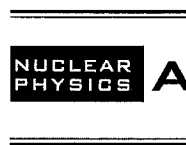




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Enhanced electron screening in $d(d,p)t$ for deuterated metals: a possible classical explanation

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The electron screening effect in the $d(d,p)t$ reaction has been studied for several deuterated metals and insulators/semiconductors. As compared to measurements performed with a gaseous D_2 target, a large effect has been observed in all metals except in the noble metals Cu, Ag, and Au. In contrast, a comparatively small effect is found for the insulators and semiconductors. An explanation of the large effect in metals is possibly provided by the classical plasma screening of Debye applied to the quasi-free metallic electrons.

1. INTRODUCTION

In the extrapolation of the cross section $\sigma(E)$ of a charged-particle- induced nuclear reaction to astrophysical energies one uses the equation [1]

$$\sigma(E) = S(E)E^{-1} \exp(-2\pi\eta(E)) \quad (1)$$

where $\eta(E)$ is the Sommerfeld parameter and $S(E)$ the astrophysical S- factor. The equation assumes that the Coulomb potential of the target nucleus and projectile is that resulting from bare nuclei. However, for nuclear reactions studied in the laboratory, the target nuclei and the projectiles are usually in the form of neutral atoms or molecules

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and ions, respectively. The electron clouds surrounding the interacting nuclides act as a screening potential: the projectile effectively sees a reduced Coulomb barrier, both in height and radial extension. This, in turn, leads to a higher cross section for the screened nuclei, $\sigma_s(E)$, than would be the case for bare nuclei, $\sigma_b(E)$. There is an enhancement factor [2],

$$f_{lab}(E) = \sigma_s(E)/\sigma_b(E) = \sigma_b(E + U_e)/\sigma_b(E) \quad (2)$$

$$= E(E + U_e)^{-1} \exp(-2\pi\eta(E + U_e) + 2\pi\eta(E)), \quad \text{for } S(E + U_e) \approx S(E) \quad (3)$$

$$= E(E + U_e)^{-1} \exp(\pi\eta(E) U_e/E), \quad \text{for } U_e/E \leq 0.1 \quad (4)$$

where U_e is an electron screening potential energy. In the adiabatic limit, U_e can be calculated from the difference in atomic binding energies between the compound atom and the projectile plus target atoms of the entrance channel [3]. For the $d(d, p)t$ reaction the adiabatic limit is $U_{ad} = 39$ eV for neutral atoms and 52 eV, if the projectile is a positively charged ion at the moment of interaction.

The screening effect in $d(d, p)t$ has been studied for the deuterated metals Al, Zr, and Ta [4], where the resulting $S(E)$ data show an exponential enhancement according to equation (3). However, the extracted U_e values ($U_e = 190 \pm 15$, 297 ± 8 , and 322 ± 15 eV for Al, Zr, and Ta, respectively) are about one order of magnitude larger than the value found in a gas-target experiment: $U_e = 25 \pm 5$ eV [5]. An anomalous enhancement was reported earlier [6] for deuterated Pd ($U_e = 250 \pm 15$ eV) and a deuterated Au/Pd/PdO multilayer ($U_e = 601 \pm 23$ eV), while deuterated Ti and Au exhibited a normal (“gaseous”) enhancement: $U_e = 36 \pm 11$ and 23 ± 11 eV, respectively. Our study of deuterated Ta led to $U_e = 340 \pm 14$ eV [7], [8] confirming the previous observation [4]. In a recent letter we reported on results for the other 5 metals studied previously as well as 23 additional metals and 5 insulators/semiconductors [8].

The experimental procedures have been described [7] and followed for each sample. Rutherford-Backscattering-Analysis of the samples exhibited no detectable surface contamination except for Al which revealed an Al_2O_3 surface layer with a thickness of about 150 monolayers. Since this thickness is larger than the energy step in our differentiation method (about 100 monolayers) the reported $U_e \leq 30$ eV result [8] corresponded to the case of an Al_2O_3 insulator and not to an Al metal (Table 1). Since Al oxides rapidly in air, we cleaned the Al surface in situ by Kr sputtering at 35 keV removing about 200 monolayers. After this cleaning the usual experimental procedure was carried out leading to $U_e = 520 \pm 50$ eV for the metal Al (Table 1). This surface cleaning by Kr sputtering was carried out subsequently as a first step in the experimental procedures, for each new sample as well as for several of the previously studied samples (Table 1).

Since the data for all metals with large U_e values could be fitted well with equation (3), the enhanced cross section is most likely due to electron effects of the environment of the target deuterons. In one experiment, we also used a deuterated Pt target and a 3He ion beam in combination with the reaction $d(^3He, p)^4He$ to study the associated electron screening effect. The result is $U_e = 730 \pm 60$ eV showing that high U_e values do not depend on the kind of ion species but are a feature of the deuterated metals. Group 14 of the periodic table shows an interesting property: the metals Sn and Pb have a high U_e value, while the semiconductors C, Si, and Ge have a low U_e value indicating that high U_e

Table 1
Summary of results^a

material ^b	U_e (eV) ^d	stoichiometry x^f	n_{eff}^d	n_{eff}^e (Hall)	
<i>Be</i> ^{cg}	180±40	12.3	0.18±0.08	0.21±0.04	
<i>Mg</i> ^{cg}	440±40	8.7	3.0±0.5	1.8±0.4	
<i>Al</i> ^{cg}	520±50	3.8	3.0±0.6	3.1±0.6	
<i>V</i>	350±30	16	1.0±0.2	1.1±0.2	
<i>Cr</i>	220±20	7.8	0.35±0.07	0.20±0.04	
<i>Mn</i>	350±40	3.7	0.90±0.19	0.81±0.16	
<i>Fe</i> ^{cg}	450±60	6.9	3.1±0.6	0.52±0.10	
<i>Co</i> ^{cg}	640±60	6.9	3.1±0.6	0.52±0.10	
<i>Ni</i>	450±80	26	1.3±0.3	1.1±0.2	
<i>Zn</i> ^{cg}	480±50	7.7	2.4±0.5	2.9±0.6	
<i>Y</i>	320±40	8.3	2.1±0.6	2.7±0.5	
<i>Nb</i>	400±40	8.7	1.7±0.4	1.2±0.2	metals
<i>Mo</i>	220±20	7.0	0.46±0.09	0.77±0.16	
<i>Ru</i> ^c	220±30	5.6	0.44±0.12	0.39±0.08	
<i>Rh</i> ^{cg}	230±40	11	0.49±0.17	≤1.7	
<i>Pd</i> ^g	800±90	35	5.7±1.3	1.2±0.2	
<i>Cd</i> ^c	390±60	6.2	2.2±0.7	2.2±0.4	
<i>Sn</i>	200±20	36	0.68±0.15	^f	
<i>Ta</i>	340±14	9.1	1.3±0.1	1.1±0.2	
<i>W</i>	220±20	3.3	0.47±0.09	0.84±0.17	
<i>Re</i> ^{cg}	420±45	7.1	1.7±0.4	0.29±0.06	
<i>Ir</i> ^{cg}	200±40	4.4	0.38±0.19	2.8±0.6	
<i>Pt</i>	440±50	14	1.8±0.5	3.9±0.	
<i>Tl</i> ^{cg}	550±90	70	5.8±1.2	7.4±1.5	
<i>Pb</i>	440±50	18	3.6±0.9	^f	
<i>Cu</i>	43±20	6.6	≤0.03	1.5±0.3	
<i>Ag</i>	23±10	10	≤0.01	1.3±0.3	noble metals
<i>Au</i>	61±20	2.6	≤0.07	1.5±0.3	
<i>BeO</i> ^c	≤ 30	4.0			
<i>B</i> ^c	≤ 30	2.6			
<i>Al₂O₃</i>	≤ 30	3.7			
<i>ScD_x</i> ^{cg}	≤ 30	0.70			
<i>TiD_x</i>	≤ 30	0.75			
<i>ZrD_x</i>	83±20	0.42			
<i>HfD_x</i>	87±20	0.55			insulators/ semiconductors
<i>ErD_x</i> ^c	≤ 50	1.0			
<i>YbD_x</i> ^c	≤ 40	0.77			
<i>SmD_x</i> ^c	≤ 30	0.75			
<i>PrD_x</i> ^c	78±20	1.0			
<i>DyD_x</i> ^c	≤ 50	0.90			
<i>C</i> ^c	52±20	1.1			
<i>Si</i> ^c	45±20	4.3			
<i>Ge</i> ^c	60±20	1.8			

^aUpdate results compared [7],[8]

^bFor a target temperature of $T = -10^\circ\text{C}$

^cFor $T = +20^\circ\text{C}$

^dError contains no systematic uncertainty in stopping power

^eFrom the observed Hall coefficient at $T = 20^\circ\text{C}$ [9], with an assumed 20% error

^fThe reported Hall coefficient for Sn and Pb [9] leads to unreasonable high values: $n_{eff}(\text{Hall})=86$ and 21, respectively

^gSurface cleaning by in-situ Kr sputtering at 35 keV

values are a feature of metals. The indication is supported by other insulators (B, BeO, Al_2O_3) as well as by deuterated metals M having an observed small stoichiometric x value (M_xD) of the order of one or smaller and thus representing also insulators (e.g. group 4 of the periodic table and the lanthanides). In summary, a large screening effect is observed in all metals except in the noble metals Cu, Ag, and Au. Various aspects of the metals were discussed previously to explain possibly the data [7],[8]: stopping power, thermal motion, channeling, diffusion, conductivity, crystal structure, electron configuration, and “Fermi shuttle” acceleration mechanism; however, none of these aspects led to a solution.

It should be pointed out that the quoted U_e values rely on the energy dependence of the stopping power values of deuterons in the metals at energies far below the Bragg peak, where no energy loss data exist and the values derived from the compilation SRIM [10] are based on extrapolations. However, recent measurements of low-energy stopping powers of protons in C, Al, Ni, and Au [11] have confirmed the SRIM extrapolations. Additional measurements of low-energy stopping powers are highly desirable for an improved determination of U_e , where the quoted errors in Table 1 contain yet no systematic uncertainty in the stopping power values.

If n_{eff} is the number of valence electrons per metallic atom which can be effectively treated - in a simplified model - as classical and quasi-free (the Drude model [12]), one may apply the classical plasma theory of Debye leading to an electron sphere of radius [1],[13]

$$R_D = (\epsilon_0 kT / e^2 n_{eff} \rho_a)^{1/2} = 69(T/n_{eff} \rho_a)^{1/2} \quad [m] \quad (5)$$

around positive singly-charged ions (here: deuterons in the lattice) with the temperature of the free electrons T in K and the atomic density ρ_a in m^{-3} . For T= 293 K, $\rho_a = 6 \times 10^{28} m^{-3}$, and $n_{eff} = 1$ one obtains a radius R_D , which is about a factor 10 smaller than the Bohr radius of a hydrogen atom. With the Coulomb energy between two deuterons at R_D set equal to U_e , one obtains $U_e = (4\pi\epsilon_0)^{-1} e^2 / R_D = 300$ eV, the order of magnitude of the observed U_e values (Table 1). A comparison of the calculated and observed U_e values leads to n_{eff} given in Table 1: for most metals n_{eff} is of the order of one. The acceleration mechanisms of the incident ions leading to the high observed U_e values is thus the electron cloud at the rather small radius R_D , while the periodic table gives the ordering of the associated number of valence electrons n_{eff} .

Since the Coulomb energy scales with the nuclear charge of the incident ion, the 3He beam case on deuterated Pt should lead to a U_e value a factor 2 larger than that for deuterons on deuterated Pt, consistent with observation (ratio = 1.7 ± 0.4).

A critical test of the classical Debye model is the predicted temperature dependence, $U_e \propto T^{-1/2}$, which needs experimental verification. First measurements were however not successful: at $T = -195^\circ C$ (liquid nitrogen temperature) and deuterated Ta, the stoichiometry x changed drastically from x = 9.1 ($T = -10^\circ C$) to x = 0.6 ($T = -195^\circ C$), whereby the deuterated Ta became an insulator and consequently the screening effect vanished. At high temperature, $T = +300^\circ C$, we could not attain a stable reaction yield at a given beam energy, probably due to a high diffusion rate of the implanted deuterons in Ta. Clearly, a new setup is needed, where the temperature of the sample can be varied in smaller steps.

An alternative determination of n_{eff} is obtained from the observed Hall coefficient for

metals at room temperature ([9] and references therein),

$$C_{Hall} = (e n_{eff}(Hall) \rho_a)^{-1}, \quad (6)$$

where for about 50% of the metals in Table 1 the coefficient is negative (electron carriers) and for the other one-half it is positive (hole carriers). Since in the later case essentially also electrons move (however in the opposite direction), we assumed that any dependence on the + or - sign of C_{Hall} can be neglected (which needs of course a theoretical verification). The resulting $n_{eff}(Hall)$ values are also given in Table 1: for most metals the agreement is better than a factor 2, but there are larger differences for a few metals and the noble metals. Since $n_{eff}(Hall)$ represents conduction electrons transporting current in a metal, while $n_{eff}(screening)$ involves no transport, the two quantities must not be exactly identical, although one may expect the condition $n_{eff}(screening) \geq n_{eff}(Hall)$. Furthermore, the Hall coefficient and thus $n_{eff}(Hall)$ may be different for deuterated metals compared to pure metals.

For the exceptional case of the noble metals, we cite Ch.Kittel [12]: “In an alkali metal the atomic cores occupy a relatively small part (about 15%) of the total volume of the crystal, but in a noble metal (Cu, Ag, Au) the atomic cores are relatively larger and may be in contact with each other”; improved theoretical work including this aspect may explain this exceptional case.

Although the classical Debye model appears to explain to a large extent the data, it is well known that most of the conduction electrons in a metal are not classical but are frozen by quantum effects and only electrons close to the Fermi energy (E_F) actually should contribute to screening. However, it was shown [12] that at room temperature the energy distribution of the electrons follows closely that of a classical Boltzmann distribution and thus quantum effects may be expected to be negligible, both for the description of electron screening and the Hall coefficient.

The classical Debye screening has been used to calculate the cross section enhancement in a stellar plasma, $f_{plasma}(E)$, such as in our sun. For the parameters at the solar core, $T = 15 \times 10^6$ K and $\rho = 150g/cm^3$ (mainly protons), and the slowest reaction $p(p, \nu e)d$ of the hydrogen-burning pp-chain, one finds $U_e = 50$ eV and thus $f_{plasma}(E_0) = 1.05$ at the Gamow energy $E_0 = 5.9$ keV, consistent with other calculations [14].

In summary, the future experimental program will include the following items: (i) study of additional metals of the periodic table, (ii) study of the temperature dependence of U_e , (iii) study of U_e for several deuterated metals using 3He , 6Li , and 7Li ions in combination with the reactions $d(^3He, p)^4He$, $d(^6Li, ^4He)^4He$, and $d(^7Li, p)^8Li$, respectively, and (iv) measurement of stopping power for hydrogen ions in various metals at energies below the Bragg peak. This program must also be accompanied by theoretical work.

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