Nuclear Cross Sections Analysis and R-matrix Tools - Minischool
Surrey Ion Beam Centre and Department of Physics
University of Surrey, Thursday May 9th – Friday May 10th 2013

Leverhulme Lecture III

Similarities between Nuclear Data for IBA and Astrophysics

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Goals of Nuclear Astrophysics

- To understand what is the energy source of the stars at all stages of their evolution
- To explain the observed relative abundances of the elements through the nuclear transmutations in different stellar conditions

Aims of IBA

- To determine composition and structure of thin films or surface layers of samples through the spectroscopy of the products of the interaction of accelerated charged particles with nuclei contained in the sample.

Similarities

- Low energy charged particle cross-sections play a key role.
- Calculated (evaluated) cross-sections rather than measured ones are commonly used.
- The same physical models are employed in the calculations.

Distinctions

Nuclear Astrophysics	IBA
Cross-sections are needed for a vast variety of stable and unstable nuclei	Cross-sections for a limited number of mainly light and medium weight nuclei are of interest
Cross-sections are needed for separate isotopes	Cross-sections are needed mostly averaged over isotopes
Total cross-sections are needed	Differential cross-sections are needed
Moderate requirements for the precision	The required precision is ~1%.
The problem is explored by nuclear physicists	The problem is being solved by IBA (material science) community
Basic (fundamental) science	Applied (technological) science

Alpha-process in stars

A so called alpha-process is responsible for the synthesis of alpha cluster nuclei in the chain:

$^{24}Mg \Rightarrow {}^{28}Si \Rightarrow {}^{32}S \Rightarrow {}^{36}Ar \Rightarrow {}^{40}Ca$

It takes place in stars during carbon and oxygen burning at temperature in the interval of $(0.5–3.0) \times 10^9$ K (43–260 keV).

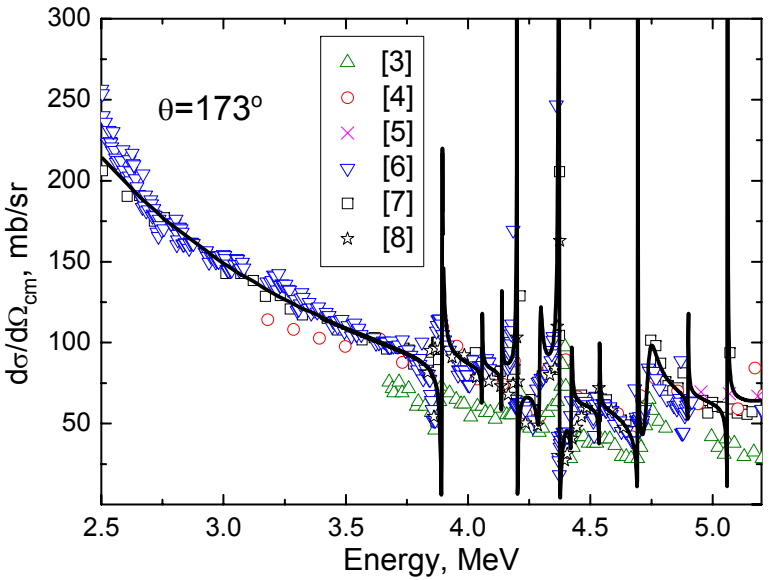
Alpha elastic scattering in IBA

There are a number of benefits in use of elastic backscattering (EBS) technique at energies for which the cross-section is non-Rutherford.

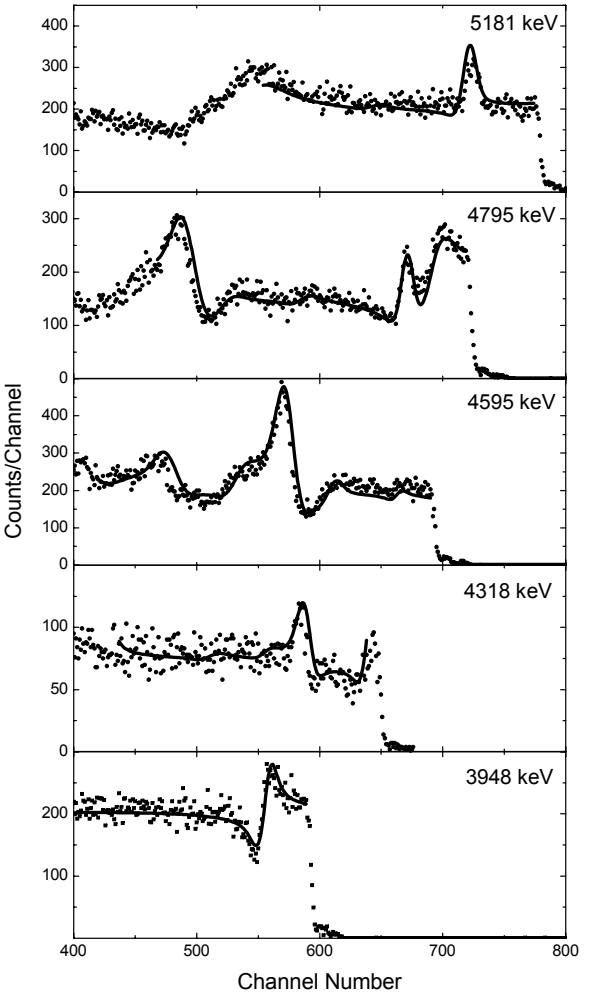
First of all at higher energies light ion elastic scattering cross section for light elements rapidly increases whereas it still follows close to $1/E^2$ energy dependence for heavy nuclei. Thus high sensitivity for determination of light contaminants in heavy matrix is achieved. Besides, a depth of sample examination is enhanced.

Alpha elastic scattering in IBA

Evaluated $^{28}Si(\alpha,\alpha)^{28}Si$ cross-section



Spectra of alphas backscattered from a thick silicon sample



Cross-section calculations for alpha-process

The cross section for this process is usually calculated by means of the *statistical model*. The *transmission coefficients* which are central quantities in such calculations are determined in frameworks of the *optical model*. It is usual in nuclear astrophysics to consider processes that incorporate a wide variety of nuclei both stable and unstable and so the main efforts so far were concentrated on the development of a global optical potential using microscopic approach.

Microscopic global optical potential

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Nuclear Physics A 707 (2002) 253–276

NUCLEAR PHYSICS A

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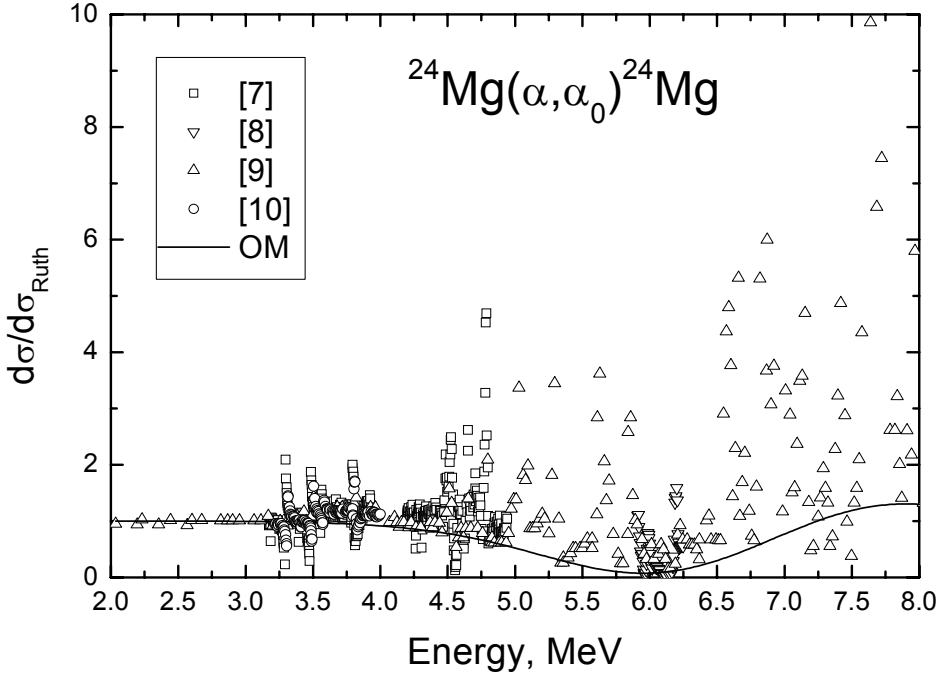
Improved global α-optical model potentials at low energies

P. Demetriou [a,*], C. Grama [b], S. Goriely [c]

The nuclei under consideration are stable and a lot of experimental information is available in the literature for the interaction of alphas with these nuclei. Consequently a phenomenological optical potential can be obtained in this case.

Alpha optical potential for ^{24}Mg

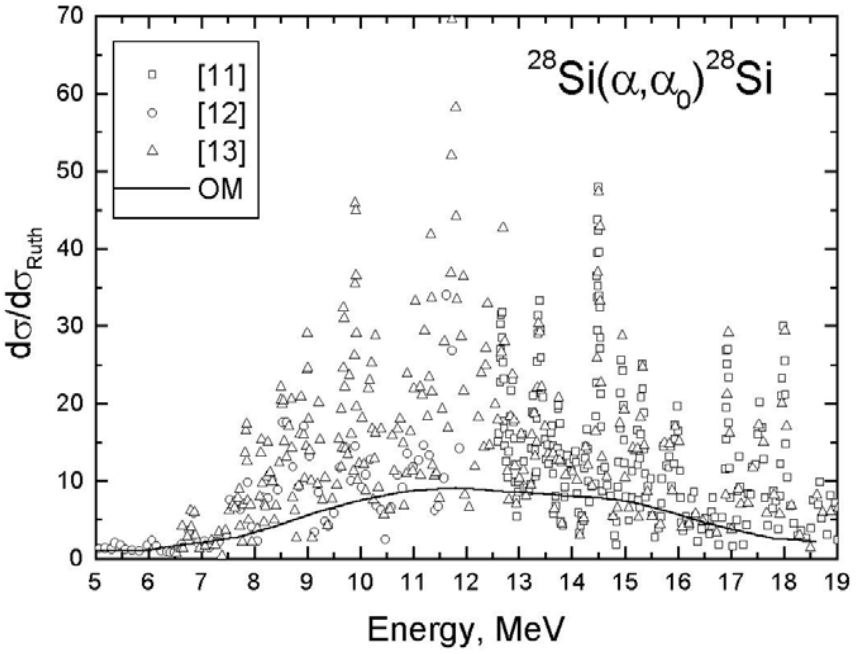


Available experimental data and results of the optical model calculations for ^{24}Mg(α,α$_0$)^{24}Mg at the scattering angle close to 165°.

The optimal potential parameters obtained for ^{24}Mg(α,α$_0$) ^{24}Mg scattering at the energy below 8.0 MeV

$V_{l=0}$ MeV	$V_{l=1}$ MeV	$V_{l=2}$ MeV	$V_{l=3}$ MeV	$V_{l=4}$ MeV	$V_{l\geq5}$ MeV	W_D MeV	r fm	a fm	r_C fm
225	235	215	215	215	225	9.0	1.40	0.52	1.40

Alpha optical potential for ^{28}Si

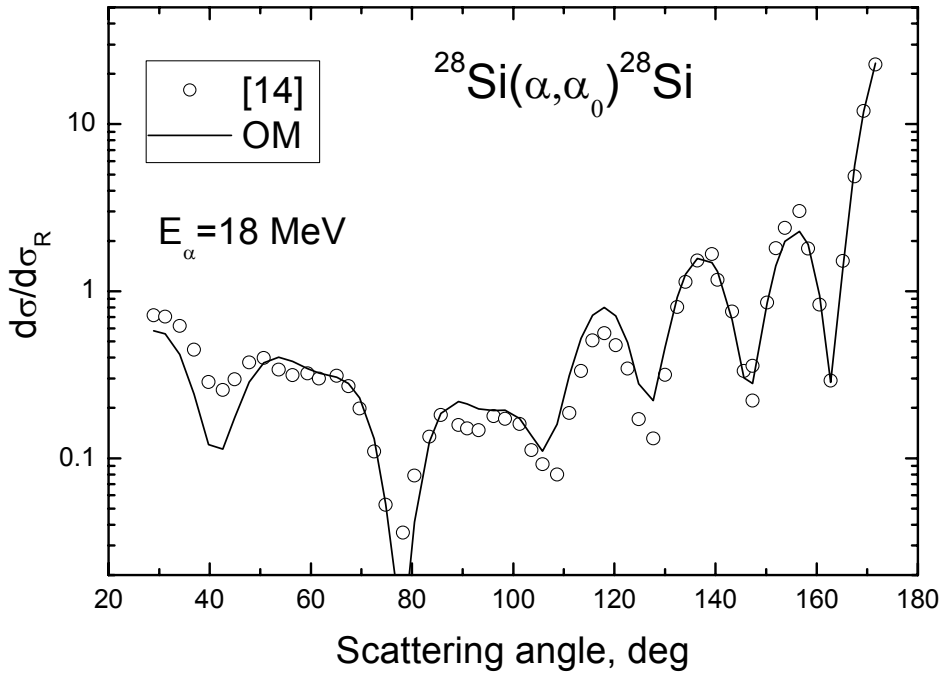


Available experimental data and results of the optical model calculations for ^{28}Si(α,α$_0$)^{28}Si excitation function at the scattering angle close to 170°.

The optimal potential parameters obtained for ^{28}Si(α,α$_0$) ^{28}Si scattering at low energy

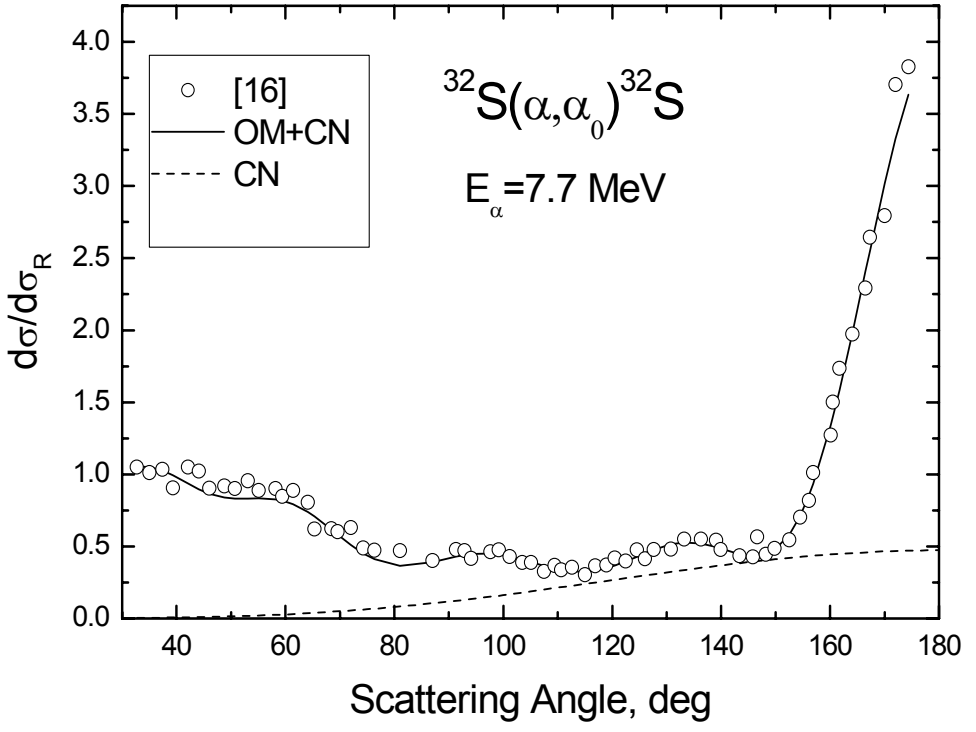
$V_{l=0}$ MeV	$V_{l=1}$ MeV	$V_{l=2}$ MeV	$V_{l=3}$ MeV	$V_{l=4}$ MeV	$V_{l\geq5}$ MeV	W_D MeV	r_R fm	a_R fm	r_D fm	a_D fm	r_C fm
155.7	159.0	157.9	156.5	155.1	156.8	1.79+0.57E	1.40	0.914	1.40	0.62	1.40

Alpha optical potential for ^{28}Si



The best fit to the angular distribution for ^{28}Si(α,α_0)^{28}Si at 18 MeV.

Alpha optical potential for ^{32}S

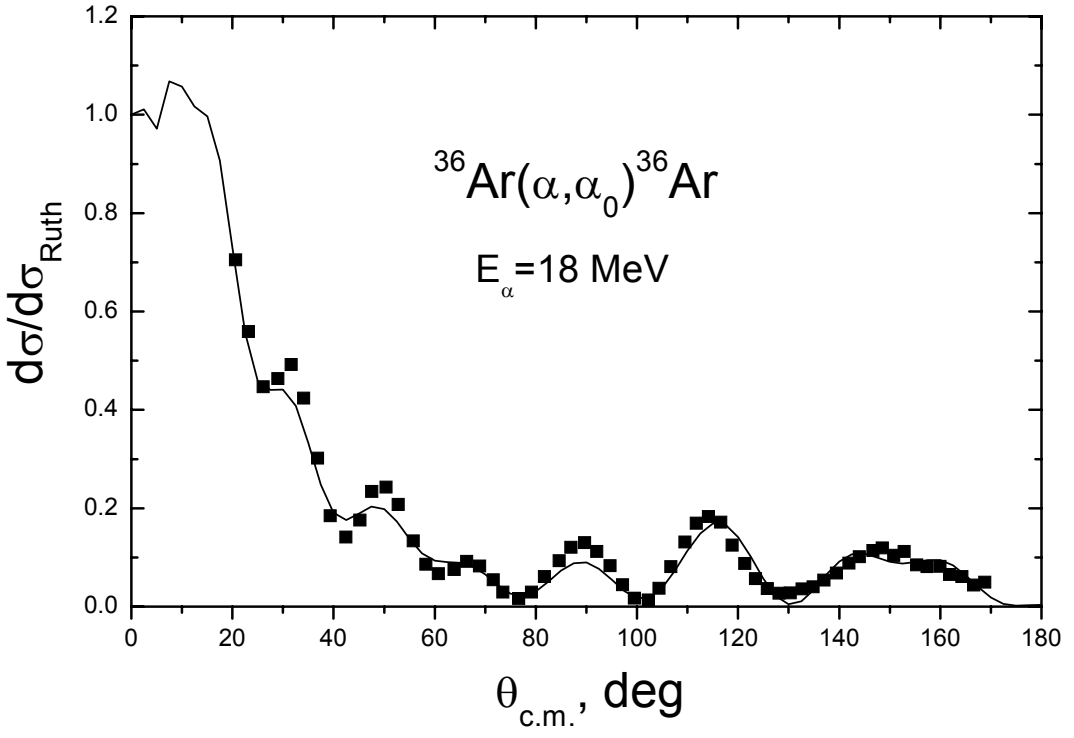


The best fit to the angular distribution for $^{32}S(\alpha,\alpha_0)^{32}S$ at 7.7 MeV.

The optimal potential parameters obtained for $^{32}S(\alpha,\alpha_0)\,^{32}S$ scattering at the energy of 7.7 MeV

$V_{l=0}$ MeV	$V_{l=1}$ MeV	$V_{l=2}$ MeV	$V_{l=3}$ MeV	$V_{l=4}$ MeV	$V_{l\geq5}$ MeV	W_D^* MeV	r_R^* fm	a_R fm	r_D fm	a_D^* fm	r_C^* fm
125.9	139.9	148.6	136.1	132.3	133.5	7.0	1.4	0.77	1.4	0.485	1.40

Alpha optical potential for ^{36}Ar

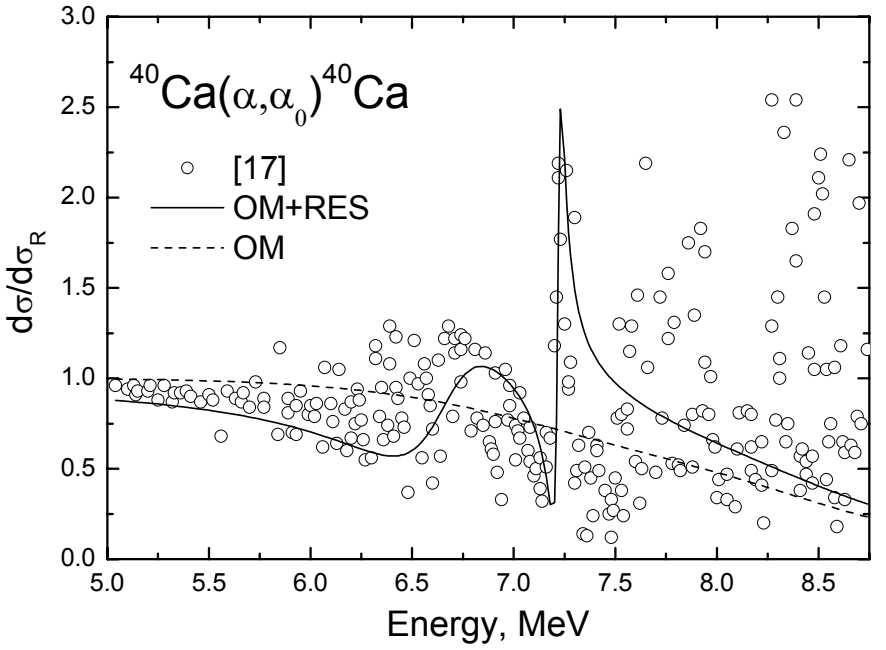


The best fit to the angular distribution for ^{36}Ar(α,α$_0$)^{36}Ar at 18 MeV.

The optimal potential parameters obtained for ^{36}Ar(α,α$_0$) ^{36}Ar scattering at the energy of 18 MeV

$V_{l=0}$ MeV	$V_{l=1}$ MeV	$V_{l=2}$ MeV	$V_{l=3}$ MeV	$V_{l=4}$ MeV	$V_{l\geq5}$ MeV	W_D^* MeV	r_R^* fm	a_R fm	r_D fm	a_D^* fm	r_C^* fm
135.6	125.4	131.0	141.9	145.5	143.7	14.0	1.281	0.749	1.625	0.485	1.30

Alpha optical potential for ^{40}Ar



The effect of quasimolecular resonances on the excitation function for ^{40}Ca(α,α$_0$)^{40}Ca at the scattering angle of 167°.

$$S_l = \exp(2i\lambda_l)\left[\exp(-2\mu_l) + \exp(2i\phi)\frac{i\Gamma_\alpha}{E_0 - E - \frac{1}{2}i\Gamma}\right]$$

Statistical model

The statistical model predicts reaction cross sections averaged over many resonances in the intermediate nuclei. The mean angle-integrated cross section for formation of the final state (E', I', P') by means of the (a,a') reaction is given as

$$\sigma_{a,a'}(\varepsilon,I,P;\ E',I',P') = \sum_{J,\pi} \sigma_a(\varepsilon,I,P;\ U,J,\pi)\ \frac{\Gamma_{a'}(U,J,\pi;\ E',I',P')}{\Gamma(U,J,\pi)} \quad , \qquad (2)$$

where (U,J,π) are the quantum numbers of the compound states through which the reactions proceed; $\sigma_a(\varepsilon,I,P;\ U,J,\pi)$ is the reaction cross section for formation of the compound nucleus with quantum numbers (U,J,π); and $\Gamma_{a'}(U,J,\pi;\ E',I',P')$ is the decay width of the compound nucleus into the state (E',I',P') of the residual nucleus by emission of the particle a'. The quantity $\Gamma(U,J,\pi)$ is the total decay width of the compound nucleus state (U,J,π) and is the sum of all possible decay widths,

$$\Gamma(U,J,\pi) = \sum_{a''} \sum_{E'',I'',P''} \Gamma_{a''}(U,J,\pi;\ E'',I'',P'') \quad , \qquad (3)$$

Transmission coefficients

The reaction cross section for formation of the compound nucleus can be expressed in terms of optical model transmission coefficients, $T_\ell^a(\varepsilon)$, as follows:

$$\sigma_a(\varepsilon,I,P;\ U,J,\pi) = \frac{\pi}{k^2}\ \frac{(2J+1)}{(2I+1)(2i+1)} \sum_{S=|I-i|}^{I+i} \sum_{\ell=|J-S|}^{J+S} f_\ell(\ell,\pi)\ T_\ell^a(\varepsilon)\ , \qquad (4)$$

where k is the wave number of relative motion, S indicates channel spin, and the function $f(\ell,\pi)$ is unity if parity is conserved and zero otherwise, as provided by Eq. (1). Through use of the reciprocity theorem (detailed balance) of nuclear reactions, the decay widths can be related to the transmission coefficients:

$$\Gamma_{a'}(U,J,\pi;E',I',P') = \frac{1}{2\pi\rho(U,J,\pi)} \sum_{S=|i'-I'|}^{i'+I'} \sum_{\ell=|J-S|}^{J+S} f(\ell,\pi)\ T_\ell^{a'}(U-E'-B_{a'}) \qquad (5)$$

where $\rho(U,J,\pi)$ is the nuclear level density of the intermediate nucleus having the quantum numbers (U,J,π). To obtain Eq. (5), the assumption is made that the optical model transmission coefficients, determined from analysis of experimental data on the ground states of nuclei, also describe the inverse reactions on excited states of the residual nuclei.

Statistical model calculations with global potential

Atomic Data and Nuclear Data Tables **75**, 1–351 (2000)
doi:10.1006/adnd.2000.0834, available online at http://www.idealibrary.com on IDEAL®

ASTROPHYSICAL REACTION RATES FROM STATISTICAL MODEL CALCULATIONS

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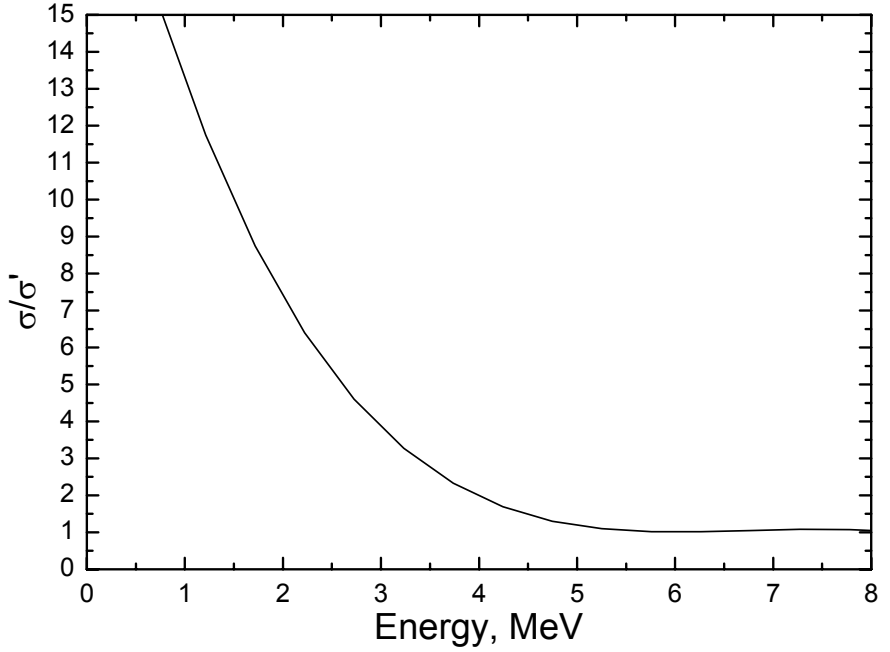
CH-4056 Basel, Switzerland

Comparison of statistical calculations with transmission coefficients obtained using different optical potentials



The ratio of the cross sections for the $^{28}Si(\alpha,\gamma)^{32}S$ reaction calculated with transmission coefficients obtained with the optical potential of the present work and with the global potential.

Elastic scattering of alphas from carbon

IBA

The fact that the $^{12}C(\alpha,\alpha)^{12}C$ cross-section is up to 100 times larger than Rutherford above 2 MeV is used for analytical purposes. The intense resonance at 4.26 MeV is used as a powerful tool for carbon profiling in various substrates.

Nuclear Astrophysics

An improvement in the elastic scattering data helps to determine the contribution of the subthreshold states, $6.92(2^+)$ and $7.12(1^-)$ MeV and restricts resonance parameters above the threshold.

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Nuclear Instruments and Methods in Physics Research B 222 (2004) 538–546
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Carbon analysis using energetic ion beams

W. Jiang *, V. Shutthanandan, S. Thevuthasan, D.E. McCready, W.J. Weber

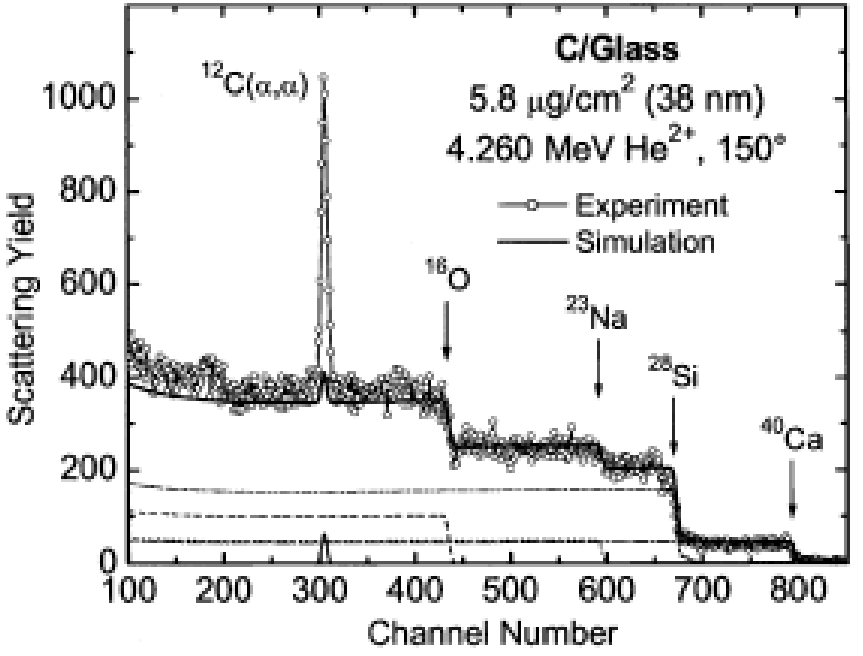
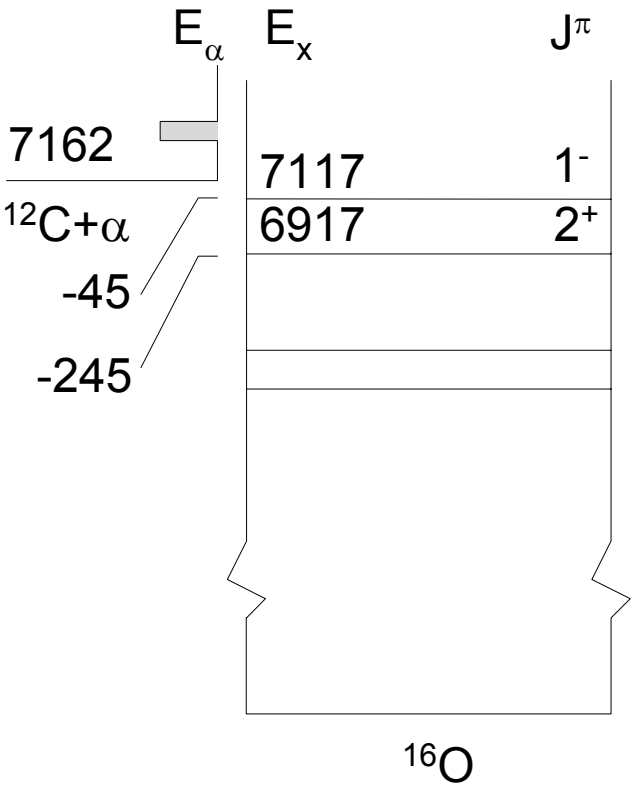


Fig. 2. Energy spectrum of 4.260 MeV He^{2+} backscattering from a thin carbon film (5.8 μg/cm²) on a silicate glass substrate at an angle of 150°. Also included are the elemental and entire spectra from SIMNRA simulations.

The problem of $^{12}C/^{16}O$ ratio in nucleosynthesis



The ratio depends on the rate of the $3\alpha \rightarrow {}^{12}C$ and $^{12}C(\alpha,\gamma)^{16}O$ reactions.

The cross-section for $3\alpha \rightarrow {}^{12}C$ is known with accuracy ~15%

For the $^{12}C(\alpha,\gamma)^{16}O$ reaction extrapolation is made from ~1.4 MeV (the lowest energy at which the measurements were performed) to ~0.3 MeV, the cross-section decreasing from $\sim 10^{-10}$ to 10^{-17} barn.

The main contribution to the cross-section at astrophysical energies comes from E1 and E2 amplitudes produced by subthreshold levels.

Measurement of elastic $^{12}C + \alpha$ scattering: Details of the experiment, analysis, and discussion of phase shifts

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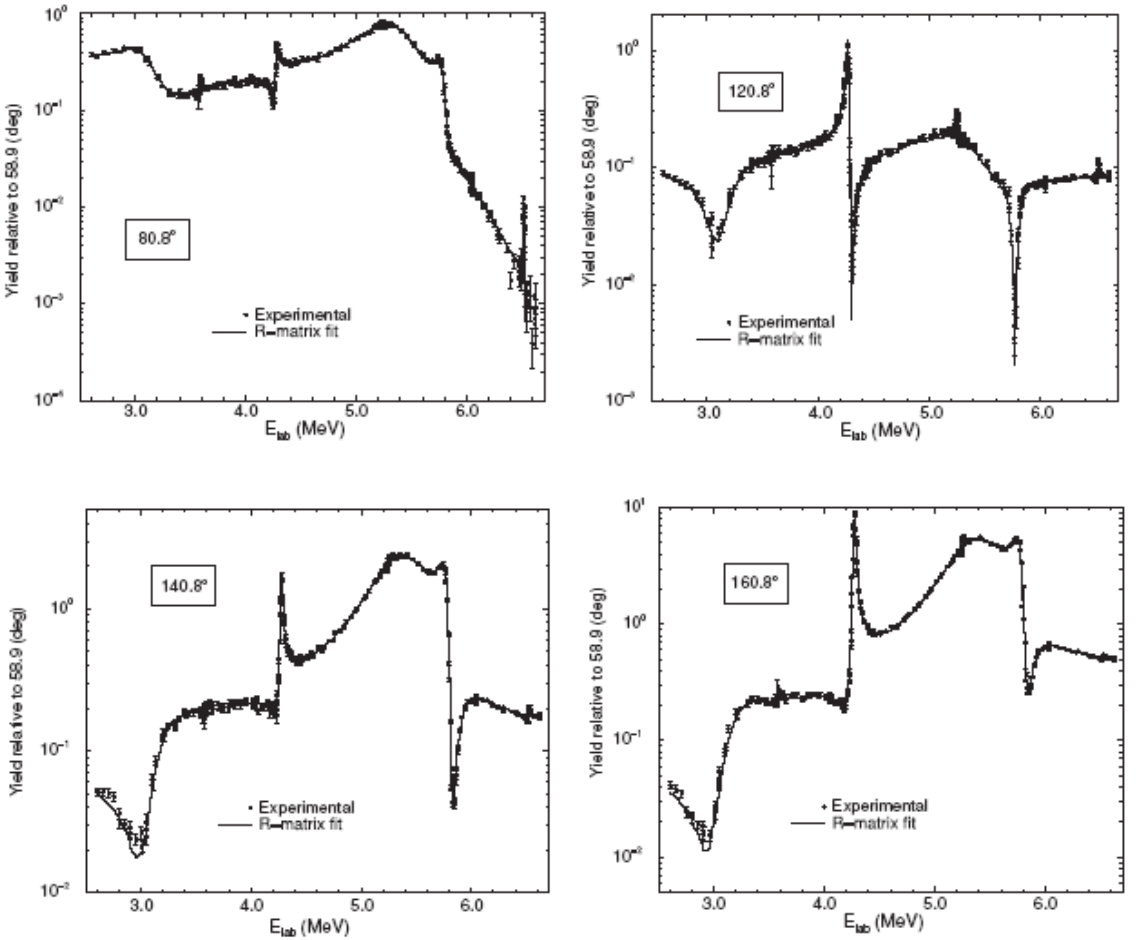

FIG. 6. Relative differential cross-section excitation curves for $^{12}C(\alpha, \alpha)^{12}C$ for eight selected detector angles $\theta = 24°$, 38°, 54°, 79°, 100°, 120°, 140°, and 160°.

Measurement of elastic $^{12}C + \alpha$ scattering: Above the proton separation energy

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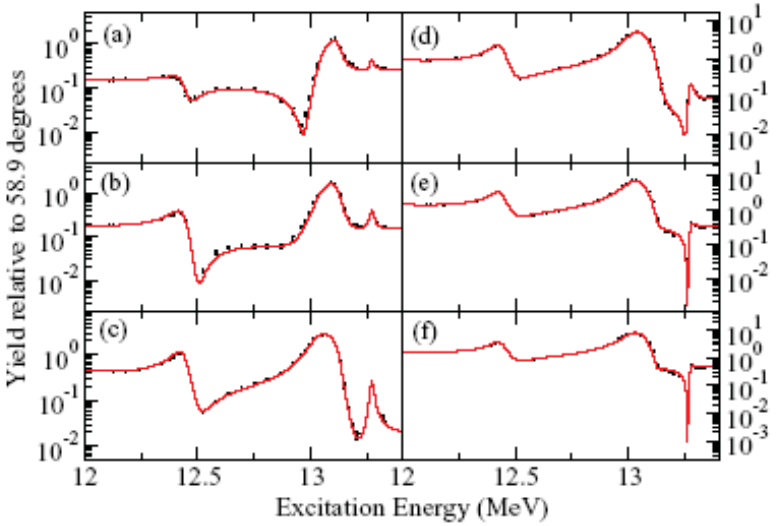

FIG. 6. (Color online) Fits to the $^{12}C(\alpha, \alpha_0)^{12}C$ yield data of this work at $\theta_{lab} = 125.8°$ (a), 130.8° (b), 140.8° (c), 150.8° (d), 160.8° (e), and 165.9° (f). The *R*-matrix fit was performed simultaneously with previous data from the literature.

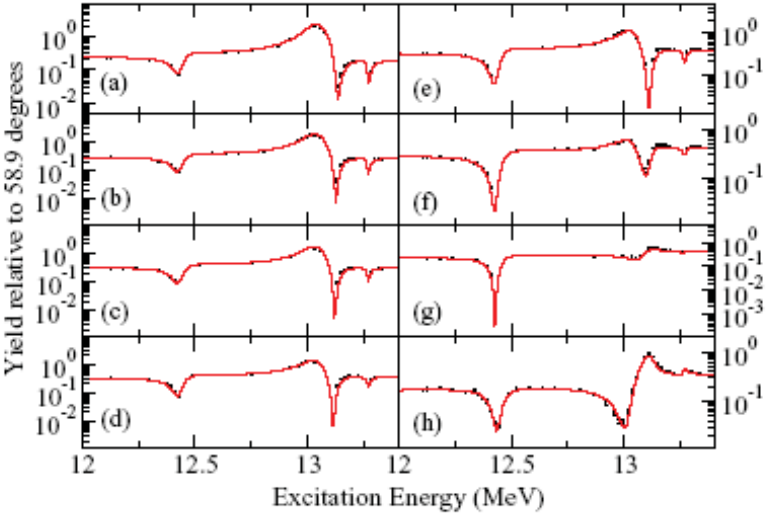

FIG. 5. (Color online) Fits to the $^{12}C(\alpha, \alpha_0)^{12}C$ yield data of this work at $\theta_{lab} = 95.8°$ (a), 99.0° (b), 100.8° (c), 103.9° (d), 105.8° (e), 110.8° (f), 115.8° (g), and 120.8° (h). The *R*-matrix fit was performed simultaneously with previous data from the literature.

ELSEVIER Nuclear Instruments and Methods in Physics Research B 161–163 (2000) 125–129

NIM B
Beam Interactions with Materials & Atoms

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Evaluation of the cross-section for elastic scattering of ^{4}He from carbon

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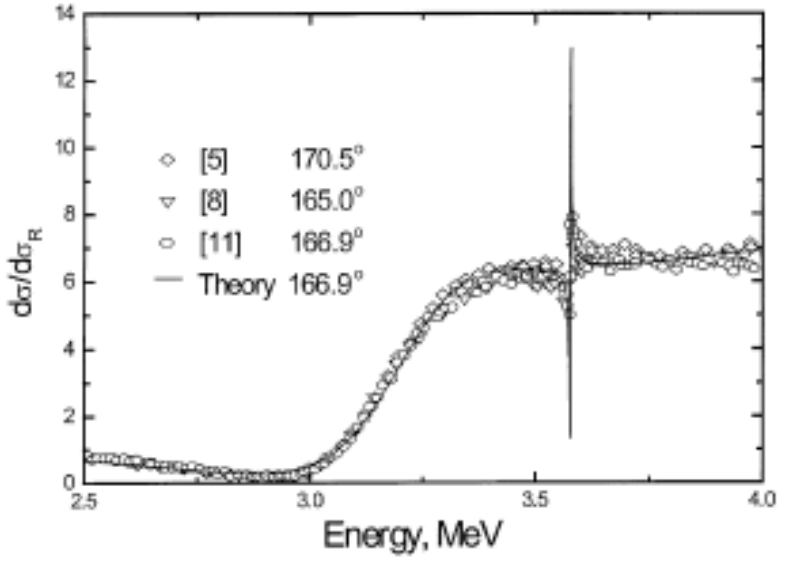

Fig. 1. The available experimental data and the evaluated excitation function for ^{4}He elastic scattering from carbon in the energy range from 2.5 to 4.0 MeV.

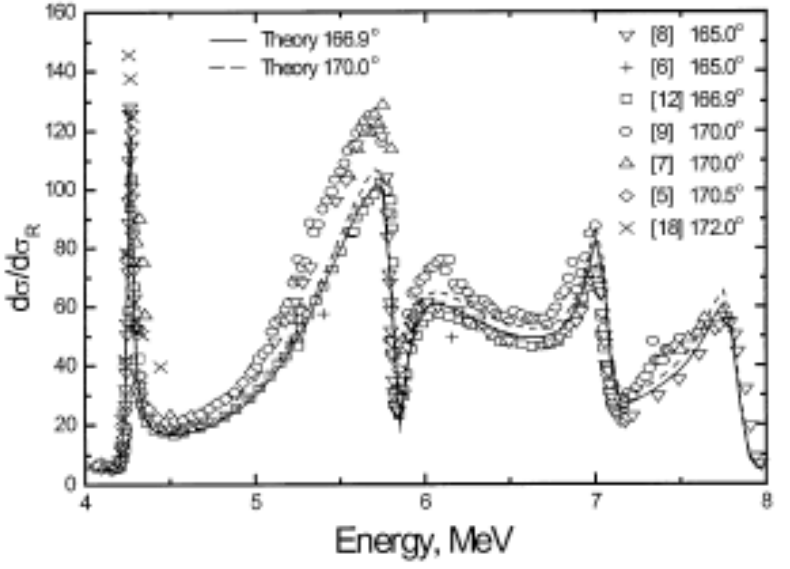

Fig. 2. The same as in Fig. 1. in the energy range from 4.0 to 8.0 MeV.

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Nuclear Instruments and Methods in Physics Research B 190 (2002) 100–106

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Helium elastic scattering from carbon for 30° to 150° in the energy region from 2 to 4.8 MeV

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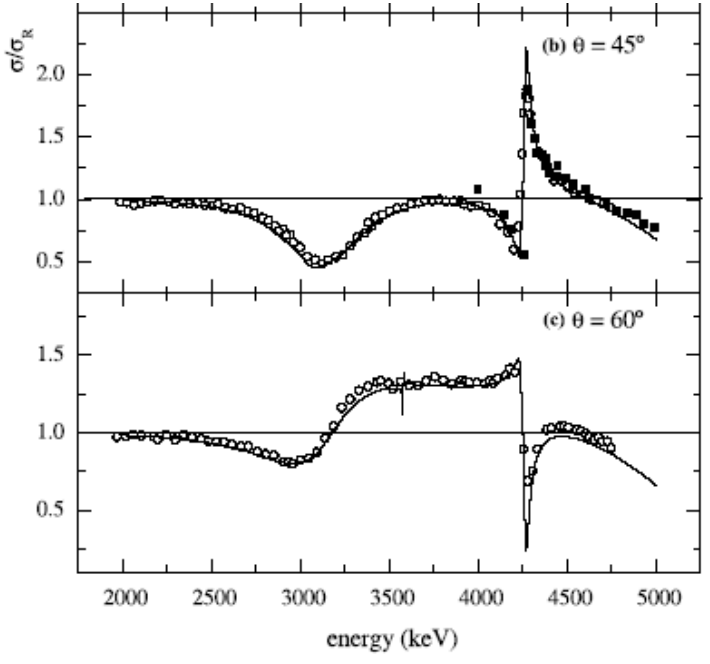

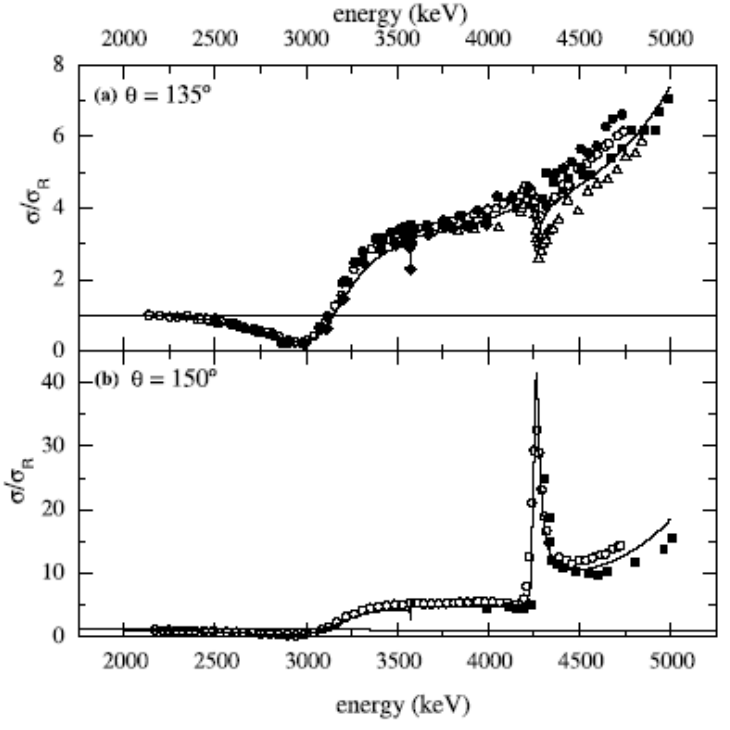

Nuclear Instruments and Methods in Physics Research B 296 (2013) 87–91

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research B

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Evaluated $^{12}C(^4He,^4He)^{12}C$ cross-section and its uncertainty

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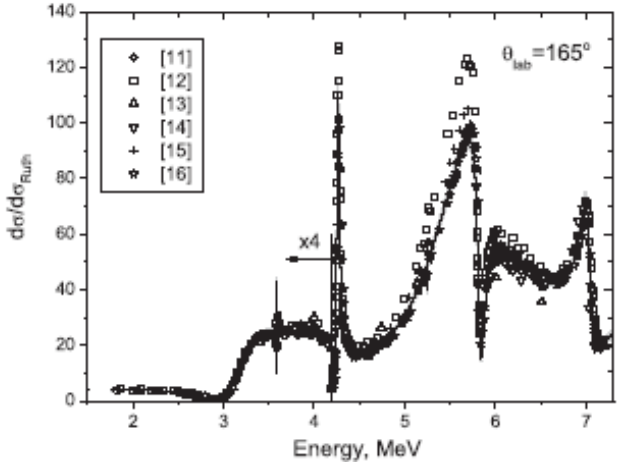

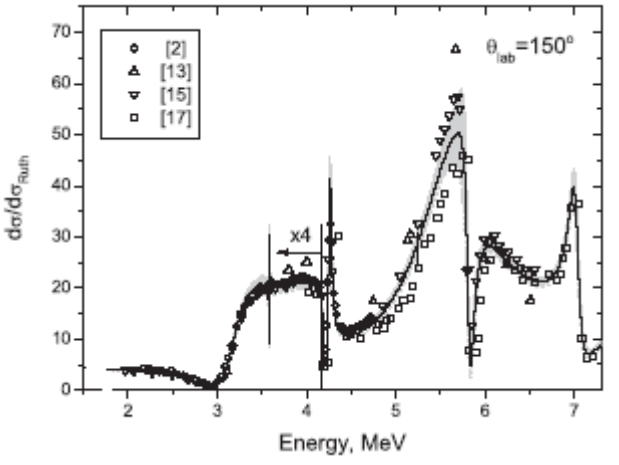

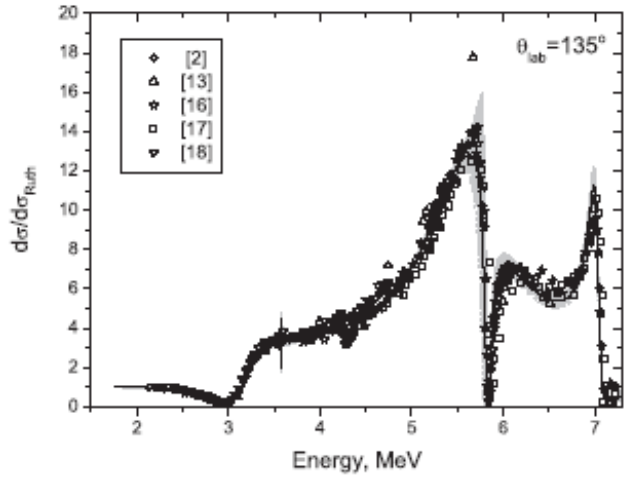

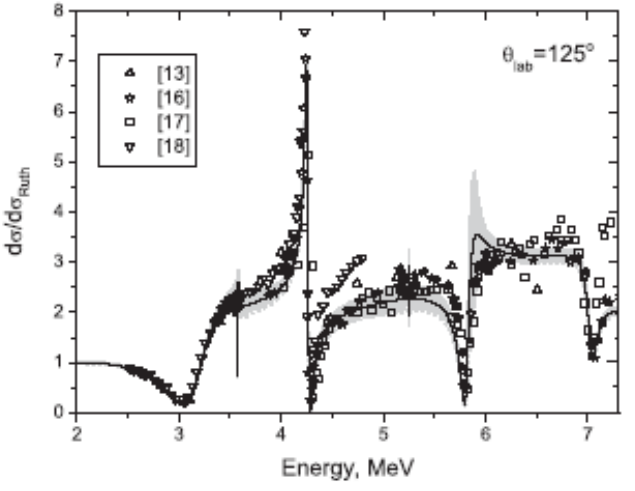

CRP on PIGE

IAEA
International Atomic Energy Agency

INDC(NDS)-0625
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INDC International Nuclear Data Committee

Summary Report

2nd Research Coordination Meeting

Development of a Reference Database for Particle-Induced Gamma ray Emission (PIGE) Spectroscopy

Cross-section measurements for PIGE

4. Action lists

Table 4.1. Completed Measurements

Isotope	Reaction	γ-ray [keV]	Energy range [MeV]	Angle [°]	Initial State, Jπ	Type of Data	Comments	Measured by:
^{7}Li	(p,p´γ)	478	2-4	130	1/2-	Differential+ Thick target	Detailed+sparse points	Pedro de Jesus
^{9}Be	(p,γ)	718	0.5-1.7	130	1+	Differential+ Thick target	Detailed	Pedro de Jesus
^{10}B	(p,α´γ)	429	2-4	130	1/2-	Thick target	Sparse points	Pedro de Jesus
^{12}C	(p,γ)		1.1-2.6	55 and 0		Differential	Detailed	Becker
^{14}N	(p,p´γ)	2313	4-7	55	0+	Differential	Detailed+sparse points	Raisanen
^{14}N	(d,p´γ)	1885	0.6-2	55	5/2+	Differential	Detailed+sparse points	Kiss
^{14}N	(d,p´γ)	2297	0.6-2	55	7/2+	Differential	Detailed+sparse points	Kiss
^{14}N	(d,p´γ)	8310	0.6-2	55	1/2+	Differential	Detailed+sparse points	Kiss
^{19}F	(p,p´γ)	110	2-4	130	1/2-	Differential+ Thick target	Detailed	Pedro de Jesus
^{19}F	(p,p´γ)	197	2-4	130	5/2+	Differential+ Thick target	Detailed	Pedro de Jesus
^{19}F	(p,α´γ)	6000-7000	0.8-4.0	130	3-	Differential+ Thick target	Detailed	Pedro de Jesus

$^{16}O(\alpha,\gamma)^{20}Ne$ *S* factor: Measurements and *R*-matrix analysis

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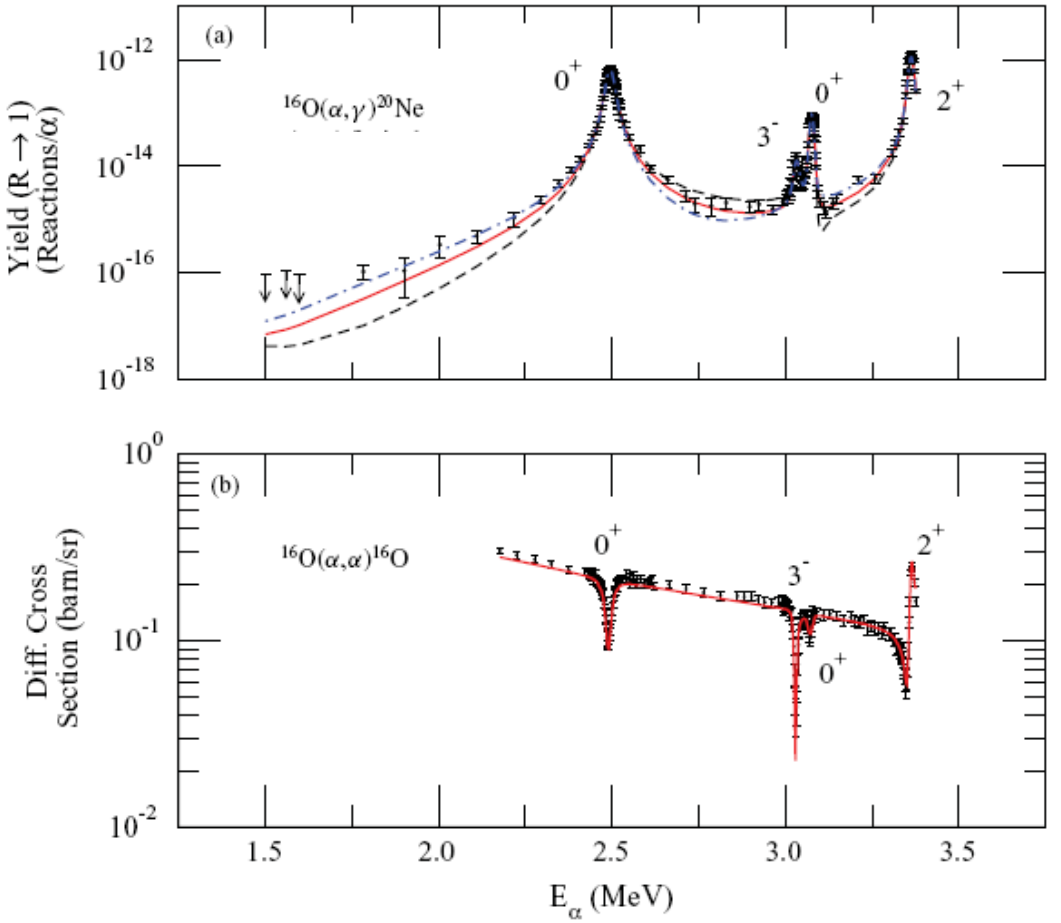
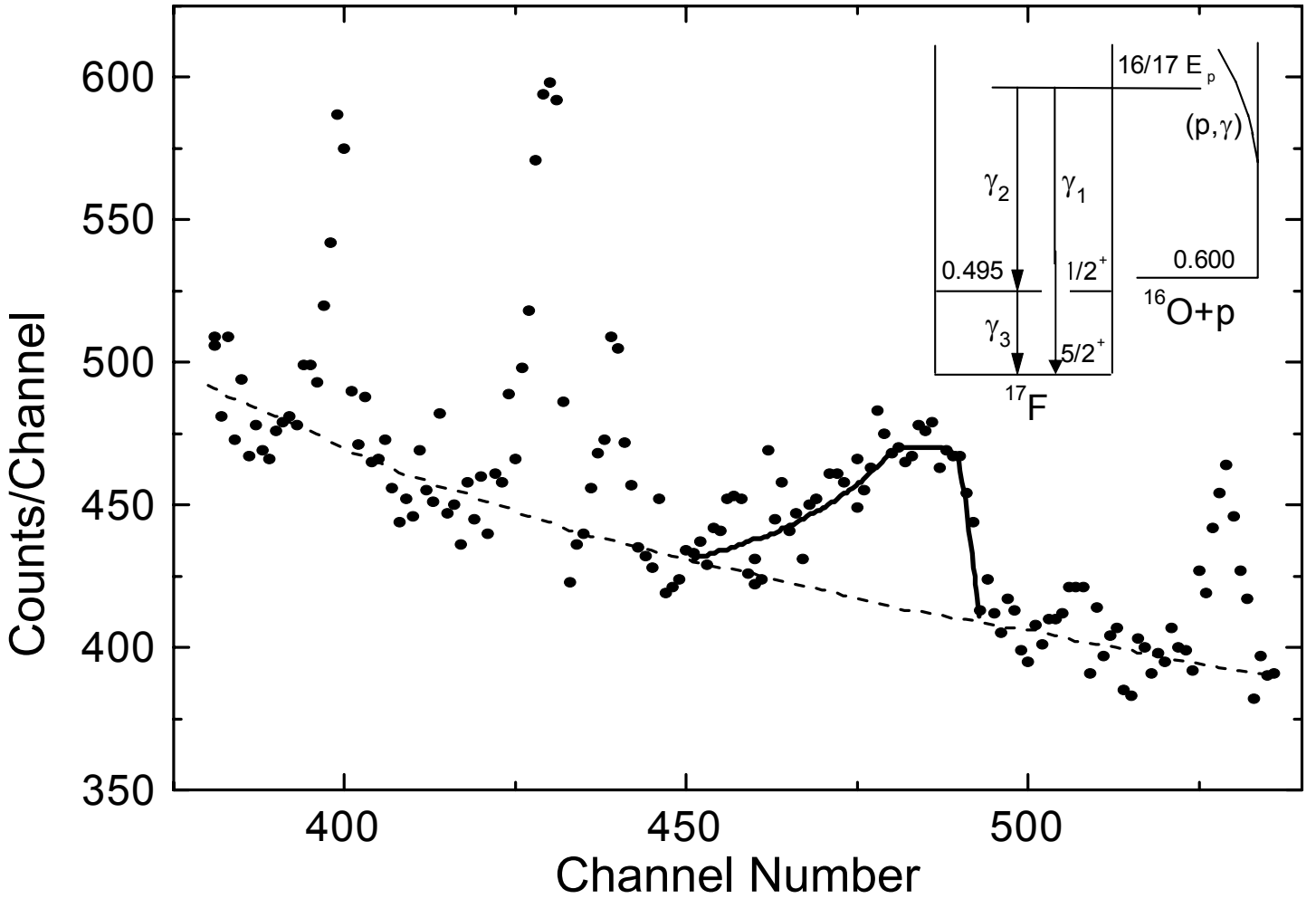


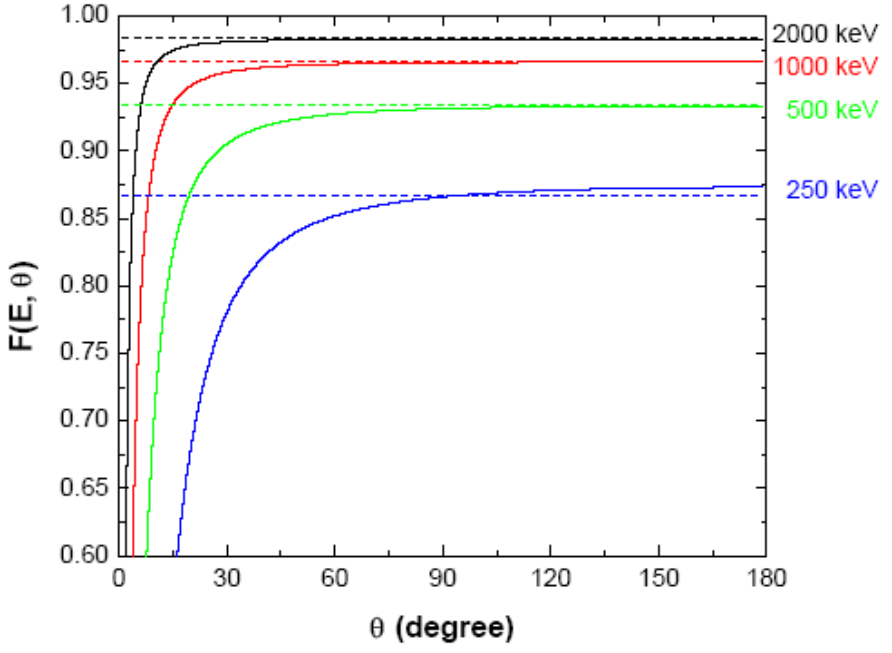
Oxygen analysis using gammas from direct non-resonant radiative capture



$$E_\gamma(E_p) = \frac{M}{M+m} E_p(x) + Q - E_1 - \Delta E_\gamma \qquad \sigma(E_p)\varepsilon(E_\gamma(E_p)) \approx const$$

$$N(E_\gamma,\theta)\delta E = \frac{N_A}{M} q\Omega c(x)\varepsilon(E_\gamma(E_p(x)))\sigma(E_p(x),\theta)\frac{\delta x}{\cos\varphi}$$

Electron screening effects in IBA

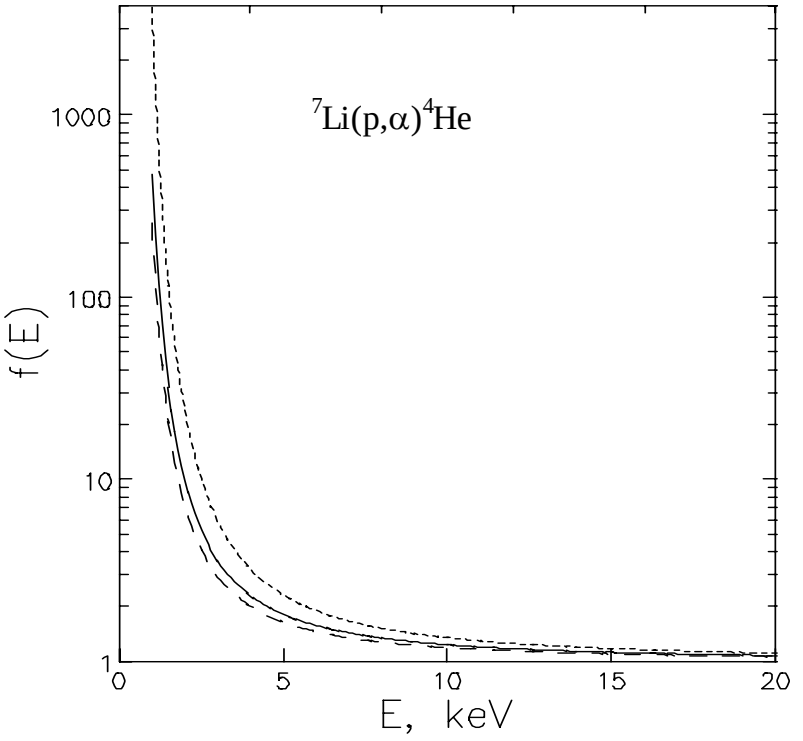


Correction factors for Rutherford cross-section – L'Ecuyer (dashed lines and Andersen (solid line) at different energies

$$F_{\mathrm{L'Ecuyer}} = 1 - \frac{0.049\, Z_1 Z_2^{4/3}}{E_{CM}} \qquad F_{\mathrm{Andersen}} = \frac{\left(1 + \frac{1}{2}\frac{V_1}{E_{CM}}\right)^2}{\left\{1 + \frac{V_1}{E_{CM}} + \left[\frac{V_1}{2E_{CM}\sin\theta_{CM}/2}\right]^2\right\}^2}$$

$$\sigma = F\sigma_R$$

Electron screening effects in nuclear astrophysics



The cross-sections measured in a laboratory should be corrected to the stellar conditions where nuclei are bare.

$$f(E) = \frac{\sigma_{\exp}(E)}{\sigma_{BN}(E)},$$

CONCLUSIONS

International Atomic Energy Agency

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INDC International Nuclear Data Committee

Summary Report of the Technical Meeting on
Long-term Needs for Nuclear Data Development
IAEA Headquarters, Vienna, Austria
2 – 4 November 2011

There is a significant overlap between astrophysics and other nuclear physics applications. Important experimental and theoretical efforts are made by the astrophysics community that can be of interest and of direct relevance to nuclear applications and vice-versa the progress made in the various applications can be of direct relevance for nuclear astrophysics. On this basis, it is recommended to the IAEA:
to continuously identify overlap of interest between astrophysics and other nuclear applications and possible cross-fertilization between the various communities…