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Electron screening in the ^{2}H(^{19}F,p)^{20}F reaction

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Abstract. The dependence of electron screening potential on the position of the target nucleus in host-material lattice was investigated by measuring the rate of the ^{2}H(^{19}F,p)^{20}F reaction in zirconium, titanium and palladium targets containing deuterium. Very different values of the screening potential were measured, thus showing the link with the valence electron densities around deuterium nuclei.

1. Introduction

When the energy of the incident beam in the center-of-mass system is far below the Coulomb barrier, the only way the reaction between nuclei can happen is by tunneling. In this case, since the projectile has to penetrate through the huge potential barrier, the reaction rate is very low and sensitive to electronic properties of target materials. Knowing precise reaction rates at these energies is crucial for understanding nucleosynthesis and stellar processes. However, accurate measurements of nuclear reactions between charged particles at thermonuclear energies show an unexpectedly large enhancement of the cross section that is attributed to the presence of atomic electrons. During the reaction, electrons screen the nuclear charge, effectively reducing the repulsive Coulomb barrier between interacting particles and as a result, the probability for the nuclear reaction is increased. The screening effect dominates reaction rates at thermonuclear energies, but at higher energies its contribution is negligible.

The enhancement factor f is defined as the ratio of the screened (σ_s) and bare-nucleus (σ_b) cross sections:

$$f = \frac{\sigma_s}{\sigma_b} = \frac{\sigma(E + U_e)}{\sigma(E)}, \tag{1}$$

where E represents the energy in the center of mass system and U_e is the electron screening potential [1]. To simplify the analysis, when nuclear reactions are studied at low energies, the cross section (σ) is usually defined using the astrophysical $S(E)$-factor, which in the case of non-resonant reactions varies smoothly with energy [2]:

$$\sigma(E) = \frac{S(E)}{E} exp(-2\pi\eta). \tag{2}$$

Here η is the Sommerfeld parameter.

Moreover, experimental results (see Refs. [3, 4, 5, 6, 7, 8, 9, 10] and refs. therein) have reported extremely high values for the electron screening potential, with amplitudes exceeding the theoretical values predicted by the available models (see Refs. [1, 3, 11, 12, 13, 14] and refs. therein) in some cases for more than an order of magnitude. Despite the large quantity of experimental results collected so far, the problem remains unsolved to this day.

2. Experiment

The experimental study of the electron screening effect was performed using the 2 MV Tandetron accelerator at Jožef Stefan Institute (JSI). The dependence of the electron screening potential on the target host lattice structure was investigated by measuring the rate of the ^{2}H(^{19}F,p)^{20}F reaction in thick zirconium, two thick and one thin titanium and two different thick deuterium-containing palladium targets. The experimental set-up consisted of a High-Purity Germanium (HPGe) detector positioned 57 mm from the target at an angle of 135° with respect to the ^{19}F ion beam direction. The intrinsic detector efficiency was 53% relative to a 3" by 3" NaI detector and it had an efficiency of 0.6% and a resolution of 2.2 keV at the 1.3 MeV ^{60}Co peak. The HPGe detector efficiency at higher energies was evaluated using a Monte Carlo simulation provided by the detector manufacturer (Canberra). The detector was used to measure the γ-rays with an energy of 1634 keV (emitted in the ^{20}Ne de-excitation to the ground state from ^{20}F β^- decay) [15]. Targets were mounted on a massive copper holder in order to effectively prevent substantial heating of the targets during the experiment and positioned in a high vacuum chamber perpendicularly to the beam direction. The ^{19}F ion beam with currents of about 0.5 μA was used to study the ^{19}F+d reaction in an energy range between 3.089 and 9.200 MeV. The numbers of incident ions were deduced by measuring the charge collected on the electrically isolated target chamber. During the experiment, we monitored deuterium loss in all targets by repeatedly measuring yields at the beam energy of 7.671 MeV before and after each measurement at other energies. Almost negligible changes in deuterium concentration were detected in Zr and Ti targets. However, Pd targets showed a loss of deuterium during all measurements. In order to correct for the deuterium loss, we normalized the detected yields for a given beam energy to the average of the two control measurements.

As the targets we chose Zr, Ti and Pd since these metals have the ability to absorb large volumetric quantities of deuterium. The Zr target was a 0.25 mm thick 99.8 % pure foil purchased at Chempur. The first Ti target was a 1 mm thick 99 % pure foil purchased at Goodfellow. The second Ti target was made by pressing the TiD powder to a thickness of 1 mm into a cylindrical hole (14 mm diameter and 1 mm depth) in 2 mm thick Cu backing. The third Ti target was a 330 nm thick Ti evaporated on Ta backing. The first Pd target was 100 μm thick soft Pd foil purchased at Chempur and the second one was a 100 μm thick hard Pd foil produced according to our specifications at Zlatarna Celje. It was cold rolled from a thickness of about 2.5 mm to 0.1 mm. This foil was much less flexible than Chempur's one. Purities of both foils were above 99.9%. In order to prepare the targets for electron screening studies, Zr and Ti foils were implanted using Tectra IonEtch ion gun. The foils were bombarded for about 24 h with the deuterium beam accelerated by an extraction voltage of 3.5 kV. The beam current was 400 μA. During implantation, the targets were also mounted on a massive copper holder. Due to the deuterium diffusion, foils had high deuterium concentrations at depths much higher than the implantation depth at 3.5 keV (41 nm [16]). Pd foils were loaded by leaving the palladium in

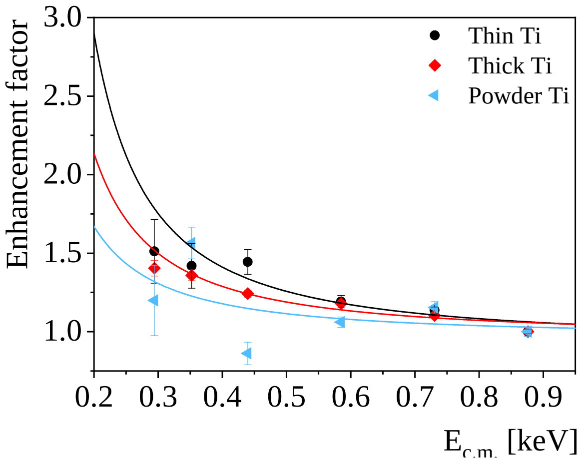

Figure 1. Integrated enhancement factors as a function of the fluorine beam energy in the center-of-mass system for the $^{2}H(^{19}F,p)^{20}F$ reaction obtained in three Ti targets. Points represent experimental data and the solid lines represent least-squares fits to the data.

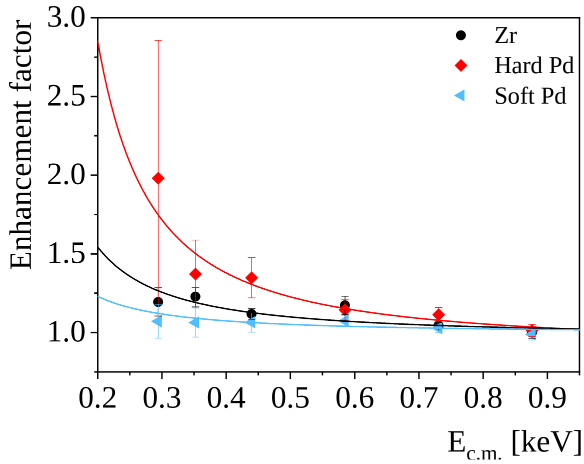

Figure 2. Integrated enhancement factors as a function of the fluorine beam energy in the center-of-mass system for the $^{2}H(^{19}F,p)^{20}F$ reaction obtained in the Zr and two Pd targets. Points represent experimental data and the solid lines represent least-squares fits to the data.

deuterium gas at the pressure of 1 bar and temperature of 24°C for 24 hours. In the soft Pd foil, maximum concentrations of 70% of H(D) per metallic atom were achieved. This is consistent with the limit of hydrogen absorption at normal pressures [17]. However, the hard Pd foil could be loaded only up to 47% of H(D) per metallic atom.

The deuterium depth distribution in the targets was determined with the Nuclear Reaction Analysis (NRA) technique. For this purpose, high-energy protons emitted in the $^{2}H(^{3}He,p)^{4}He$ reaction were measured at six ^{3}He energies, in an energy region from 0.629 to 4.297 MeV. The deuterium depth profiles were obtained by fitting the NRA spectra using the SIMNRA code [18]. The depth profiles showed uniform deuterium concentrations.

3. Results

In order to calculate enhancement factors from our experimental data, we need the cross section which is not influenced by screening effect. However, there is no available cross section in the literature for the ^{19}F+d reaction in the energy region that we studied. So, we measured the same reaction, but this time in forward kinematics in order to determine the nuclear cross section that is not influenced by electron screening. This was possible since in the forward kinematics we never observed a large electron screening effect [19, 20], except for the p+d reaction. This measurement was performed Max Planck Institute for Plasma Physics in Garching. We employed the 3MV accelerator in order to study the reaction in an energy range from E_d=(303 to 998 keV) on thin CaF_2 targets positioned perpendicularly to the beam. The same HPGe detector as we used for the experiments in inverse kinematics, was positioned 4.82 mm from the target at an angle of 0° with respect to the ion beam direction to measure the 1634 keV γ-ray yield. More details on the used experimental technique and the cross section can be found in Ref. [21]. By fitting the experimental data obtained in this experiment, we obtained the astrophysical S-factor (the center-of-mass energy E is given in MeV.):

$$S(E)_{^{19}F+d} = 19380 - 4596E - 3218E^2\,[MeVb]\,, \quad (3)$$

that we used to calculate the enhancement factors and screening potentials (employing Eq. 1 and 2) in our targets.

Resulting integrated enhancement factors as a function of fluorine beam energy in the center-of-mass system are given in the Fig. 1 and 2. The obtained screening potentials for each target are listed in Table 1.

Table 1. The electron screening potentials U_e measured in the ^{2}H(^{19}F,p)^{20}F reaction in six different targets in comparison with the predicted screening potential given by the adiabatic model.

Target	U_e [keV]
Zr	7.0±1.9
Soft Pd	3.2±1.9
Hard Pd	18.2±3.3
Thin Ti	18.0±4.9
Thick Ti	12.3±2.8
Powder Ti	8.4±9.2
U_{ad} [keV]	2.19

4. Conclusions

The electron screening effect was studied in the ^{2}H(^{19}F,p)^{20}F nuclear reaction on six different targets containing deuterium. In all targets we measured different values of the electron screening potentials (see Table 1). In our powder Ti target we did not detect electron screening different from zero, within the error bars. In the soft Pd target the measured screening potential was in agreement with the theoretical value (U_{ad}=2.19 keV). In the remaining four targets we measured high electron screening potentials, that were up to an order of magnitude above the theoretical model. Contrary to the predictions given by the available theoretical models, in each target we measured a different screening potential for the same nuclear reaction. From this we can conclude that the screening effect is not linked to the static electron densities around interacting nuclei and that probably, a dynamic approach should be applied. Our findings clearly show that electron screening is strongly linked to the electron densities at locations of the target nuclei in the metallic lattice, as it can be seen in Ref. [21]. However, in order to understand this link, additional investigations are required.

References

[1] H. J. Assenbaum et al. *Z. Phys. A: At. Nucl.*, 327:461, 1987.
[2] C. Iliadis. *Nuclear Physics of Stars - Second, Revised and Enlarged Edition*, Wiley-VCH, Weinheim, 2015.
[3] K. Czerski et al. *Europhys. Lett.*, 68:363, 2004.
[4] J. Kasagi et al. *J. Phys. Soc. Jpn.*, 73:608, 2004.
[5] F. Raiola et al. *J. Phys., G*, 31:1141, 2005.
[6] J. Cruz et al. *Phys. Lett., B*, 624:181, 2005.
[7] T. S. Wang et al. *J. Phys. G: Nucl. Part. Phys.*, 34:2255, 2007.
[8] A. Huke et al. *Phys. Rev. C*, 78:015803, 2008.
[9] M. Lipoglavšek et al. *Eur. Phys. J., A*, 44:71, 2010.
[10] A. Cvetinović et al. *Phys. Rev., C*, 92:065801, 2015.
[11] E. E. Salpeter. *Austr. J. Phys.*, 7:373, 1954.
[12] S. Ichimaru. *Rev. Mod. Phys.*, 65:255, 1993.
[13] T. D. Shoppa et al. *Phys. Rev. C*, 48:837, 1993.
[14] C. Rolfs and W. S. Rodney. *Cauldrons in the Cosmos, University of Chicago Press, Chicago*, 1988.
[15] D. R. Tilley et al. *Nucl. Phys. A*, 636:249, 1998.
[16] J. F. Ziegler et al. *The Stopping and Range of Ions in Matter(Lulu Press Co., Morrisville, NC, 2008)*, www.srim.org.

[17] G. Alefeld and J. Völkl. *Hydrogen in metals II, Application-oriented properties*, 29:p. 81, 1978.
[18] M. Mayer. *"SIMNRA User's Guide", Report IPP 9/113, Max-Planck-Institut fr Plasmaphysik, Garching, Germany, 1997*, page https://mam.home.ipp.mpg.de.
[19] M. Lipoglavšek et al. *Phys. Lett., B*, 773:553, 2017.
[20] J. Vesić et al. *Eur. Phys. J., A*, 50:153, 2014.
[21] A. Cvetinovic et al. *Physics Letters B*, 838:137684, 2023.