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α-capture reactions and the α-nucleus optical potential for p-process nucleosynthesis

S. Harissopulos*, **P. Demetriou, A. Spyrou, A. Lagoyannis, and M. Axiotis**
Institute of Nuclear Physics, NCSR "Demokritos", 153.10 Aghia Paraskevi, Athens, Greece

H. W. Becker, and C. Rolfs
DTL, Ruhr-Universität Bochum, Universitätsstrasse 150, 40781 Bochum, Germany

Systematic measurements of cross sections of α-capture reactions at sub-Coulomb energies relevant to the p process were perfomed in the Ge–Sn region. At the same time, we have updated a recent global, α-nucleus optical model potential (OMP) based on the double-folding method, on all existing data on α-induced reactions. In this paper, we report on some of our new measurements and present comparisons with calculations using the improved α-nucleus OMP.

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1. Motivation

The *p* process [1] is the production mechanism for a certain number of proton-rich, stable nuclei, that cannot be produced by neutron captures. These 35 nuclei, lying between Se and Hg, are referred to as *p* nuclei. The most favoured scenarios for the *p* process involve the photodisintegration of intermediate and heavy elements at high tempeatures (2–3 billion degrees Kelvin) that can be achieved only during the explosive burning phases of massive stars. One of the persistent puzzles of the current *p*-nuclei abundance calculations, is the underproduction of the Mo–Ru region. These discrepancies could be due to uncertainties in the astrophysical models or in the nuclear physics data used. During the photodisintegration process, neutron, proton and α-particle emission compete with one another and with β decays.

Reproduction of the abundances of the *p* nuclei requires a reaction network calculation involving almost 20000 reactions. However, only very few of these reactions can or have been measured in the laboratory, so the network calculations rely largely on theoretical estimates of the relevant reaction rates. Considerable effort has been devoted in the recent years to determine the nuclear properties entering the theoretical calculatons of reaction rates. One such property is the α-nucleus optical model potential (OMP), which is poorly known at low energies close to the Coulomb barrier. The uncertainties in the α OMP lead to large uncertainties in the cross sections of α-induced reactions and their inverse processes (by up to a factor 10), and can therefore affect the *p*-process network calculations. This has motivated us to carry out a systematic investigation of α-induced reactions on nuclei of relevance to the *p* process.

2. Experiments

Experiments have been carried out at the Dynamitron accelerator of the University of Bochum using a 4π large-volume cylinder-shaped (12 inch $\times$ 12 inch) NaI(Tl) single crystal with a borehole of 35 mm diameter along its axis. Targets were placed at the centre of the crystal, which covers almost 98% of 4π. The targets used in our measurements are shown in Fig. 1. They were either self-supporting or backed with Gold and highly enriched in the corresponding isotope. Their thickness ranged from 0.4 to 1 mg/cm^2 and was determined before as well as after the experiments using Rutherford Backscattering (RBS) and/or the X-ray Fluorecence (XRF) technique. As the targets were cooled with air during all measurments and the beam current on target was low (10 to 20 nA), no significant target deterioration effects were found.

Due to the 4π geometry covered by the NaI detector, angle-integrated γ fluxes were measured and, thus, corrections for angular distribution effects were not necessary. The main advantage, however, of using such a *summing* detector is that the response function of this detector leads predominantly to a single peak, called *sum peak*, at an energy $E_\Sigma = Q + E_{cm}$, where Q is the Q value of the reaction and E_{cm} is the center-of-mass projectile energy. Some typical angle-integrated γ spectra measured with the 4π NaI summing detector are given in [2]. As the sum peak results from the summation of the various γ cascades “starting" from the entry state and “ending" at the ground state of the produced compound nucleus its intensity can be used to obtain the total reaction yield and, hence, the cross section of the capture reaction of interest (see in [2]).

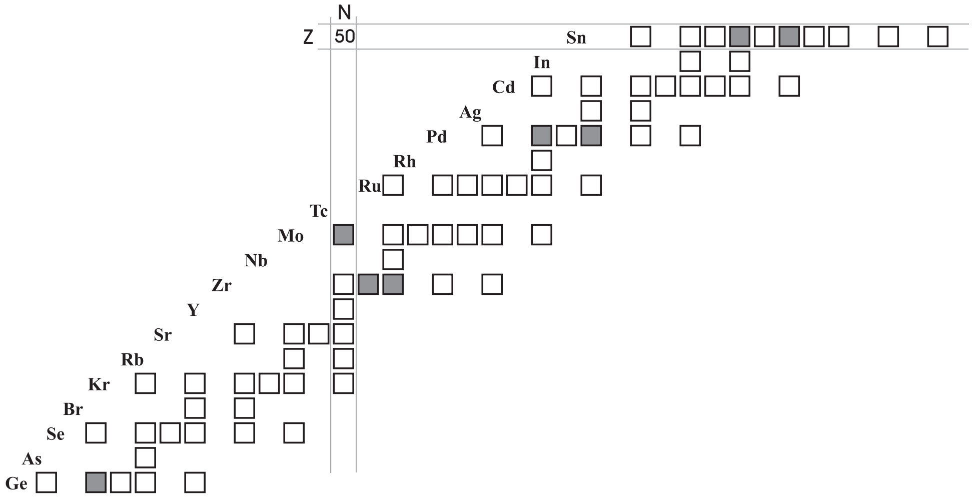

Figure 1: Stable medium-mass nuclei (grey boxes) used in cross section measurements of (α,γ) reactions.

3. Calculations

The α-capture cross sections were calculated by the statistical model code MOST [3]. The code includes all the available experimental information on nuclear masses, deformation, and spectra of low-lying states. The nuclear masses are obtained from the experimental compilation of Audi and Wapstra [4] and the ground state properties (matter density, single-particle level scheme) are predicted from the microscopic Hartree-Fock-BCS model [5]. The E1 transition strength functions are described by the hybrid model of [6], while the M1 transitions are parameterized following [7], with the energies and widths taken from [8]. The nucleon transmission coefficients are obtained from the nucleon-nucleus global phenomenological OMP of [9], while the nuclear level densities (NLD) are taken from the microscopic statistical model of [10].

Below the neutron emission threshold, the α-capture cross sections are sensitive only to the α-nucleus optical potential. An effort to develop a global semi-microscopic α-nucleus OMP led to three different types of potentials (I, II, III) [11], all of which were adjusted to the bulk of existing data on α-elastic scattering and α-induced reactions at low energies. The most complete of these potentials, OMP III, includes a volume and surface imaginary part, as well as dispersive corrections to the real part. The real potential was obtained from a double-folding method on a realistic effective nucleon-nucleon interaction, using projectile- and target-density distributions based on experimental data and Hartree-Fock calculations (for details see Ref. [11]). OMP III was able to give a reasonable description of all the (α,α), (α,γ), (α,n), (α,p) and (n,α) data at low energies. However, the lack of sufficient data in the mass region around $A \sim 100$ and $A \sim 200$, together with the fact that most of the existing data extended over energies where other nuclear properties (nucleon OMPs, NLDs) also had an impact, meant that uncertainties in the phenomenological imaginary part of the potential remained at large.

In this paper, we put further constraints on the parameters of the imaginary potential OMP III, by re-fitting them to an extended database of experimental (α,γ) cross sections that includes the new measurements shown in Fig. 1 and also, other data that have been made available since 2001.

The latter include (α,γ) cross sections on ^{63}Cu [12], ^{96}Ru[13], ^{106}Cd[14], and ^{107}Ag [15].

In a first step, we modified the diffuseness *a* of the volume and surface terms, and the damping coefficient *C* of the surface term shown in Fig. 2. As can be seen in the figure, the re-fitting procedure resulted in a more diffuse imaginary potential for nuclei with $A \leq 150$ compared to nuclei with higher mass values. The new data also required less surface absorption at lower energies as is indicated from the higher values of *C* in Fig. 2.

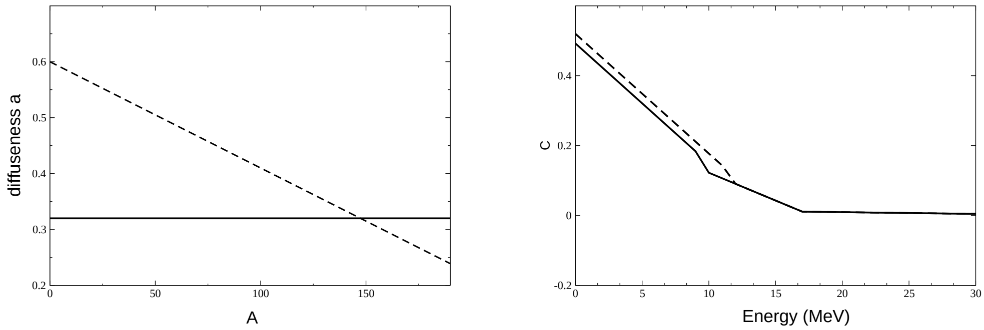

Figure 2: Diffuseness *a* and surface damping coefficient *C* of the original OMP III (solid line) [11] and updated present potential (dashed line).

The calculations are compared with the experimental data and the original OMP III results in Fig. 3. An improvement is observed in the case of ^{56}Fe, ^{70}Ge, ^{96}Ru, and ^{106}Cd while for all the other nuclides there is hardly any difference from the original OMP III. Overall, the agreement with the data is very good. The shaded areas in the figure are formed by using different nucleon OMPs and NLD formulas, and outline the range of uncertainties of the calculations. Work is underway to further improve the geometry of the imaginary OMP III by adjusting to old and new data on α-elastic scattering and all the other α-induced reaction data available.

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References

[1] M. Arnould and S. Goriely, Phys. Rep. **384**, 1 (2003).

[2] S. Harissopulos *et al.*, Nucl. Phys. **A 758**, 505c (2005).

[3] S. Goriely, in *Nuclei in the Cosmos V*, edited by N. Prantzos and S. Harissopulos, (Edition Frontières, Paris, 1998), p. 314 (see also http://www-astro.ulb.ac.be).

[4] G. Audi, A.H. Wapstra, and C. Thibault, Nucl. Phys. **A 729**, 3 (2003).

[5] S. Goriely, F. Tondeur, J.M. Pearson, At. Data. Nucl. Data Tables **77**, 311 (2001).

[6] S. Goriely, Phys. Lett. **B 436**, 10 (1998).

[7] J. Kopecky, and R.E. Chrien, Nucl. Phys. **A 468**, 285 (1987).

[8] Reference Input Parameter Library, IAEA-Tecdoc-1034 (1998), (see also http://iaeand.iaea.or.at/ripl).

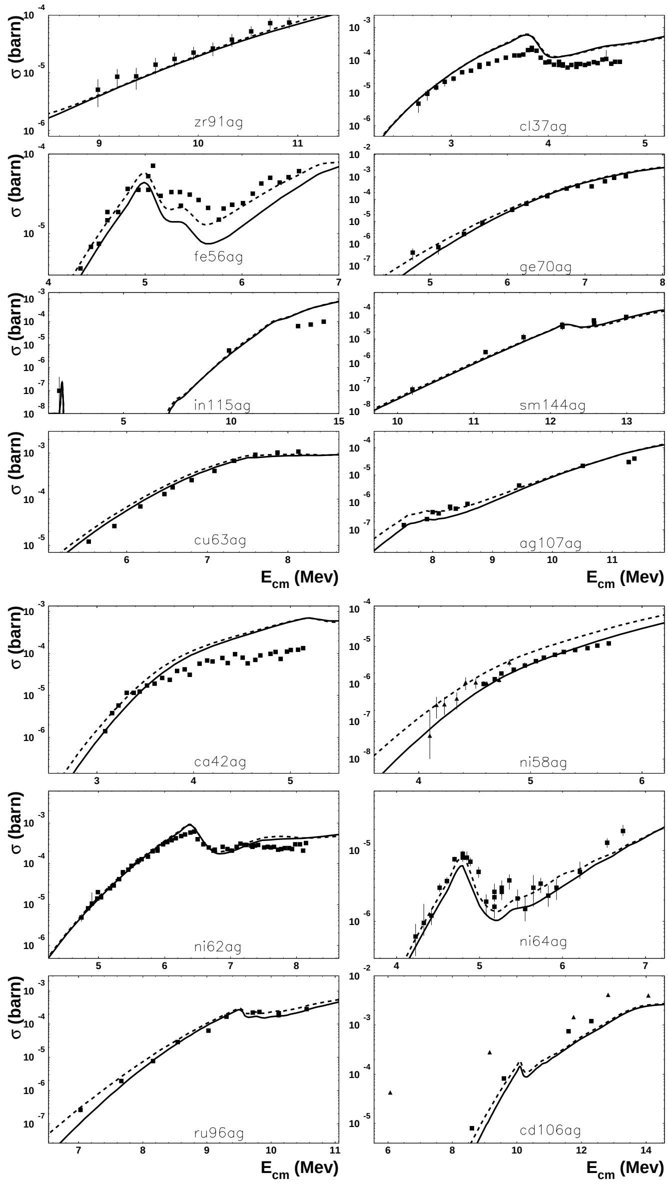

Figure 3: Cross sections for the (α,γ) reaction on nuclei included in Ref. [11], ^{63}Cu [12], ^{96}Ru [13], ^{106}Cd [14], ^{107}Ag [15], and ^{91}Zr measured in the present work.

[9] A.J. Koning and J.P. Delaroche, Nucl. Phys. **A 713**, 231 (2003).

[10] P. Demetriou, and S. Goriely, Nucl. Phys. **A 695** 95 (2001).

[11] P. Demetriou, C. Grama, and S. Goriely, Nucl. Phys. **A 707**, 141 (2002).

[12] M.S. Basunia *et al.*, Phys. Rev. C **71**, 035801 (2005).

[13] W. Rapp *et al.*, Phys. Rev. C **66**, 015803 (2002).

[14] Gy.Gyürky *et al.*, Nucl. Phys. **A 758**, 517c (2005).

[15] C.M. Baglin *et al.*, in proceedings of Int. Conf. Nucl. Data for Sci. Tech. ND2004, Santa Fe 2004, AIP 769 (N.Y. 2005), p.1370.