Enhanced Electron Screening and Nuclear Mechanism of Cold Fusion

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Abstract: The enhanced electron screening effect observed in accelerator experiments for the $^2H(d,p)^3H$ and $^2H(d,n)^3He$ reaction in deuterized metallic targets may be a breakthrough in understanding the phenomenon of cold fusion. The dielectric function theory enables an extrapolation of experimental cross sections determined at higher energies down to room temperature, leading to an enhancement of the fusion reaction rates by a factor of 10^{40} compared to the value predicted for the deuterium molecule. An additional enhancement can be obtained due to a 0^+ resonance which should exist in the compound nucleus ^4He very close to the D-D reaction threshold. Combination of both processes offers a simple explanation of high penetration probability through the Coulomb barrier and the reaction branching ratio preferring the ^4He channel in heavy-water electrolysis experiments.

1. Introduction

Observation of a heat excess [1] and neutron emission [2] in the first heavy-water electrolysis experiments in 1989 seemed to be in contradiction to laws of nuclear physics. A simple calculation of the penetration factor through the Coulomb barrier at room temperature [3] gave reaction rates for the d+d fusion reactions being a factor of 10^{50} smaller than the rates needed for explanation the experimental results. On the other hand, the observed neutron emission should be about a factor of 10^7 weaker than a reaction channel responsible for the heat production and clearly correlated to the fusion of the ^4He nucleus [4]. Thus, the reaction branching ratios at room temperature completely contradict the experimental results obtained by means of the accelerator technique at deuteron energies of a few keV for which the mirror stripping reactions $^2H(d,p)^3H$ and $^2H(d,n)^3He$, being equally probable, dominate by a factor $>10^6$ the electromagnetic transition $^2H(d,\gamma)^4He$. Reproducibility of the cold fusion experiments has been highly increased in the last decade [5,6] and some important experimental conditions, under which the heat production takes place, has been found [7,8]. Nevertheless, a lack of reliable nuclear theory explaining at least some of the room temperature effects leads to an ongoing scepticism in the scientific community. Therefore, finding of the enhanced electron screening effect in metallic targets for the d+d stripping reactions [9], and similar observations of other groups [10-13] can play a key role in understanding of the cold fusion phenomenon. Screening of charges of the reacting nuclei by surrounding electrons in metallic environments increases the Coulomb barrier penetrability and results in an exponential-like enhancement of the cross sections compared to those measured for a gas target. That effect cannot explain, however, the change of branching ratios for the d+d reaction at room temperature and domination of the ^4He reaction channel. A simple mechanism of a single particle resonance located very close to the D+D reaction threshold in the compound nucleus ^4He will be presented here. Combination of the electron screening effect and the resonant process can explain most of the observed phenomena usually connected to the cold fusion and the heat excess production in heavy-water electrolysis experiments.

2. Enhanced electron screening effect

Electron screening effect can be described by a screening length a that corresponds to a distance from which the nuclear charges (ions) embedded in an electron gas can be treated as neutral. For strongly coupled plasmas where the average Coulomb potential energy between ions is larger than their kinetic energy, the screening length does not depend on the temperature and is of order of the Wigner-Seitz radius

$$a_{WS} = \left(\frac{3Z}{4\pi\, n_e} \right)^{1/3} \tag{1}$$

where Z and n_e are the ion charge and the density of free electrons, respectively. Dense astrophysical plasmas of White and Brown Dwarfs or of Giant Planets [14] are very good examples for strongly coupled plasmas.

Similarly, deuterons moving in metallic environments can also be considered using plasma physics methods. For the simple Bohr screening, the screened Coulomb potential energy between two reacting deuterons can be presented as follows

$$V(r) = \frac{e^2}{r} \exp\left(-\frac{r}{a}\right) \approx \frac{e^2}{r} - \frac{e^2}{a} \tag{2}$$

Now the screening length a is of order of the Bohr radius. For projectile energies used in accelerator experiments where $r << a$, the deuteron-deuteron potential can be simply described as the Coulomb potential reduced by a constant, the screening energy $U_e = e^2/a$. Thus, the "screened" cross section dependent on the penetration factor through the Coulomb barrier P corrected for the electron screening, can be expressed by the only weakly on energy dependent astrophysical S-factor

$$\sigma_{scr}(E_{cm}) = \frac{1}{\sqrt{E_{cm}(E_{cm}+U_e)}} S(E_{cm}) \exp\left(-\sqrt{\frac{E_G}{E_{cm}+U_e}}\right) \tag{3}$$

$$= \frac{1}{\sqrt{E_{cm}E_G}} S(E_{cm}) P(E_{cm}+U_e)$$

Here E_{cm} denotes the energy in the center of mass system and E_G is the Gamow energy defined as follows:

$$E_G = 2\mu\pi^2 \frac{(Z_1 Z_2)^2 e^2}{\hbar^2}$$

where Z_1 and Z_2 are the charges of reacting nuclei and μ stays for the reduced mass. The screening energy U_e corresponds to a reduction of the Coulomb barrier height in the expression for the penetration factor. In comparison to the bare nuclei, the cross section for reactions in metallic environments exponentially increases for decreasing projectile energies, whereby U_e can be taken from fits to the experimental data. The U_e values determined in our experiments for C, Al, Zr, Pd and Ta targets are depicted in Fig. 1. For heavier metals the screening energy amounts to about 300 eV that is one order of magnitude larger than the value 25±5 eV obtained in the gas target experiment [15].

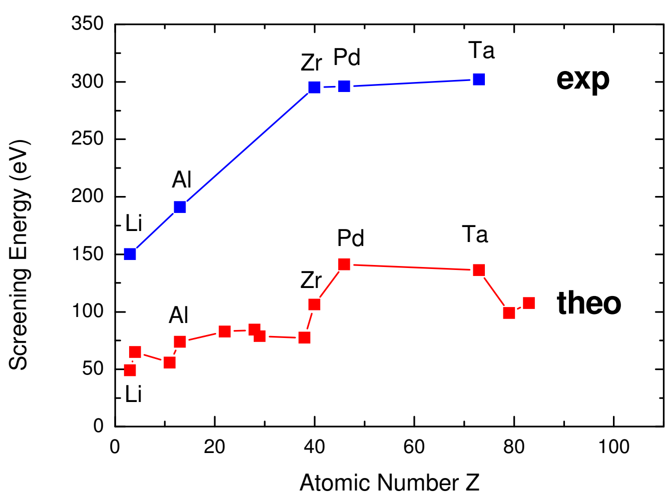

Fig. 1. - Experimental and theoretical electron screening energies obtained for C, Al, Zr, Pd and Ta targets.

The screening effect in metals can be described within the self-consistent dielectric function theory [9]. It enables to treat the electron screening as a static polarization of the metallic medium induced by the positively charged deuterons. The screened Coulomb potential $V(r)$ is a solution of the Poisson equation and can be expressed as a Fourier transform

$$V(r) = \frac{e^2}{r}\ \Phi(r)\ = \frac{1}{(2\pi)^3}\ \int \frac{4\pi\ e\varphi_1(q)\ e\varphi_2(q)}{\varepsilon_v(q)\ \varepsilon_c(q)\ q^2}\ \exp(i\vec{q}\vec{r})\ d^3q \tag{4}$$

The wave-number dependent dielectric functions ε_v and ε_c describe polarization of valence and core electrons of host atoms induced by a charged impurity. $\Phi(r)$ and $\varphi_i(q)$ functions are the screening function and electronic charge-form factors of reacting nuclei, respectively (for details see [9,18]). Additionally, the cohesion screening contribution arising from the difference in binding energies between two reacting deuterons and the compound nucleus ^{4}He in the crystal lattice has to be included [9]. The theoretical calculations describe the observed material dependence of the screening energy qualitatively correctly (see Fig. 1). The main contribution to the theoretical values is provided by polarization of the free valence electrons, although the contribution of bound electrons (core polarization) and the cohesion screening cannot be neglected. However, the absolute values of the theoretically calculated U_e fail by a factor of about two. No reason for such a large discrepancy between theoretical and experimental values has been found so far. Recent experiments carried out under ultra high vacuum conditions [16,17] show that this discrepancy can be even larger. On the other hand, since the experimental screening energies obtained for insulating materials are rather small (<50eV) [12,13] we can conclude that the large screening energies should result from conduction electrons.

An independent test of the enhanced screening effect can be obtained by study alpha radioactive decays in different insulating and metallic environments. Higher screening energies for metallic environments result in a slight decrease of life times of alpha decays [17,20].

3. Nuclear reactions at room temperature

Since the astrophysical S-factors for fusion reactions are usually known down to lowest projectile energies the only uncertainty of nuclear reaction rates at room temperature results from the screening energy U_e. However, the screening energy as defined in Eq.(2) loses its physical sense for the closest approach distances comparable with the screening length a. That corresponds to projectile energies comparable or smaller than the value e^2/a . Thus, in order to apply Eq.(3) for calculation of the reaction cross section at room temperature, we have to replace U_e by an energy-dependent effective screening energy U_{eff} . Similar to U_e, the effective screening energy can be still interpreted as an appropriate reduction of the bare Coulomb barrier which should match to the penetration through the screened Coulomb potential. Therefore, U_{eff} has to be calculated from a condition setting equal the penetration factors as applied in Eq.(2) and that obtained within the WKB approximation with the screened potential $V(r)$:

$$\sqrt{\frac{E_G}{E_{cm}+U_{eff}}}\ \exp\left(-\sqrt{\frac{E_G}{E_{cm}+U_{eff}}}\right)\ =\ \exp\left(-\frac{2\sqrt{M}}{\hbar}\int_{R_1}^{R_2}\sqrt{V(r)-E_{cm}}\,dr\right) \tag{5}$$

Here R_1 and R_2 are the classical turning points in the WKB expression, and M is the deuteron mass. The results of calculations for Pd are presented in Fig.2. There are two well defined limits: at the high energy (E_{cm}>1 keV) and at the low energy (E_{cm}<10 eV). The ratio between the low-energy and the high-energy U_{eff} value amounts to about 0.58, being nearly independent of the actual deuteron-deuteron potential. Additionally, the cohesion screening energy has to be added leading to the total screening energy at the zero projectile energy U_0 that is equal to about 0.78 of the high-energy limit U_e [9].

At deuteron energies below 10 eV, the effective screening energy remains almost constant, hence the expression for the cross section takes a very simple form. Starting from Eq.(3) we obtain

$$\sigma_{scr}(E_{cm}) \cong \frac{1}{\sqrt{U_0 E_{cm}}} S_0 \exp\left(-\sqrt{\frac{E_G}{U_0}}\right)\ \propto \frac{1}{\sqrt{E_{cm}}} \qquad \text{for} \qquad E_{cm} \to 0 \tag{6}$$

where U_0 and S_0 are the screening energy and the S-factor taken at the projectile energy zero, respectively. Surprisingly, the cross section increases at low energies as the barrier-penetration factor stays constant and the wave-length dependence dominates [9]. The same expression is also valid for other nuclear reactions at room temperature. Taking into account that the U_e for the deuteron stripping reaction ^{2}H(d,p)^{3}H amounts to about 500 eV [17] (U_0=360eV), the reaction cross section at room temperature reaches value σ_{scr}=10^{-15} b which is comparable with the cross sections for nuclear transitions induced by the weak interactions. It means that the fusion reaction at room temperature should be measurable by use a suitable experimental set-up.

For the electrolysis experiments, a very useful quantity that can experimentally be determined is the nuclear reaction rate defined here without number densities of involved nuclei as follows

$$R_{scr}(E_{cm}) = \sigma_{scr}(E_{cm})v_{rel} = \sigma_{scr}(E_{cm})\sqrt{\frac{2E_{cm}}{\mu}} \cong \frac{\sqrt{2}S_0}{\sqrt{\mu U_0}}\exp\left(-\sqrt{\frac{E_G}{U_0}}\right) \quad (7)$$

Here v_{rel} is the relative velocity between the reacting nuclei and μ denotes the reduced mass. Due to the energy dependence of the cross section at very low energies (see Eq.(6)), the reaction rate depends only on U_0 and not on E_{cm}. Therefore, no assumption about the distribution of the deuteron velocity at room temperature is necessary.

Nuclear reaction rates at room temperature very strongly depend on both the Gamow and screening energies. In order to illustrate it we compare the nuclear reaction rates of three fusion reactions between hydrogen isotopes for which the screening energy should be the same: ^{2}H(d,p)^{3}H, ^{2}H(p,γ)^{3}He and ^{3}H(p,γ)^{4}He. Without any electron screening contribution, the first reaction induced by nuclear forces ought to be much more probable than the others mediated by electromagnetic interaction, which is confirmed by large differences between the values of the astrophysical S-factors (see Table 1). However, as it was argued in the work of Koonin and Nauerberg [3], the small reduced masses in the channels p+d and p+t result in small Gamow energies, which consequently leads to an increase of reaction rates at very small projectile energies (see Fig. 2). Correspondingly, for small screening energies below 200 eV, the ^{2}H(p,γ)^{3}He reaction is the most probable reaction at room temperature. However, if the screening energies would be higher the ^{2}H(d,p)^{3}H reaction dominates. Its reaction rate will be for U_0=360 eV by a factor of about 10^3 larger than the values for the other reactions. On the other hand, this relatively large screening energy can provide the neutron production rate in the ^{2}H(d,n)^{3}He reaction of about 10^{-15} neutrons per deuteron pair and second. This is above the neutron production rate estimated in the experiment of Jones et al. [2] but significantly below the nuclear reaction rates necessary for explanation of the heat excess observed in the experiment of Fleischmann and Pones [1].

4. D-D threshold resonance

The observation of the excess heat production is probably connected to the fusion of ^{4}He [4] with the rate by about a factor of 10^7 larger than the neutron emission. Thus, beside the screening effect an additional phenomenon changing the branching ratios and increasing the reaction rates at room temperature should obviously exist. Alteration of the branching ratio by a factor of 10^7 might be achieved within the classical nuclear physics without any exceptional mechanisms. An example for such an approach could be a narrow resonance in the ^{4}He nucleus lying close to the d+d reaction threshold. Supposing a nearly single-particle width of this resonance for the deuteron channel and simultaneous quenching of the nucleon decay channels, one can explain major experimental results concerning the cold fusion. The deuteron width of the resonance can be expressed by the R-Matrix formula

Table 1. Astrophysical S-factors, Gamow energies and reduced masses for three different fusion reactions between hydrogen isotopes.

Reaction	d + d → t + p	p + d → ^{3}He + γ	p + t → ^{4}He + γ
S_0 (keV barn)	55.5	$2.5 \cdot 10^{-4}$	$2.6 \cdot 10^{-3}$
E_G (keV)	986.3	657.7	739.7
μ (amu)	1.00728	0.67141	0.75506

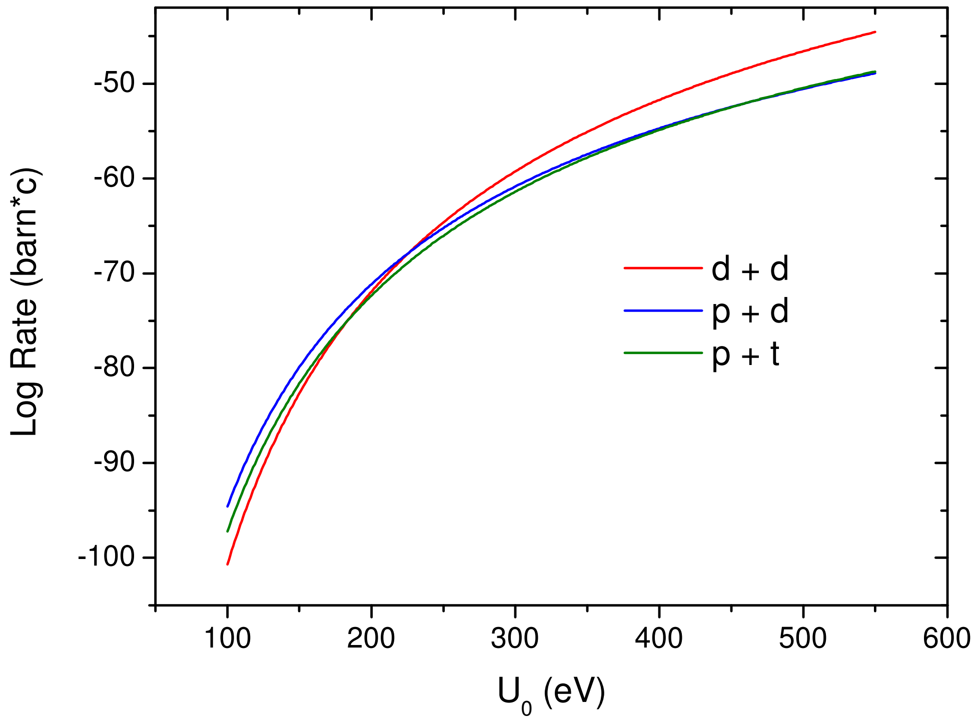

Fig. 2. - Nuclear reaction rates for three different fusion reactions in dependence of the electron screening energy U_0 (presented in log scale).

$$\Gamma_d = 2P_d \frac{3\hbar^2}{2\mu\ a_d}\left|\theta_d\right|^2 \tag{8}$$

where P_d, μ and a_d are the penetration factor, the reduced mass and the channel radius for the d+d channel, respectively, and $\left|\theta_d\right|^2$ denotes the dimensionless reduced resonance width. Since the total resonance width Γ is assumed to be dominated by the deuteron width ($\Gamma \approx \Gamma_d$), its value will drop for low sub-Coulomb deuteron energies very rapidly with decreasing penetration factor. On the other hand, the resonance strength, observed for instance for the proton decay channel, is given by the ratio $\Gamma_d\Gamma_p/\Gamma$ and should be independent of the resonance energy if we take into account that the proton width Γ_p remains nearly constant. Thus, the height of the single particle resonance ($\sim \Gamma_d\Gamma_p/\Gamma^2 \approx 1/\Gamma_d$) strongly increases as the resonance energy decreases – we speak about so-called narrowing of the single particle resonance. For the resonance energy of about 10 eV, the resonance width would be of a few eV and its height would raise by a factor larger than 10^6. Furthermore, the hypothetical resonance could change the reaction branching ratios within the resonance width in favour of those supposed for the cold fusion. The 0^+ assessment of spin and parity of this resonance makes forbidden its gamma decay to the ground state being also 0^+ in agreement with heavy-water electrolysis experiments where no gamma emission has been observed. Due to the single particle nature of this resonance, the neutron and proton decay channels should be negligible compared to the d+d partial width. Therefore, the decay of the resonance can only take place by non-radiative electromagnetic channels as the internal pair creation, the electron conversion or in the process we call the deuteron conversion where the energy excess of the compound nucleus ^4He of about 24 MeV will be transferred to a neighbouring deuteron. Decay probabilities of non-radiative channels leading to a direct fusion of ^4He in metallic environments will be discuss in a separated paper [19].

The small width of the supposed resonance would also explain the problems connected to the reproducibility of cold fusion experiments. Small local changes of the lattice structure can vary the resonance energy by e few eV due to alteration of the screening energy as already determined for alpha decays [17]. Thus, dependently on local crystal defects, the deuteron density and other target material parameters that are not usually controlled in the experiments, the ^{4}He fusion cross section can be resonant or not and consequently we could observe an enhanced production of helium by many orders of magnitude only at special material conditions.

5. Conclusions

We have shown that the electron screening effect plays a crucial role for room temperature nuclear reactions. The enhancement factor of the nuclear reactions due to electron screening is material dependent and reaches at room temperature for heavy metals a factor of about 10^{40} compared to the cross sections calculated for the gaseous deuterium [3]. The electron screening effect makes possible to observe experimentally also other reactions between hydrogen isotopes using an appreciate set-up (see Table 1). Contradictory to previous calculations, the $^{2}H(d,n)^{3}He$ and $^{2}H(d,p)^{3}H$ reactions should still have the largest cross sections at room temperature. The corresponding reaction rates are in agreement with small amounts of ^{3}H and ^{3}He found in the heavy-water electrolysis experiments.

Domination of the ^{4}He channel by a factor of about 10^{7} over other open channels in experiments where a heat excess has been measured can be explained by a 0^{+} single particle resonance placed in the compound nucleus very close to the reaction threshold. De-excitation of this resonance state should only take place by non-radiative electromagnetic channels that are very difficult to detect experimentally. Furthermore, an interplay between the electron screening effect that strength depends on local crystal structure of the target material and the resonance reaction mechanisms is able to clarify difficulties with regard to a bad reproducibility of the cold fusion experiments. Crystal defects or changes of local deuteron density can shift the resonance energy even by a few eV resulting in the non-resonant reaction mechanism and suppression of the ^{4}He fusion channel. Thus, controlling of the microscopic structure of target materials in future cold fusion experiments ought to be very important.

On the other hand, a material enabling large fusion rates at room temperature should also ensure a high deuteron density and a relatively low deuteron binding energy in the lattice. The latter condition is necessary in order to reach large deuteron mobility, which further increases the reaction probability by many orders of magnitude. Therefore, Pd still seems to be an ideal material for study nuclear reactions at room temperature.

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