Electron screening in metals

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J Gajević[1] M Lipoglavšek[1] A Likar[1,2] T Petrovič[1,3] P Pelicon[1] A Sánchez Ortiz[1] and A Cvetinović[1]

[1] Jožef Stefan Institute, Jamova cesta 39, Ljubljana, Slovenia
[2] Faculty of Mathematics and Physics, Jadranska ulica 19, Ljubljana, Slovenia
[3] Cosylab d.d, Teslova ulica 30, Ljubljana, Slovenia

E-mail: jelena.gajevic@ijs.si

Abstract. In order to further investigate electron screening effect we studied proton induced nuclear reactions over an energy range from 0.8 to 2.6 MeV for different environments: Mn and Cd metals and MnO and CdO insulators. Shifts in resonance energy for metallic relative to insulator targets were not observed. No large electron screening could be deduced for (p,γ) and (p,n) reactions in Mn. Moreover, no large electron screening can be deduced with certainty for the (p,n) reaction in Cd.

1. Introduction

The fusion reaction can be divided into two parts which are approximately independent of each other, namely the atomic physics of the nuclei approaching each other and the nuclear physics valid if they are close enough to feel the nuclear forces. In order to fuse, two positively charged nuclei must come into contact overcoming the Coulomb repulsion. Due to Coulomb repulsion, the cross section σ for charged-particle-induced nuclear reactions drops rapidly with decreasing beam energy. The astrophysical S-factor is usually introduced to separate the strong energy dependence from effects of pure nuclear interaction and in the case of non-resonant reactions it only slowly varies with energy [1]. The S-factor is defined by writing the cross section as [1]:

$$\sigma(E) = \frac{S(E)}{E} e^{-2\pi\eta}, \tag{1}$$

where E is the center of mass energy, $\eta = Z_1 Z_2 e^2/4\pi\epsilon_0\hbar\sqrt{2E/\mu}$ is the Sommerfeld parameter, Z_1 and Z_2 are the charge numbers of interacting nuclei and μ is their reduced mass. The Gamow factor $e^{-2\pi\eta}$ describes the s-wave penetration through the Coulomb barrier of point-like charges and thus with the geometrical factor $1/E$ accounts for a strong energy dependence of the cross sections at sub-Coulomb energies. The cross section increases at low energies when the interacting nuclei are not bare but surrounded with atomic electron clouds [1]. As a result, the measured cross sections are enhanced compared to cross sections for bare nuclei with an enhancement factor:

$$f(E) = \frac{\sigma(E + U_e)}{\sigma(E)}, \tag{2}$$

where U_e is the electron screening potential. Experimental studies of various nuclear reactions in metallic environments have shown the expected cross section enhancement at low energies

[2-6]. Furthermore, it was observed that the magnitude of the screening effect strongly depends on the host material and the reason of this dependence is still not known. A large electron screening potential of $U_D = 27 \pm 9$ keV [4] (U_D is the difference between screening potentials in metallic and insulating targets) was observed for the (p,n) reaction in V metal relative to the VO_2 insulator, while an electron screening potential of $U_D = 31 \pm 13$ keV was deduced for the (p,n) reaction in Ni metal relative to the NiO insulator [5]. Moreover, Kettner et al. [4] observed a narrow resonance in the ^{176}Lu(p, n)^{176}Hf reaction at proton energy $E_p = 810$ keV and noticed a lowering of this resonance energy by $U_D = 32 \pm 2$ keV for the Lu metal relative to the insulator. The sizeable resonance shifts were interpreted as a demonstration of the acceleration effect by the valence electrons.

2. Experiment

Proton beams with energies between 0.8 and 2.6 MeV were accelerated by the 2 MV Tandetron accelerator at Jožef Stefan Institute. Neutrons and γ rays produced in reactions: ^{55}Mn(p, n)^{55}Fe, ^{55}Mn(p, γ)^{56}Fe, ^{55}Mn(p, p$'\gamma$)^{55}Mn, ^{110,111,112,113,114,116}Cd(p, p$'\gamma$)^{110,111,112,113,114,116}Cd, ^{113}Cd(p, n)^{113}In and ^{112,114}Cd(p, γ)^{113,115}In were detected with a neutron detector and a HPGe detector placed 4.2 cm from the target at an angle of 135° with respect to the beam direction. Neutrons were detected in a liquid organic scintillator detector positioned 4.8 cm from the target at an angle of 45° with respect to the beam direction. This scintillator detector was chosen because of the good neutron-γ separation at low energies. The detector was connected to a fast asynchronous digitizer which digitized the incoming signals. In order to suppress the large γ-ray background, a 6 mm thick lead absorber was placed in front of the neutron detector. The method employed for neutron-γ separation was the digital charge comparison method [7]. In order to properly take into account background neutrons, we measured background neutron activity continuously for 238 h. A SiLi X-ray detector positioned 9.1 cm from the target at an angle of 135° with respect to the beam direction was used for measurement of X rays. Beam current was on the average about 1μA. Only targets with natural isotopic abundance were used. A 125 μm thick $Mn_{88\%}Ni_{12\%}$ foil was obtained from Goodfellow while a 99.99 % pure and 250 μm thick Cd foil was obtained from Chempur. 99 % pure MnO powder and 99.99 % pure CdO powder were obtained from Chempur. Oxide targets were prepared by pressing the powder into a 14 mm diameter and 1 mm deep cylindrical hole of a 2 mm thick Cu backing. The conductive backing helped cooling the insulating targets.

3. Results

We chose to study the (p,n) reaction in Mn due to the reasonably low threshold (E_{th}=1.032 MeV) for this reaction and due to the fact that Mn has only one naturally occurring isotope, ^{55}Mn. We searched for a shift in resonance energy in metallic compared to insulator environment, similarly to the one observed in ^{176}Lu(p, n)^{176}Hf. To search for a shift in resonance energy, we studied two low energy resonances at respective beam energies of 1.38 and 1.54 MeV [8]. Thick target neutron yields from the ^{55}Mn(p, n)^{55}Fe reaction near the $E_p = 1.54$ MeV resonance as a function of laboratory beam energy E_p for Mn metal and MnO insulator are shown in fig. 1. From the observed thick target neutron yields near both studied resonances in Mn, we did not notice any shifts in ^{55}Fe resonance energies in metallic Mn compared to insulating MnO targets. We used a 125 keV Coulomb excitation peak for inferring incident dose. While studying the (p,n) reaction in Mn we also observed the (p,γ) resonances in ^{56}Fe. Thick target 847 keV γ-ray yields from the ^{55}Mn(p, γ)^{56}Fe reaction near E_p=1.54 MeV are shown in fig. 2. Shifts in ^{56}Fe resonance energy in metallic Mn compared to insulating MnO target were not observed. Moreover, the ratios of 847 keV γ-ray (see fig. 3) and neutron yields for Mn and MnO targets do not show any expected enhancement with decreasing beam energy and therefore no large electron screening can be deduced for (p,γ) and (p,n) reactions in Mn. We chose to study the (p,n) reaction in Cd,

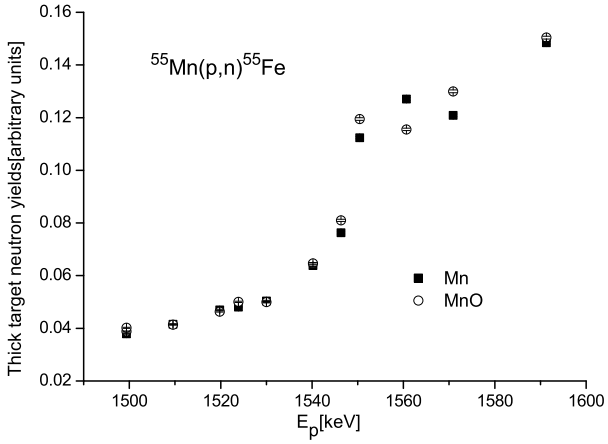

Figure 1. Thick target neutron yields from the ^{55}Mn(p, n)^{55}Fe reaction near the E_p= 1.54 MeV resonance.

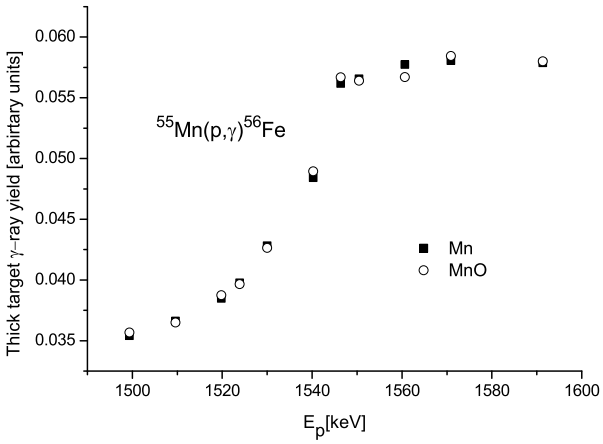

Figure 2. Thick target 847 keV γ-ray yields from the ^{55}Mn(p, γ)^{56}Fe reaction near the E_p= 1.54 MeV resonance.

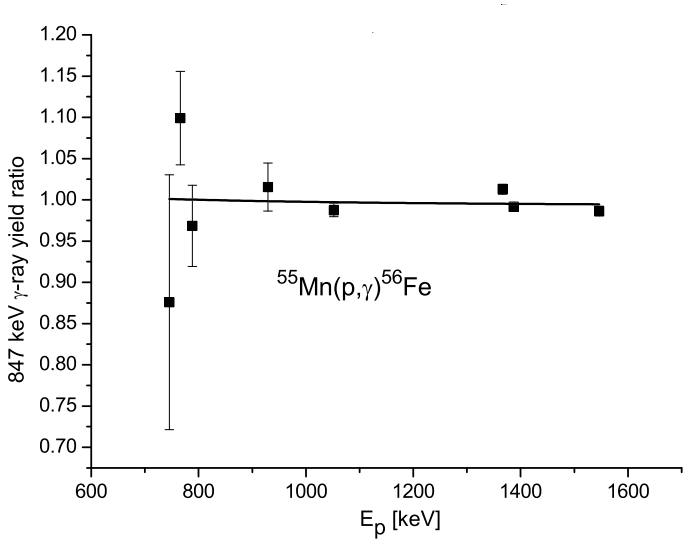

Figure 3. The ratio of 847 keV γ-ray yields from the ^{55}Mn(p, γ)^{56}Fe reaction as a function of laboratory beam energy for Mn metal and MnO insulator.

since it has an even lower threshold than Mn that is for the ^{113}Cd(p, n)^{113}In reaction E_{th} =0.46 MeV. Cd has a higher atomic number than Ni and V and if we take into account the suggested increment of the screening potential that is roughly proportional to the proton number Z of the target [2-6], we expected a higher electron screening potential in Cd. Thick target neutron yields from the ^{113}Cd(p, n)^{113}In reaction as a function of laboratory beam energy for Cd metal and CdO insulator are shown in fig. 4. The 299 keV Coulomb excitation peak was used for dose normalization. The neutron yields in Cd and CdO show a trend that is not well understood at the moment. The lowest energy point in fig. 4 is significantly higher in Cd than in CdO. This enchancement could be due to electron screening. However, the increase of the neutron yields at the lowest energy is not presently understood. Improved measurements are certainly needed to clarify the mentioned data point.

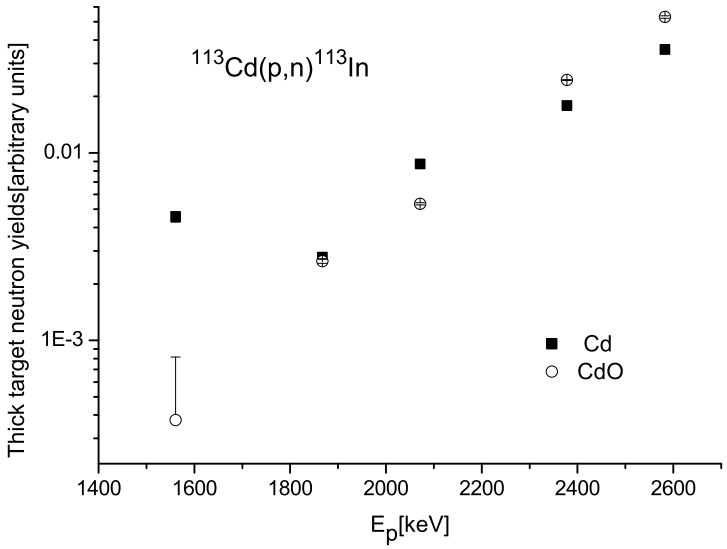

Figure 4. Thick target neutron yields from the $^{113}\mathrm{Cd(p,n)}^{113}\mathrm{In}$ reaction as a function of laboratory beam energy for Cd metal and CdO insulator.

4. Conclusions

Contrary to observed shifts in $^{176}\mathrm{Hf(p,n)}^{176}\mathrm{Lu}$ reaction, shifts in resonance energy for metallic targets relative to insulator ones were not observed in $^{55}\mathrm{Mn(p,n)}^{55}\mathrm{Fe}$ and $^{55}\mathrm{Mn(p,\gamma)}^{56}\mathrm{Fe}$ reactions. Besides, no large electron screening was observed in $^{55}\mathrm{Mn(p,n)}^{55}\mathrm{Fe}$ and $^{55}\mathrm{Mn(p,\gamma)}^{56}\mathrm{Fe}$ reactions, although similar electron screening values to the measured ones in Ni and V were expected. However, there is an indication of a large electron screeing in Cd, although more precise measurements are needed to confirm this indication. The reported results are quite unexpected and certainly motivate further studies of the electron screening effect.

5. References

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