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Alpha induced reactions for ^{106}Cd at near Coulomb barrier energies

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Abstract. Alpha induced nuclear reactions at near Coulomb barrier energies are of current interest in astrophysics from the point of view of p-process in medium mass nuclides. Recently, (α,γ), (α,p) and (α,n) reaction cross sections for ^{106}Cd have been measured in the Gamow window energy range of alpha particles from 8 to 12 MeV. The data have been analyzed with the statistical model code NON-SMOKER using different input parameters. Using McFadden-Satchler alpha potential, the calculated (α,n) cross sections are consistent with the measured data. While the (α,p) cross sections are under-predicted by the theory, the (α,γ) cross sections are over-predicted in the whole range of alpha energy. Using a hybrid of microscopic and phenomenological approaches, we have recently given a prescription of obtaining α-nucleus optical potential usable for the energy range from Coulomb barrier to 140 MeV and valid for a range of nuclides with A ~12 to 209. Using the α optical potential parameters derived from this prescription, comprehensive and systematic calculations have been performed to determine the (α,γ), (α,p) and (α,n) reaction cross sections for ^{106}Cd in the α energy range from 8 to 12 MeV employing the most recent and versatile statistical model code EMPIRE-II. The IAEA recommended Koning potentials have been used for neutrons and protons in the outgoing channels. Using this prescription we have been able to obtain better agreement of the measured cross section data of ^{106}Cd throughout the energy range.

1 Introduction

The stable isotopes of mass above iron on the proton rich side of the valley of stability are synthesized by the so-called p-process. These so called p-nuclei between Se and Hg are shielded by stable nuclei formed via the slow neutron capture process (s-process) and the rapid neutron capture process (r-process). The s-process isotopes are produced by the slow neutron capture in stellar helium and carbon burning environments with steady neutron production reactions. The r-isotopes are produced by the rapid neutron capture process that takes place in explosive stellar environment like type-II supernovae [1]. Both s- and r-processes have their contributions for the production of a number of isotopes located along the valley of stable nuclei.

The p-nuclei, however, are not produced by the neutron capture reactions but as a sequence of photodisintegration processes in a high γ-flux scenario [2]. The p-nuclei are driven by a sequence of (γ,n) reactions on s- and r-nuclei producing the proton-rich nuclei where the binding energies of neutrons become gradually larger and subsequently (γ,p) and (γ,α) reactions takes over the (γ,n) reactions. The (γ,p) and (γ,α) reactions therefore may play an important role in determining the final p-nuclei abundances in this mass range. The detailed overview of the p-process is given in ref. [3].

The accurate knowledge of large data on reaction rates involving stable as well as unstable proton-rich nuclei is essential to describe the p-process nucleosynthesis. However not much experimental effort has been devoted to relevant cross section determination. The γ-induced reactions are difficult to measure directly. These can, however, be derived using the detailed balance theorem from the charged particle induced reaction cross sections that can be measured experimentally. The experimental data for the charged particle induced reaction cross sections are scarce above Fe. There are more experiments for proton capture cross sections as compared to that for α-capture cross sections. This is due to the fact that the corresponding energies for α-capture reactions are well below the Coulomb barrier, making the cross sections very small. There are, however, few experiments recently for the α-capture reactions in the medium mass region of interest for p-nuclei.

Measurements for α induced reaction cross sections of ^{106}Cd have been reported [4] recently in the energy range of Gamow window for the astrophysical p-process scenario. The results are compared with predictions of the statistical model code NON-SMOKER using different input parameters. Their analysis shows that using McFadden-Satchler [5] alpha potential, the calculated (α,n) cross sections are consistent with the measured data. While the (α,p) cross sections are under-predicted by the theory, the (α,γ) cross sections are over-predicted in the whole range of alpha energy.

Alpha potential is an important input for any statistical model calculations of cross sections of nuclear reactions induced by α-particles. Using a hybrid of microscopic and phenomenological approaches, we have recently given a prescription of obtaining global α-nucleus optical potential [6] usable for the energy range from Coulomb barrier to 140 MeV and valid for a range of nuclides with A ~ 12 to 209. Using the alpha optical potential parameters derived from this prescription, comprehensive and systematic calculations have been performed to determine the (α,γ), (α,p) and (α,n) reaction cross sections for ^{106}Cd in the α energy range from 8 to 12 MeV. The Q values for these reactions are 0.88 MeV, –6.05 MeV and –10.14 MeV, respectively. The calculations are

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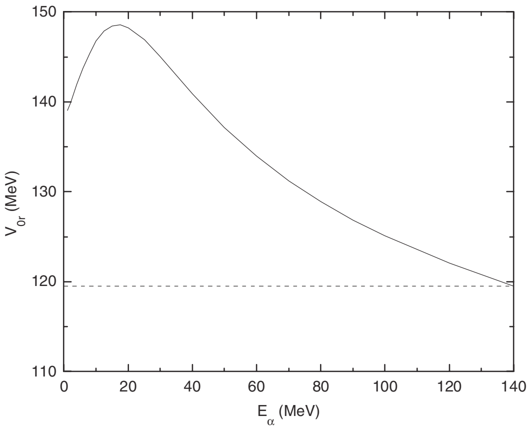

Fig. 1. Real potential depth parameter V_{0r} as function of α energy for ^{106}Cd. The dotted line shows the energy independent value obtained without dispersion correction.

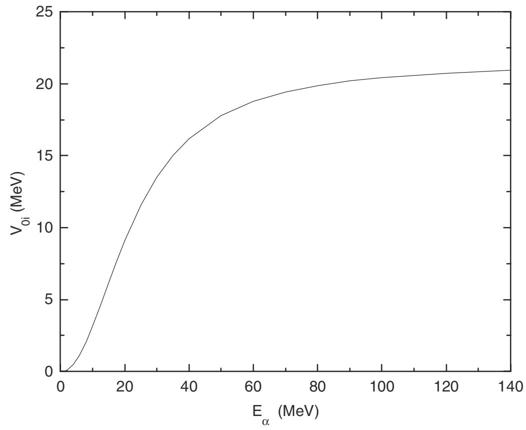

Fig. 2. Imaginary potential depth parameter V_{0i} as function of α energy for ^{106}Cd.

performed in the framework of Hauser-Feshbach statistical model. The results are presented in this paper.

2 Calculations

Synthesizing microscopic and phenomenological approaches, a simplified method of obtaining global α-nucleus optical model potential parameters has been proposed by us [6] for use in model based calculations of reaction cross sections where α is in either entrance or exit channel. It has applicability for α energy ranging from Coulomb barrier to ~140 MeV and for wide range of nuclei with mass A ~ 12 to 209.

The optical potential is expressed as

$$V(r) = V_C(r) - V_r(r) - iV_i(r)$$

where V_C is the Coulomb potential, V_r and V_i are respectively the real and imaginary parts of the nuclear potential. Further, the radial variation of the real and imaginary parts of the potential are expressed in the Wood-Saxon form as $V_x(r) = V_{0x}f_x(r)$, where

$$f_x(r) = 1/[1 + \exp(r - R_xA^{1/3})/a_x]$$

with $x = r$ or i stands for real or imaginary part, respectively. The parameters V_{0x}, R_x and a_x for real as well as imaginary parts of the potential for ^{106}Cd were derived using our prescription [6]. The real and imaginary potential depths V_{0r} and V_{0i} are plotted in figures 1 and 2 and the radius and diffuseness parameters R_x and a_x for real and imaginary parts of the potential are given in table 1.

Table 1. The radius and diffuseness parameters (R_x and a_x) in fm for real as well as imaginary parts of the potential obtained for ^{106}Cd.

	R_x(fm)	a_x (fm)
Real	1.24	0.76
Imaginary	1.53	0.60

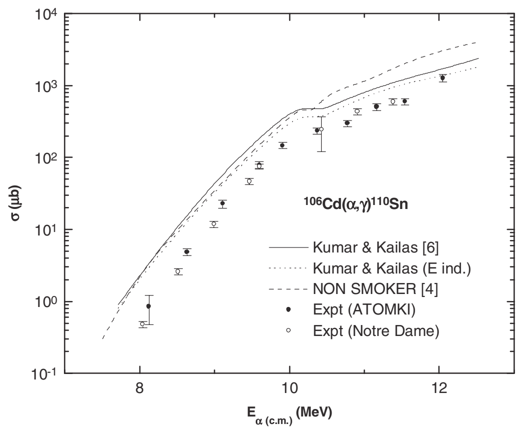

Fig. 3. Comparison of ^{106}Cd$(\alpha, \gamma)^{110}$Sn reaction cross sections as a function of α energy (in center of mass) obtained using α potential by us [6] (continuous line) with the experimental data as well as NON SMOKER values (dashed line) reported in ref. [4]. Also shown are the values (dotted line) obtained using our α potential derived without dispersion correction.

These parameters have been used to determine the (α, γ), (α,p) and (α,n) reaction cross sections for ^{106}Cd in the energy range from 8 to 12 MeV employing the most recent and versatile statistical model code EMPIRE-II [7]. The EMPIRE specific default options for the masses and level densities of the nuclei involved in the calculations have been used. The RIPL-2 recommended Koning potentials [8] have been used for neutrons and protons in the outgoing channels.

3 Results and discussion

The results of the present calculations of (α, γ), (α,p) and (α,n) reaction cross sections for ^{106}Cd in the energy range from 8 to 12 MeV determined using the α optical potential parameter derived from our prescription are shown (continuous line) in figures 3, 4 and 5, respectively. These have been compared with the corresponding experimental data as well as the NON-SMOKER values (dashed line) recently reported in ref. [4].

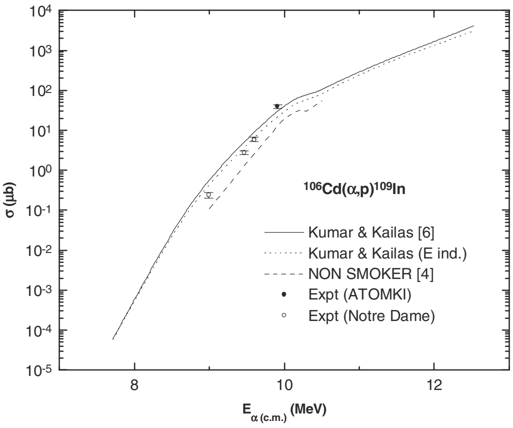

Fig. 4. Comparison of ^{106}Cd(α,p)^{109}In reaction cross sections as a function of α energy (in center of mass) obtained using α potential by us [6] (continuous line) with the experimental data as well as NON SMOKER values (dashed line) reported in ref. [4]. Also shown are the values (dotted line) obtained using our α potential derived without dispersion correction.

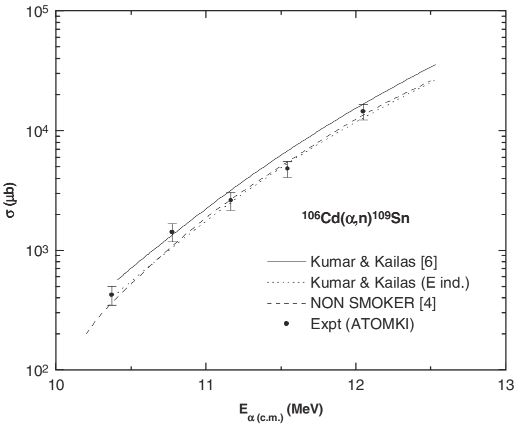

Fig. 5. Comparison of ^{106}Cd(α,n)^{109}Sn reaction cross sections as a function of α energy (in center of mass) obtained using α potential by us [6] (continuous line) with the experimental data as well as NON SMOKER values (dashed line) reported in ref. [4]. Also shown are the values (dotted line) obtained using our α potential derived without dispersion correction.

It can be seen from the figures 4 and 5 that ^{106}Cd(α,p)^{109}In as well as ^{106}Cd(α,n)^{109}Sn reaction cross sections are very well reproduced in the whole energy range from 8 to 12 MeV using our α potential. However, ^{106}Cd(α,γ)^{110}Sn reaction cross sections shown in figure 3 are predicted little higher over the entire energy range of interest. It is also seen that the (α,γ) excitation function exhibits the well-known "cusp" around 10.2 MeV corresponding to the opening of the (α,n) channel.

As is discussed in ref. [6] and can be seen from figure 1, the depth of the real part of the potential increases by nearly 20% at lower energies as compared to the highest energy values when dispersion corrections are used in deriving the potential parameters. This effect enhances the reaction cross sections by about 20% at lower energies close to Coulomb barrier.

The (α,γ), (α,p) and (α,n) reaction cross sections for ^{106}Cd at the α energies of interest have also been determined using the energy independent potential parameters derived from our prescription without dispersion correction and the corresponding values are also plotted in figures 3, 4 and 5 for comparison (dotted line) with the experimental data. As can be seen from the figures, these cross section values are lower in the whole energy range as compared to the values obtained using the α potential derived with dispersion correction and are in good agreement with the experimental data.

4 Conclusions

The α induced (α,γ), (α,p) and (α,n) reaction cross sections for ^{106}Cd at α energies near the Coulomb barrier in the range from 8 to 12 MeV have been determined in the framework of Hauser-Feshbach statistical model using the α potential derived from the prescription given by us [6] based on synthesizing microscopic and phenomenological approaches. The most recent and versatile statistical model code EMPIRE-II [7] has been used with default options for the masses and level densities of the nuclei involved in the calculations and RIPL-2 recommended Koning potentials for neutrons and protons in the outgoing channels. The results of our calculations are compared with the recent experiments performed at ATOMKI and Notre Dame to measure these cross sections for ^{106}Cd in the Gamow window energy range in the interest of the astrophysical p-processes reported in ref. [4]. Comparison is also made with the values determined using the NON-SMOKER code in ref. [4].

The cross sections in general are better reproduced by the α potential proposed by us. The (α,p) and (α,n) reaction cross sections are in very good agreement with the experimental data in the entire energy range of consideration. The (α,γ) reaction cross sections are also better reproduced as compared to the NON-SMOKER results. It is noticed that the (α,γ) reaction cross sections are slightly higher than the measured data in the whole range of α energy. This needs further investigations.

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