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Electron screening in Al and Ni metals

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Proton induced nuclear reactions were studied over the bombarding energy range from 0.98 to 3.15 MeV for different environments: Ni and Al metals, Al_2O_3 and NiO insulators. The measurements were based on observation of the yields of ^{59,61,63,64,65}Cu,^{58,60,62}Ni and ^{28}Si de-excitation γ rays. The resonances: $^{58}\mathrm{Ni}(\mathrm{p},\gamma)^{59}\mathrm{Cu}$, $^{58}\mathrm{Ni}(\mathrm{p},\mathrm{p}'\gamma)^{58}\mathrm{Ni}$ and $^{27}\mathrm{Al}(\mathrm{p},\gamma)^{28}\mathrm{Si}$ were measured. Shifts in resonance energy for the metalic target relative to the insulator ones were not observed. Large electron screening was seen only in the $^{64}\mathrm{Ni}(\mathrm{p},\mathrm{n}\gamma)^{64}\mathrm{Cu}$ reaction.

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1. Introduction

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 interactions [1]. The cross section σ is then written as a function of the c.m.s energy E as:

$$\sigma(E) = \frac{S(E)}{E} e^{-2\pi\eta} \tag{1.1}$$

where $\eta = Z_1 Z_2 e^2/4\pi\varepsilon_0\hbar\sqrt{2E/\mu}$ is the Sommerfeld parameter, Z_1 and Z_2 are the charge numbers of interacting nuclei and μ their reduced mass. In this way, all nuclear interactions are described by $S(E)$, which in case of non-resonant reactions varie slowly with energy while the exponential Gamow factor $e^{-2\pi\eta}$ describes the s-wave penetration through the Coulomb barrier of point-like charges and thus accounts for strong energy dependence of the cross sections at sub-Coulomb barrier energies. It is known that the cross-section increases at low energies when the interacting nuclei are not bare but embedded in the electron cloud of an atom [1]. The enhancement factor, f, could be written as:

$$f(E) = \frac{\sigma(E+U_e)}{\sigma(E)} \tag{1.2}$$

Experimental studies of different nuclear reactions (see for instance [2] - [4]) have shown the expected enhancement at low energies, corresponding to a screening potentials U_e significantly larger than theoretically expected. It was observed that the magnitude of the screening effect strongly depends on the host material and the reason for this dependence is not precisely known. In addition, an increase of the screening potential proportional to proton number Z_2 of the target was observed in Li, Be, V and Lu targets [3], [5]. Also, shifts in resonance energy for Lu metallic targets relative to the insulator ones were observed.

2. Experiment

To further investigate the electron screening effects at high Z, we studied proton induced nuclear reactions induced on different environments; Ni and Al metals, Al_2O_3 and NiO insulators. Proton beams with energies between 0.98 and 3.15 MeV were accelerated by the 2MV Tandetron accelerator at Jožef Stefan Institute. The measurements were based on observation of the yields of ^{59,61,63,64,65}Cu, ^{58,60,62}Ni and ^{28}Si de-excitation γ rays, populated in the reactions ^{58}Ni$(\mathrm{p},\gamma)^{59}$Cu, ^{60}Ni$(\mathrm{p},\gamma)^{61}$Cu, ^{62}Ni$(\mathrm{p},\gamma)^{63}$Cu, ^{64}Ni$(\mathrm{p},\gamma)^{65}$Cu and ^{58}Ni$(\mathrm{p},\mathrm{p}'\gamma)^{58}$Ni, ^{60}Ni$(\mathrm{p},\mathrm{p}'\gamma)^{60}$Ni, ^{62}Ni$(\mathrm{p},\mathrm{p}'\gamma)^{62}$Ni, ^{64}Ni$(\mathrm{p},\mathrm{n}\gamma)^{64}$Cu and ^{27}Al$(\mathrm{p},\gamma)^{28}$Si. All the reactions, except ^{64}Ni$(\mathrm{p},\mathrm{n})^{64}$Cu $(Q = -2457.381$ keV$)$, have positive Q values. Gamma rays were detected with a high purity germanium (HPGe) detector positioned 5 cm from the target at an angle of 60° wih respect to the proton beam direction. Proton dose was deduced from the peak area in the Rutherford back-scattering (RBS) spectrum pertaining to protons which are backscattered from a beam chopper. A thin Au foil is deposited on the surface of a rotating graphite chopper which intersects the proton beam with a frequency of 10 Hz [6]. Backscattered protons were detected with a passivated implanted planar silicon (PIPS) detector. The beam current was of the order of 90 nA. The natural Ni target with 99.98 % purity obtained from Goodfellow was 100 µm thick. The thickness of the Al target, from

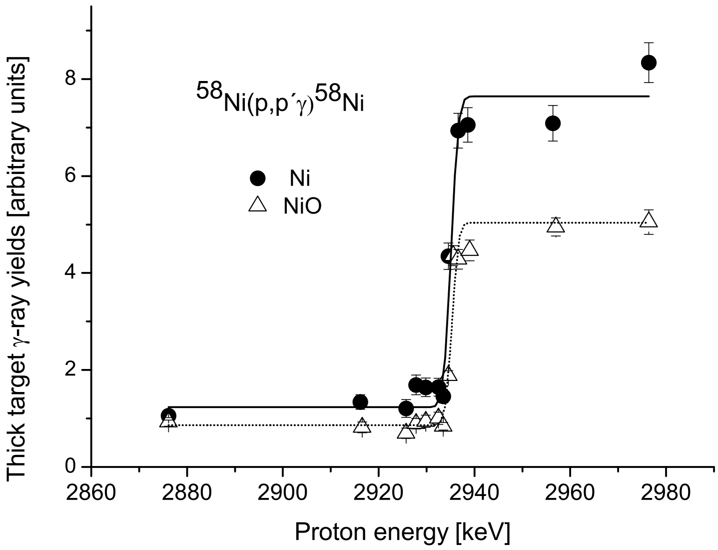

Figure 1: Thick target 1454 keV γ-ray yields from the ^{58}Ni$(\mathrm{p},\mathrm{p}'\gamma)^{58}$Ni reaction near the E_p= 2935 keV resonance. Lines are fits to the data (see text).

which the Al_2O_3 layer has been removed before starting the measurements, was 1mm. NiO powder with 99.995 % purity was obtained from Chempur. A 1 mm thick NiO target was prepared by pressing the NiO powder, while Al_2O_3 target was prepared by heating $\mathrm{Al(OH_3)}$ on tantalum substrate. The resonances ^{58}Ni$(\mathrm{p},\gamma)^{59}$Cu at proton energy $E_p = 1424$ keV and 1844 keV, ^{58}Ni$(\mathrm{p},\mathrm{p}')^{58}$Ni at $E_p = 2935$ keV (all energies obtained from [8]) and ^{27}Al$(\mathrm{p},\gamma)^{28}$Si at $E_p = 992$ keV [9] were measured. We chose these Ni resonances because they were the strongest in our energy range and the well known $E_p = 992$ keV ^{27}Al$(\mathrm{p},\gamma)^{28}$Si [8] resonance to reexamine a previous accelerator energy calibration. Thick target 1454 keV γ-ray yields produced in deexcitation of first excited state in ^{58}Ni from the ^{58}Ni$(\mathrm{p},\mathrm{p}'\gamma)^{58}$Ni reaction near the $E_p = 2935$ keV resonance as a function of laboratory beam energy are shown in fig.1 for Ni metal and NiO insulator. Thick target 1779 keV γ-ray yields produced in deexcitation of ^{28}Si from the ^{27}Al$(\mathrm{p},\gamma)^{28}$Si reaction near the $E_p = 992$ keV resonance are shown in fig.2 for Al metal and Al_2O_3 insulator.

3. Results

We fitted the thick target γ-ray yield N_γ near resonance energy E_r by using the equation:

$$N_\gamma = A + B \cdot \mathrm{erf}\left(\frac{E_p - E_r}{\sqrt{2}\Gamma}\right) \tag{3.1}$$

where the parameter A is the mean value, B is the resonance height and $\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int e^{-x^2} \mathrm{d}x$. From the observed thick target γ-ray yields near all the studied resonances in Ni and Al, we didn't notice any shifts in resonance energy for the metallic targets relative to the insulator ones, furthermore the values were the same within experimental errors of about 2 keV. We observed no resonance shifts

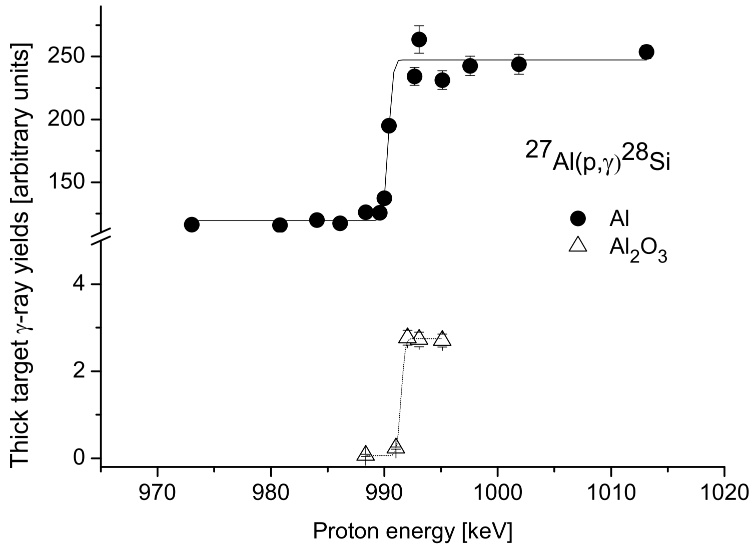

Figure 2: Thick target 1779 keV γ-ray yields from the $^{27}Al(p,\gamma)^{28}Si$ reaction near the E_p= 992 keV resonance. Lines are fits to the data (see text).

in our reaction and consequently no large electron screening. The height of resonance fit is equal to the integrated cross section, which is nearly equal to the product of the resonance width and height. Since cross-section strongly depends on the Coulomb barrier effect (at sub-Coulomb energies), one might expect noticable difference in resonance heights at low energies. In resonant $^{58}Ni(p,p'\gamma)^{58}Ni$ reaction the proton must penetrate Coulomb barrier two times, firstly in the entrance channel it will penetrate the Coulomb barrier of ^{58}Ni (with incident energy E_p) forming a compound ^{59}Cu nucleus which will consequently decay by emitting a proton and a γ ray. In order to leave the ^{59}Cu nucleus, the proton has to again penetrate Coulomb barrier (with energy $E_p - E_\gamma$). Therefore, we expected a large difference in resonance heights for metalic and insulator target. The heights of resonance at $E_p = 2935$ keV populating the first excited state in ^{58}Ni at 1454 keV differed only by the differences in stoichiometry and stopping power for nickel metal and insulator targets, implying no large electron screening in this reaction. Results were the same for resonances in $^{58}Ni(p,\gamma)^{59}Cu$ reaction at $E_p = 1424$ keV and $E_p = 1844$ keV. On the other hand, results obtained for population of the first excited state in ^{64}Cu at 159 keV [7] produced in the $^{64}Ni(p,n\gamma)^{64}Cu$ reaction show significantly higher cross section for the metallic nickel compared to the insulator target indicating a large electron screening.

The measured number of γ rays, N_γ in the case of a thin target is according to the definition of the cross section:

$$N_\gamma = \varepsilon N_p \frac{\rho N_A x}{M} \sigma \tag{3.2}$$

where ε is the γ-ray detection efficiency, N_p the number of incident protons, N_A Avogardo's number and σ, x, and M the density, thickness and molar mass of the target, respectively. The thick target proton particle yields had to be calculated by transforming eq.(3.2) into a differential form and integrating over energies from threshold energy E_{th} to the beam energy E_p:

$$N_\gamma = \varepsilon N_p \frac{\rho N_A}{M} \int_{E_{th}}^{E_p} \frac{\sigma(E)}{\mathrm{d}E_0/\mathrm{d}x} \mathrm{d}E_0 \tag{3.3}$$

The stopping power $\mathrm{dE_0/dx}$ was calculated using SRIM [10]. Gamma ray efficiency was determined using a calibrated Eu^{152} source. We assumed that there is no electron screening in NiO [2] and took the cross section for populating the 159 keV state in ^{64}Cu from ref. [11] from threshold energy at 2.66 MeV to 2.71 MeV. Above this energy the cross section from ref. [11] did not fit our data well. Therefore, we took the cross section for the $^{64}\mathrm{Ni(p,n)}^{64}\mathrm{Cu}$ reaction from [12] from 2.71 MeV to the end of our energy range. We scaled this cross section to make the combined cross section continuous at 2.71 MeV. With the combined cross section we fitted our data on NiO target and got good agreement (see fig.3). We compared the γ-ray yields of metallic target with the γ-ray yields of the insulator for all the studied γ rays in (p,γ) and $(\mathrm{p},\mathrm{p}'\gamma)$ reactions. An average value $\alpha = N_\gamma^{\mathrm{Ni}}/N_\gamma^{\mathrm{NiO}}$ has been then determined. In this way, we got yield enhancement factor, α, not influenced by electron screening. The energy dependence of the stopping powers [10] of Ni and NiO is identical within 1% in our energy range leading to a constant $\alpha = 1.42$ because of the different stoichiometries. However, we must stress that our fitted α was slightly larger than we expected, $\alpha = 1.510(9)$. A similar difference was also observed in ref. [5] for V and $\mathrm{VO_2}$. Due to the the reaction threshold, the electron screening could not be taken into account in the usual way by replacing $\sigma(E)$ with $\sigma(E+U_e)$. Instead, the electron screening was taken into account by replacing $\sigma(E)$ in the case of the insulator with $p(U_e)\sigma(E)$ in the case of metallic target where $p(U_e)$ is the ratio of Coulomb barrier pentrabilities (given by Gamow factors) for metalic nickel and nickel oxide:

$$p(U_e) = \frac{e^{(-2\pi\eta(E+U_e))}}{e^{(-2\pi\eta(E))}} = \frac{e^{(-2\pi\alpha Z_1 Z_2 c\sqrt{\frac{\mu}{2(E+U_e)}})}}{e^{(-2\pi\alpha Z_1 Z_2 c\sqrt{\frac{\mu}{2E}})}} \tag{3.4}$$

Using Taylor expansion for $U_e/E \ll 1$ we get:

$$p(U_e) = e^{\pi\alpha Z_1 Z_2 \sqrt{\frac{\mu c^2}{2E}} \cdot U_e/E} \tag{3.5}$$

The electron screening potential was fitted to the data using $N_\gamma^{\mathrm{Ni}} = \alpha N_\gamma^{\mathrm{NiO}}(E+U_e)$. Experimentally obtained α was used for fitting. A value of $U_e = 44$ keV was obtained from one-parameter least-sqares fit to the data. Statistical error of the fit is 2.9 keV while systematic error due to uncertainty in the experimentaly obtained α is 2.1 keV and due to uncertainty of self absorption of the 159 keV γ-ray in the target is 17.3 keV giving the systematic error of 17.4 keV. The combined error is 18 keV. Additional sources of systematic error might be found in ε and the cross section for $^{64}\mathrm{Ni(p,n}\gamma)^{64}\mathrm{Cu}$ reaction but these are much smaller than above quoted errors. It must be stressed that we have not determined U_e by the above procedure, since we assumed no screening in NiO. Instead we measured $U_D = U_e - U_A$, which is the difference between screening potentials in Ni and NiO. For further explanation see ref. [5]. The results are shown in fig.3 for Ni metal and NiO insulator, where the solid curve represents the fit due to $U_D = 44$ keV for Ni and dotted curve the fit with $U_A = 0$ keV for NiO.

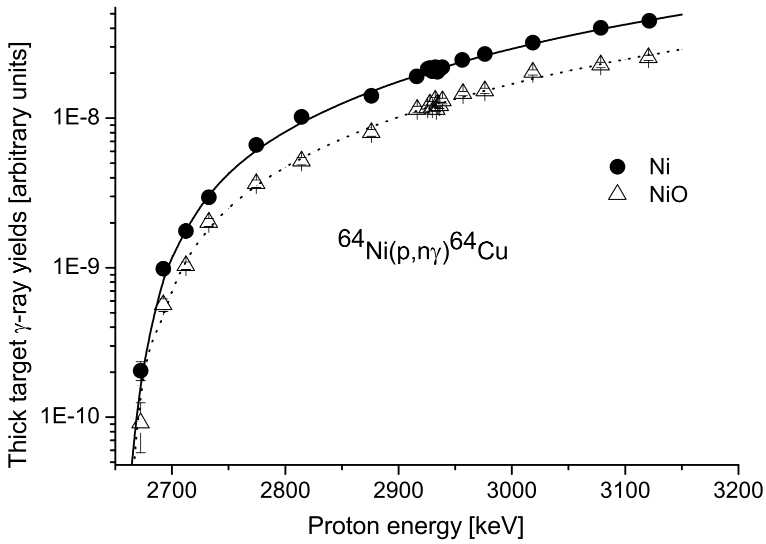

Figure 3: Thick target γ-ray yields of the 159 keV γ ray from ^{64}Ni$(\mathrm{p,n}\gamma)^{64}$Cu reaction for Ni and NiO targets. Lines are fits to the data.

4. Conclusions

Kettner et al. [5] observed a narrow resonance in the $^{176}\mathrm{Lu(p,n)}^{176}$Hf reaction at $E_p = 810$ keV and reported lowering of this resonance energy by $U_D = 32 \pm 2$ keV and $U_D = 33 \pm 2$ keV for the Lu metal and PdV$_{10\%}$ alloy respectively, relative to the insulator. The sizable resonance shifts were interpreted as a demonstration of the acceleration effect by the valence electrons.

We have not observed shifts in resonance energy for metallic targets relative to insulator ones neither for Al nor Ni target. Our results seem to indicate that large electron screening is present only in $(\mathrm{p,n})$ reactions and not in the relatively slower (p,γ) and $(\mathrm{p,p'}\gamma)$ reactions. The main difference between these reactions is the time scale on which they occur. While a neutron can be emitted from a compound nucleus relatively quickly, (comparable to the reaction time of the order $10^{-22}s$) the half lives of the resonances studied are several orders of magnitude larger, about $10^{-17}s$ [8]. In a very similar $(\mathrm{p,n})$ reaction in vanadium, which has only three protons less than nickel, an electron screening potential of $U_D = 27 \pm 9$ keV was measured [5]. Due to the prediction [5] of the linear dependance of U_D on target Z, we expected U_D in Ni to be around 30 keV. Our expectation was corroborated by the measurement of $U_D = 32 \pm 2$ keV in lutetium. Suprisingly, our result of $U_D = 44 \pm 18$ keV is substantially higher than expected. Although the large error bars still allow U_D to be the same in Ni and V, our screening potential for Ni is actually the highest screening potential ever measured. Due to its suprising nature, our result will require a lot of scrutiny in the future, but it anyway points to a conclusion that electron screening dependence on Z is not simply linear. It seems that electron screening depends on the target material in a more complicated way, similar to the case of implanted deuterons and the d(d,p)t reaction.

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