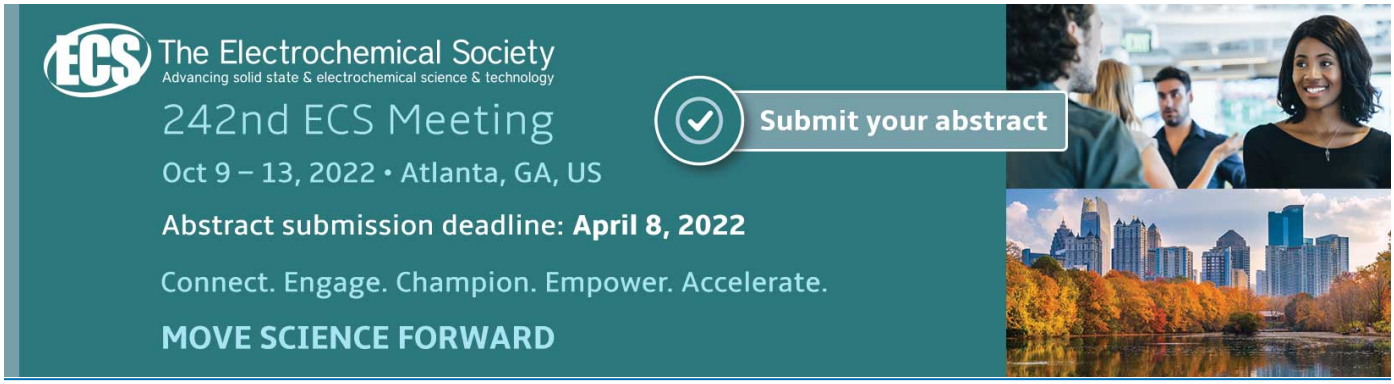
Electron screening effects in nuclear reactions: still an unsolved problem



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Electron screening effects in nuclear reactions: still an unsolved problem

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Abstract. Electron screening for nuclear reactions in metals plays an unexpected and important role in enhancing reaction cross sections in the ultra-low energy region. Even though there are still some discrepancies between experimental data from different authors, the enhanced screening effect in metallic environments is well established, and attributed to the quasi-free valence electrons in the metals. However, there is still no solid theory which can describe quantitatively the observed enhancements. In the present work, experimental and theoretical results obtained so far will be overviewed, and a proposal to improve our knowledge on this subject.

1. Introduction

Electron screening effects in charged particle induced nuclear reactions have been investigated for many years. Usually, the observed effect is very small, below 1%, due to the huge difference on the interaction energies; i.e., eV in an atomic system, versus MeV in a nuclear system. However, a surprisingly large effect has been measured when studying the D(d,p)T reaction in metallic environments at ultra-low energies, which stirred up attention more strongly on the influence of the environment where nuclear reactions take place.

2. Overview of D+D reaction in metallic environment

With the cold fusion claim in 1989, the enhancement of the reaction rates of the D+D reaction in metal host has been intentionally searched for by several authors. Yuki *et al* [1] measured the reaction rates at energies down to 2.5 keV, obtaining the first clear evidence that the fusion reaction rate can be enhanced in the metal environment during keV deuteron bombardment.

Such a large screening energy of the D+D reaction was found also in other materials by other groups. Czersky *et al* [2] has reported enhanced screening energy of the D+D reactions in Ta; it was about 300 eV, and was confirmed by Raiola *et al* [3]. Also Raiola *et al* [4] have carried out a systematic measurement of the screening potentials of the D+D reaction for a wide range of host materials including metals, semiconductors and insulators, in a total of 54 elements, clearly showing that the large screening energies ($U_e > 150$ eV) were obtained only for metals, while insulators and semiconductors show screening energies similar to the one obtained for a D_2 gas target ($U_e = 25 \pm 5$ eV [5]), being this last value in agreement with atomic physics models.

Kasagi [6] and Huke *et al* [7], reported an enhanced screening energy of the D+D reactions in different metals, showing discrepancies with Raiola *et al* [4] values. Huke *et al* claim that the differencies between their results and Raiola *et al* ones would arise from major experimental pitfalls in [4], namelly oxygen and/or carbon build-up on the target surface and unstable deuteron density profiles. For the carbon contamination, it is known that carbon can achive high deuteron densities but it does not show the enhanced electron screening effect [4]. So, a thin deuterated carbon layer could, in fact, simulate a screening enhancement due to its high capacity of retaining deuterium. However, taking into account that for each deuterium implanted target, data taking lasts several days, continuous carbon build-up would completely supress any enhancement after a few hours.

With respect to oxygen contamination, metal oxides show low deuterium solubilities, which according to [7] would promote an unstable deuterium depth profile that could simulate the exponential like screening enhancement. Once again, for long data taking, oxygen build-up would result on a thick oxide layer at the target surface. The presence of oxygen was investigated by Raiola *et al* [4] by Rutherford Backscattering Spectroscopy (RBS) of deuterated metal targets, and was below the detection limit which is quite low as can be inferred from the simulation of a RBS spectrum of ^{4}He particles with $E_{lab} = 3038$ keV [^{16}O$(\alpha,\alpha)^{16}$O resonance - figure 1] hitting a 15 nm thick ($\approx$ 30 monolayers) TiO_2 layer on top of bulk Ti target. The simulation of the ^{4}He backscattered at 150° was done using the NDF code [8], and clearly shows the oxygen peak on top of the Ti barrier (figure 2). These results show that the discrepancies between these two experimental groups should not come from target contamination by either carbon or oxygen.

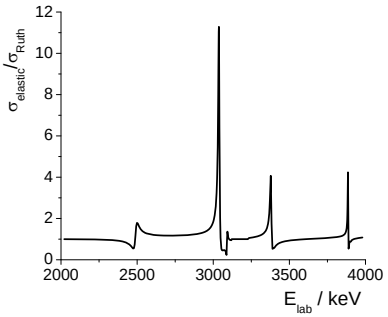

Figure 1. Non-Rutherford Elastic Scattering Cross Section of ^{4}He by ^{16}O - $\theta_{lab} = 150°$.

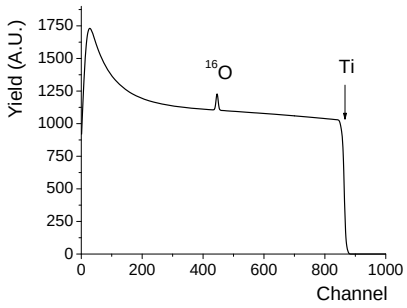

Figure 2. The 3038 keV ^{4}He backscattered at $\theta_{lab} = 150°$ simulated spectrum of a TiO_2 + Ti target.

Huke *et al* [7] claim that, as for the oxide, low deuteron density in the host metal also creates an unstable deuteron density profile that simulates a large screening, and, therefore, the correct screening is obtained only when the metal host is saturated with deuterium in a proportion close to 1:1. On the other hand, Kasagi [6] showed that there may be a relevant correlation: a large screening goes with a small deuteron density, suggesting the possibility of a dynamic screening mechanism during the deuteron bombardment and penetration into the host. However, for the ^{6}Li(p,α)^{3}He and ^{7}Li(p,α)^{4}He nuclear reactions, density dynamic effects can not explain the large screening energies obtained by Cruz *et al* [9], consistent with the D(d,p)T measurements, since the lithium mobility is orders of magnitude lower than for deuterium.

The screening energy for the deuteron in metals and non-metals was also theoretically studied. The simplest model is a static model since it is assumed an a priori electron distribution (at the Bohr radius) which does not change during the collision process. Here, the predicted electron

screening energy is 27 eV. A refinement is obtained by introducing dynamic models as the one proposed by Bracci *et al* [10] which considered changes in the electron cloud configuration due to the incoming projectile. Here the maximum screening energy is 36.6 eV. Both these models predict a constant U_e value independent of the host material, so they fail in explaining the large screening energies measured in metals. A more revolutionary approach came from Raiola *et al* [4], which applied the classical Debye screening theory in metals, in which the quasi-free valence electrons form a Debye sphere around the deuterons yielding large U_e values compatible with experimental data. This model is, however, very controversial since is not applicable for low temperatures and dense plasmas (solid states). Czersky *et al* [11] calculated the screening energy for the D+D reactions in metal by applying a dielectric functional method which allows to treat the electron screening as a static polarization of the metallic medium induced by the positively charged deuteron. Their results including the cohesion effects give clearly larger values for the screening energy as compared with [10], but still tipically less than half of the observed values.

3. PIXE, XPS and plasmons

Such a striking effect with origin on the metal electronic cloud should somehow be noticeable in other analytical techniques which are also sensitive to the electronic configuration of the material being analysed. In fact, Proton Induced X-ray Emission (PIXE) studies using very high resolution setups have measured that the K_α diagram and satellite line energies depend crucially on dynamic factors [beam energy and type of beam particle (proton or α particle)] and static factors (the chemical state of the compound) [12]. Interpretation of these results is still an open question, but it has been proposed very recently by Reis *et al* [13] that plasmons can help giving an interpretation of these results. On the other hand, plasmons in metals play a well known effect in X-ray Photoelectron Spectroscopy (XPS), as the outgoing photoelectron may suffer quantized energy losses or energy gains before escaping out of the material. The effects that plasmons may have on the screening enhancement are still under study and we hope to present new results soon.

4. Conclusions

Low energy D+D and ^{6,7}Li + p reactions are greatly enhanced when the reactions occurs in a metal environment. The mechanism of the enhancement is not fully understood, even though it is well established that it is due to the quasi-free valence electrons of the metal. These arguments motivate further studies. Screening due to plasmons is one of the studies which is being carried out.

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