Vol. 40 (2009) ACTA PHYSICA POLONICA B No 3

DYNAMIC ELECTRON SCREENING IN NUCLEAR REACTIONS AND ALPHA DECAYS*

K. Czerski[a], P. Heide[b], A. Huke[b], A.I. Kilić[a], I. Kulesza[a]
N. Targosz-Ślęczka[a]

[a]Institute of Physics, University of Szczecin, 70-451 Szczecin, Poland
[b]Institut für Optik und Atomare Physik, Technische Universität Berlin
10623 Berlin, Germany

(Received December 18, 2008)

Electron screening of the Coulomb barrier between reacting nuclei leads to an exponential-like enhancement of nuclear cross sections for lowering projectile energies. Recently, this effect has been demonstrated by many groups for the ^{2}H$(d,p)^3$H and ^{2}H$(d,n)^3$He reactions taking place in metallic environments. The experimental results show a much stronger effect for metals than for gaseous or insulator targets. Similar effects are also expected for radioactive alpha decays. Based on experimental and theoretical results achieved for nuclear reactions and a dynamic approach to the electron screening in the electron gas, an increase of alpha-decay constants of order of a few per cent is anticipated for metallic environments.

PACS numbers: 25.45.–z, 26.60.Pj, 26.20.+f, 23.90.+w

1. Introduction

First experimental investigations of the enhanced electron screening effect in the $d+d$ fusion reactions in metallic environments have been motivated by its importance for dense astrophysical plasmas [1] where the screening of the Coulomb barrier can lead to an increase of nuclear reactions rates by many orders of magnitude. From the theoretical point of view the deuterized metals can be treated as a strongly coupled plasma and therefore provide a unique possibility for experimental studies of nuclear pycnoreactions under terrestrial conditions. The theoretical calculations [2,3] based on the self-consistent dielectric function theory can qualitatively explain the target material dependence of the experimentally determined screening energies, however, the absolute theoretical values are underestimated by a factor

* Presented at the Zakopane Conference on Nuclear Physics, September 1–7, 2008, Zakopane, Poland.

of two (see Fig. 1). The reason for this discrepancy is still unknown. Large screening energies in metallic environments have been also demonstrated by other groups [4,5] and for other reactions [6,7]. Some differences between experimental results obtained by different groups probably result from a target surface contamination or an inhomogeneous distribution of deuterons within the target [3]. Generally, the experimental screening energies reach about 300 eV for heavier metals and are much smaller (below 50 eV) for insulating materials.

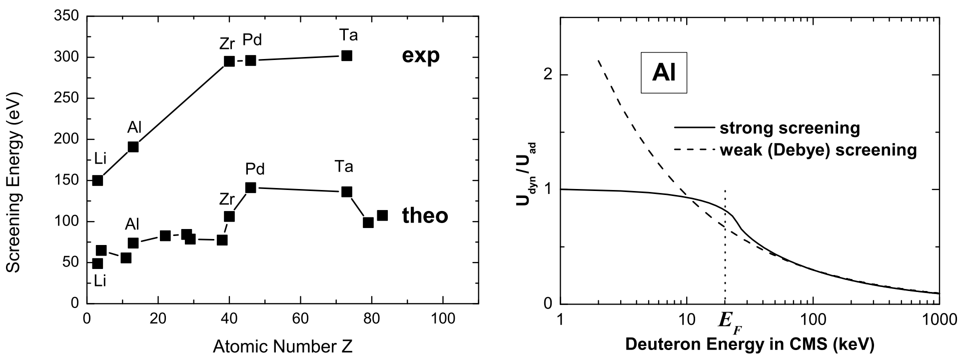

Fig. 1. Left: Experimental and theoretical screening energies. Right: Ratio of the dynamic and the adiabatic screening energies (the deuteron Fermi energy has been marked).

Since a probability of radioactive alpha decays is also determined by the tunneling effect through the Coulomb barrier one could expect a corresponding alteration of decay constants for insulating and metallic environments. Recently, it has been shown, however, that even large differences in screening energies for various host materials should not lead to significant changes of decay constants [8]. In the present work, we would like to show that a consequent application of a dynamic approach to the electron screening effect results in a measurable increase of alpha-decay constants for metallic environments.

2. Electron screening in nuclear reactions

The electron screening effect observed in the $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction in metallic environments results in an exponential-like increase of the total cross section for deuteron energies below 20 keV, which can be expressed as follows:

$$f = \frac{\sigma_{\mathrm{scr}}(E)}{\sigma_{\mathrm{bare}}(E)} \approx \frac{P(E+U_e)}{P(E)} = \frac{\sqrt{\frac{E_{\mathrm{G}}}{E+U_e}}\ \exp\left(-\sqrt{\frac{E_{\mathrm{G}}}{E+U_e}}\right)}{\sqrt{\frac{E_{\mathrm{G}}}{E}}\ \exp\left(-\sqrt{\frac{E_{\mathrm{G}}}{E}}\right)}\,. \qquad (1)$$

Here, the enhancement factor f is the ratio of the corresponding penetration factors for screened and bare nuclei. The screening energy U_e describes the reduction of the Coulomb barrier and can be effectively treated as an increase of the center mass energy $E \rightarrow E+U_e$. The Gamow energy is given by $E_{\mathrm{G}} = (\frac{4\pi Ze^2}{\hbar c})^2(\mu/2)$ where μ denotes the reduced mass. Our experimental values of U_e are presented in Fig. 1 together with the theoretical screening energies calculated within the self-consistent dielectric function theory [2,3]. The screening energies moderately increase with the atomic number of host atoms reaching for heavier nuclei the value of about 300 eV. The experimental target material dependence agrees with theoretical calculations. However, the experimental screening energies are larger by a factor of about 2 compared to the theoretical values.

The dielectric function theory does not include any dynamic effects of moving ions in the electron gas and assumes that the velocity of ions is lower than the Fermi velocity. For velocities higher than the Fermi velocity the electrons are not able to follow the ions and the electron screening gets weaker corresponding to the classical limit of a weakly coupled plasma (Debye–Hückel limit). In that limit, the screening energy is inversely proportional to the square root of the kinetic energy or equivalently of the plasma temperature ($U_e \sim 1/\sqrt{E}$). Both limits can be described using an analytical formula for the velocity dependence of the screening energy [3,9]:

$$U_{\mathrm{dyn}}^2 = U_{\mathrm{ad}}^2 \left(\frac{1}{2} + \frac{\nu_{\mathrm{F}}^2 - \nu^2}{4\nu_{\mathrm{F}}\nu} \ln \left| \frac{\nu + \nu_{\mathrm{F}}}{\nu - \nu_{\mathrm{F}}} \right| \right) , \tag{2}$$

where U_{dyn} and U_{ad} denote dynamic and adiabatic screening energies, respectively. The Fermi velocity ν_{F} depends on the valence electron density and therefore is characteristic for the target material. The above relation calculated for the Al environment is presented in Fig. 1. The screening energy below the Fermi velocity does not change significantly supporting application of the adiabatic approximation for nuclear reactions at low projectile energies.

3. Electron screening in alpha decay

In alpha decays, alpha particles have to tunnel the Coulomb barrier in opposite direction compared to low-energy nuclear reactions. Thus, the decay constant of alpha-decay is proportional to the penetration factor through the Coulomb barrier and consequently depends on the electron screening effect. On the other hand, the electron screening reduces not only the Coulomb barrier between interacting nuclei but also influences the repulsion Coulomb potential inside the nucleus. The latter leads, in the case of an alpha decay, to lowering the nuclear level from which the alpha decay precedes.

If the "internal" and "external" screening energies have the same values, the penetration coefficient and the decay constant do not change at all.

However, the kinetic energy of the alpha particle inside the nucleus is very large (of order 100 MeV) compared to that outside the nucleus (4–10 MeV). Therefore, application of Eq. (2) to the alpha decay provides estimation for the dynamic screening energy in the internal region of about 0.01 $U_{\rm ad}$ and in the external region of about 0.1 $U_{\rm ad}$. Consequently, the "internal" screening can be neglected in the first approximation and the penetration coefficient will be only influenced by a reduction of the Coulomb barrier in the external nuclear region. For an estimation of the adiabatic screening energy in metallic environments, the experimental values obtained for the $d+d$ reactions can be adopted and scaled according to the prescription given in [11,12].

An increase of the alpha-decay probability due to the screening effect can be calculate by means of the enhancement factor defined as a ratio of penetration factors according to Eq. (2). The results obtained for the alpha decay of uranium in different host materials are presented in Fig. 2. For the alpha decay of ^{238}U with the energy 4.27 MeV, the decay constant in metallic environment should be larger than that for an insulating host material by about 3%.

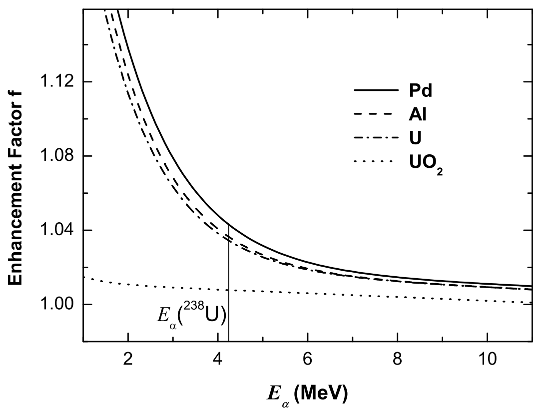

Fig. 2. Enhancement factor for the uranium alpha decay in different host materials.

4. Conclusions

Utilization of the screening energies determined for the deuteron fusion reactions and the dynamic screening approach leads to an increase of the alpha decay probability in metallic environments of a few per cent compared to an insulator. The predicted enhancement is of the same order as recently experimentally found for ^{221}Fr [10]. Thus, the alpha decay experiments can provide an independent test of unexpectedly large screening energies observed in deuteron fusion reactions and should help us to understand this effect theoretically.

REFERENCES

[1] K. Czerski, A. Huke, A. Biller, P. Heide, M. Hoeft, G. Ruprecht, *Europhys. Lett.* **54**, 449 (2001).

[2] K. Czerski, A. Huke, P. Heide, G. Ruprecht, *Europhys. Lett.* **68**, 363 (2004).

[3] A. Huke, K. Czerski, P. Heide, G. Ruprecht, N. Targosz, W. Żebrowski, *Phys. Rev.* **C78**, 015803 (2008).

[4] J. Kasagi *et al., J. Phys. Soc. Jpn.* **71**, 2281 (2002).

[5] F. Raiola *et al., Eur. Phys. J.* **A13**, 377 (2002).

[6] J. Kasagi *et al., J. Phys. Soc. Jpn.* **73**, 608 (2004).

[7] J. Cruz *et al., Phys. Lett.* **B624**, 181 (2005).

[8] N.T. Zinner, *Nucl. Phys.* **A781**, 81 (2007).

[9] K. Czerski, A. Huke, P. Heide, G. Ruprecht, *Eur. Phys. J.* **A27**, 83 (2006).

[10] H.B. Jeppesen *et al., Eur. Phys. J.* **A32**, 31 (2007).