better agreement with high-precision measurements, and the (n,$\alpha_0$) cross section agrees with the data of B&H73, IRMM07 (Giorginis).
- The evaluated $^{16}O$ file Cielo 3/16 extends to 150 MeV, and is the same as ENDF/B VII.1 above 9 MeV (except for capture).