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Screening in cold fusion derived from D–D reactions

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Based on the few reliable and reproducible cold fusion experiments, the power law of reaction probability on nuclear distance arrived at a value of 3 pm which is in agreement with results derived by a different method (Vigier and Rambaut) of 2.5 pm. For our plasma and swimming electron model we calculate a screening factor of 14.

1. Introduction

Many experiments on nuclear reactions of deuterium or hydrogen in palladium metal (cold fusion) were reported and have been summarized by Storms [1]. There are two classes of processes: (a) burst and (b) continuous reactions. The experimental studies of Yamaguchi and Nishioka [2] clearly show that the burst-like processes are related to strong energy release by simple phase transitions in the palladium metal accompanied by very short time bursts of emission of more than a million neutrons. This contrasts with other types of experiments [3,4], where the observation of continuous emission of nuclear reaction products has been established and confirmed. The initial experiments of Yamaguchi and Nishioka [2] showed that bursts of enormous heat production, plastic bending of the palladium and explosive gas release, without nuclear reactions, could be observed when the palladium was covered on one side with gold and on the other with manganese-oxide and treated either with hydrogen or deuterium at various pressures and temperatures. The irregularly occurring bursts were related to phase transitions in the palladium producing temperatures above 800 °C which alloyed the gold surface later with the palladium. The events occurred within hours or did not happen at all for other specimens. This variation is similar to that reported from electrolytic experiments with palladium electrodes [1,5]. No neutrons were emitted during the bursts using hydrogen instead of deuterium in the electrolyte [2]. The initial experiment by Yamaguchi in 1989 used a gas atmosphere instead of electrolyte. The emission of three bursts of more than a million neutrons, during the very short time of the thermal and other bursts, was observed three times from one specimen, but twenty specimens treated later showed no such effect. It seems that the large number of reports of irregular bursts of heat production from the palladium with time intervals of hours, or with no effects at all have to be re-examined with respect to the crystalline phase transition and heat generation. Nevertheless the occasional detection of nuclear reaction products such as neutrons or ^{4}He has to be taken seriously.

A series of experiments demonstrating continuous cold fusion have been reported [1,4]. One of these experiments, performed shortly after the disclosure of Pons and Fleischmann, specifically examined the cold fusion reaction using a Maxwellian plasma as the deuteron source [3]. A broad range of diagnostics were used to detect neutrons, gamma rays, charged particles, and particle mass. The observations from these experiments were basically different from those observed in the electrolytic observations

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[5]. No bursts of activity were seen, but a continuous detection of nuclear signals. The essential properties of these experiments were the use of palladium probes that had been cleaned using an argon ion plasma. Following the cleaning procedure, a deuterium plasma was created. Continuous low levels of neutrons and gamma rays were detected and interrupted by stopping the plasma reaction. The reaction was also observed to stop when air was let into the system due to surface change by oxydation or similar. Higher energy gamma-ray peaks at 5.2 and 8.1 MeV were detected [3] in seeking a peak above 20 MeV associated with ^{4}He generation. Most of the later measurements of X-ray spectra [1] concentrated on lower energies only. An independent measurement of the long period generation of neutrons with peaks near 5 and 8 MeV was reported by Takahashi et al. [6,7] for which models of multi-particle nuclear reaction processes have been proposed [7]. The experiments of Yamaguchi and Nishioka [2] clarified that the inconsistently occurring burst mechanisms are highly complicated. These mechanisms will need a careful further analysis in view of the classical material effects before theoretical models of nuclear mechanisms may be applied. We now elaborate a model for cold fusion for steady state conditions with clean surface experiments [3,4] avoiding electrolytic techniques. The following section concentrates on the evaluation of plasma screening effects in as far as these can be derived from the measurements [3] which agree with many of the later experimental results [1]. In the next section we examine how these results compare with the appropriately extended plasmon model of Preparata [8]. We then present some less precisely formulated relations on the reported ^{4}He production and related aspects.

2. Screening in the plasma and swimming electron layer model

The plasma [9] and swimming electron layer [10] model is basically different from the numerous attempts to localize deuterons inside the crystal structure of palladium, titanium or related metals of which an extensive literature has been produced. The plasma model is based on the assumption [9] that the deuterium atom inside the host crystal is ionized and the electron may or may not be localized within the lower unoccupied electron shells of the host metal while the ions essentially are then moving within the host crystal freely as a classical (nondegenerate) plasma thus causing no essential increase of the lattice constant. The repulsion of the deuterons within this kind of "exotic plasma" is strongly reduced not only by the degenerate electron gas of conducting electrons (whose collective screening effects were considered by several other authors [11]) but also by the clouds of the bound electrons of the metal through which the deuteron ions are moving, as in a Ramsauer effect. This is basically different from the numerous models localizing the deuteron in fixed places in the crystal [6]. What was added to this screening was the effect of the swimming electron layer at the clean surface of a metal, or at the interface between different metals [10], providing the possibility of a multilayer system producing a high volume concentration of cold fusion reactions. The model of the swimming electron layer was derived from the physics of high temperature plasmas [12], where the fact of the electron gas leaving a finite sized plasma faster than the ions generates a surface double layer of the value of the thermal work function. We have extended this idea to the degenerate plasma of conduction electrons in a metal. The electron cloud in the metal likes to leave the lattice with the Fermi energy until it is stopped by the generated electric double layer at the surface giving the potential step of the work function. All clean metals hence have a "swimming" electron layer at the surface of the lattice of a thickness of about 1 Å. The resulting surface tension of metals can then be calculated in good agreement with measured values [13]. The surface tension is obviously always positive contrary to the similarly looking jellium model where the surface tension can have negative values [14], if no complicated additional assumptions are introduced. If the deuterium ions of the exotic plasma in the metal are thermally moved into the surface swimming electron layer, a further screening effect occurs and the repulsion of the deuterons is reduced again, which should lead to a preferential cold fusion within the swimming electron layer, in addition to any volume effects. A necessary condition is that the surface is free from oxide or adsorbed molecules. Such clean surfaces of palladium have been produced by ion impact. In the experiment [3] all the neutron and X-ray emission immediately stopped if the palladium was put under normal air pressure. A similar observation was reported in a rather sophisticated experiment where titanium was placed in a glow discharge and the surface cleaned by the plasma [15]. Deuterium plasma with a minimum ion energy of 100 eV produced neutron emission and the generation of about 10^8 times more tritium than neutrons [15]. For the screening calculation and the necessary distance between the deuterons for the fusion reaction we use the relation of a power law for the time necessary for a fusion reaction between two deuterons [10]. Contrary to all the suggestions of an exponential relation as known from the tunneling mechanism and Gamov potentials, we derived a reaction given by the power law from the following three facts accepted for the fusion reactions (fig. 1). The extremely long reaction time for the fusion of the deuterons in a deuterium molecule are taken from early estimates [16], while that of myonic fusion reactions is taken from calculations [17] and that for the hot fusion reaction is based on the minimum distance d (in cm) for central collision,

$$d=e^2/E=1.43\times10^{-11}/E\,, \qquad (1)$$

where the energy E between the deuterons is given in units of 10 keV. It is most remarkable that this minimum distance for hot fusion is in the range of 100 fm, i.e. about 50 times larger than the diameter of the deuterons measured by Hofstadter detecting the radial distribution of the positive charge cloud of the nuclei. Relation (1) also shows that for energies E of some MeV, the distance given by the Coulomb repulsion is in the range of fm, just where Rutherford observed the first nuclear reactions with the well-known cross sections in the range of a few millibarns. The D–D and D–T fusion reactions are rather exceptional as the cross sections are up to several barns and the nuclei react at distances 50 or more times larger than the nuclear diameters. This permits a longer time of interaction and obviously is related to the theory of nuclear resonances [18] (contrary to some cold fusion models [19]). One other explanation of this large cross section was discussed by Rambaut [20] and Fedorovich [21] who considered a spin rotation potential of 50 keV. The power law derived from fig. 1 for the interaction time U of fusion is then [10]

$$U=8.139\times10^4 d^{34.8}\ \mathrm{s}\,, \qquad (2)$$

where d (in pm) is the minimum distance between the deuterons at fusion. We now use the result of Jones et al. [22] that the interaction time for continuous cold fusion per reaction is 10^{20} s which arrives at a real distance between the nuclei of about 3 pm.

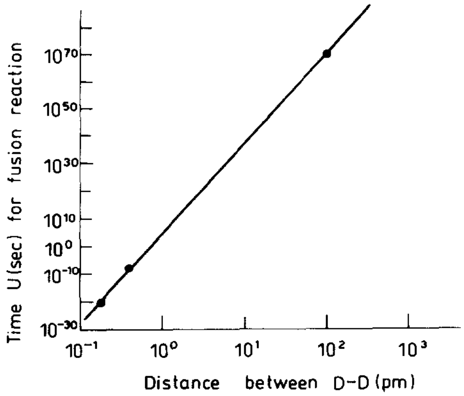

Fig. 1. Interaction time for fusion reactions at various nuclear separations for the hot fusion reaction, the myonic fusion reaction [19] and the reaction for deuterons in a hydrogen molecule [16].

It should be noted that the power law in eq. (2) gives a similar distance for cold fusion (3 pm) as the distance derived from Vigier's model (2.5 pm) by Rambaut [20] where the initially calculated screening [21] had to be increased.

Using a screening factor S (the number by which the electron charge has to be divided to arrive at the effective repulsion force between the deuterons in the screened plasma), the distance d (1) is modified to

$$d=(1/S)^2e^2/E\,. \qquad (3)$$

The number of reactions producing fusion neutrons comes from ref. [3], where 3 neutrons per 7 min ($A=7.14\times10^{-3}$ neutrons/s) above the background level of less than 1 neutron per 7 min were produced. Assuming a deuteron density of $6\times10^{22}\ \mathrm{cm}^{-3}$ in the palladium, a thickness of the swimming electron layer of 1 Å and taking the surface area of the palladium as 0.5 cm^2 [10], we find

$$N=3\times10^{14} \tag{4}$$

deuterons in the active surface area. The classical collision frequency for deuterons of density n_i (see eq. (2.37) of ref. [12]) corrected by the square root of the mass ratio between electrons and ions is

$$f=(1/S)^2\times1.4\times10^{-8}\,n_i/T^{3/2}\,, \tag{5}$$

where the ion temperature T is in eV. For a first iteration we use $S=1$. The number of collisions is then 1.62×10^{17} per second and the probability for a fusion reaction is $A/Nf=1.468\times10^{-34}$. Using a Boltzmann factor

$$\exp(-E/kT) \tag{6}$$

for the probability that one of the particles with a probability A/Nf has an energy E if the average temperature of the deuterons is room temperature, about 0.03 eV, we arrive at $E=2.33$ eV. In order to get the separation of two deuterons of 3 pm for 470 eV, the screening factor in eq. (3) has to be $S=14.1$. Using this S in eq. (5) we get the second iteration for f and with this the second iteration of S from eq. (3), etc. The iteration converges to $S=14$. This means that the screening causes a reduction of the repulsion such that the reacting deuterons interact as if they have an energy of 470 eV. The real energy of 2.33 eV defines the long interaction time and therefore the branching ratio or the then high probability of neutron swapping.

We further found that if the number of fusion reactions per second, A, is varied by five orders of magnitude the screening effect only changes by only a few percent. Thus a screening value of approximately 14 would be valid for all of the continuous cold fusion results reported [1]. This amount of screening appears to be rather high but one has to take into account the Ramsauer-like screening by the electron clouds in the metal ions in addition to the screening in the swimming electron layer.

3. Preparata's plasmon model

An alternative to the screening effect which arrives at the same consistent number is given by the plasmon model of Preparata [8]. In his case the screening is implicitly included in the plasmon description to give a plasmon energy of the palladium nuclei of 0.85 eV. Converting this to the plasmon energy of deuterons of the same density (by the square of the mass ratio), the plasmon energy of the deuterons is then 6.12 eV. One should clearly understand that this high value takes into account the screening in an implicit way. The following confirmation of the numerical agreement explains the degree of screening in connection with the just derived value of $S=14$. The Boltzmann distribution of the plasmons for the above probability A/Nf gives an energy of 476 eV for the plasmon energy leading to the fusion reaction. This is just within a few percent of the value to give a distance of 3 pm between the deuterons at the fusion reaction. While there are several models to explain the branching ratio of the 100 million times higher tritium production than neutron generation, a simple comparison with the power law of fig. 1 would indicate half the distance between the deuterons to produce such a larger number of reactions. It is understandable that the neutron swapping mechanism [10] easily produces the observed effect. There seems to be a resonance effect for this neutron swapping, like normal nuclear resonances [18], during the extremely long time of interaction for the cold fusion at a distance of 3 pm. This resonance may well be related to the fact that the measured 8.11 MeV gamma energy maximum just corresponds to twice the energy released from the tritium reaction branch. No other explanation has yet been offered to explain the observed high energy gamma spectrum.

4. ^{4}He generation

The above rough agreement between the predictions of the plasma and swimming electron layer screening model may explain the continuous neutron generation process or the measured generation of tritium and ^{4}He [3,4]. The burst mechanism however needs a number of further parameters to be analyzed, before quantitative comparisons can be made. Any of the phase transition mechanisms may produce cold fusion reactions in the interfaces between crystals due to the transient formation of clean surfaces with swimming electron layers. A further remark seems to be appropriate in view of the possible energy generation. If the swimming electron layer is extended to the cases of interfaces one simply has then to produce a large number of interfaces by a series of a number of metals with the biggest possible difference in Fermi energies. As we have shown before [10] there are several further options apart from palladium and titanium, of which the combination of cerium with nickel or of thorium with nickel seems to be of special interest provided that all the host metals would be able to incorporate high concentrations of deuterium. In the helium production which has been reported before by numerous authors [1] the key result seems to be that reported by Yamaguchi and Nishioka [4] where the bursts of the earlier observed particles of mass 4 are not so much deuterium molecules but ^{4}He. The mechanism of the reaction of the deuterons at the small separation of 3 pm with a relatively long interaction time could well have favored the highly exothermal reaction of deuterons via neutron swapping [10] with palladium nuclei resulting in a strong shift of the palladium isotopes [23]. Out of a large number of possible reactions one distinguishes the following highly exothermal ones,

$$^{105}_{46}\mathrm{Pd}+\mathrm{d}={}^{103}_{45}\mathrm{Rh}+{}^{4}\mathrm{He}+10.507\ \mathrm{MeV}\,, \tag{7}$$

where the only stable rhenium isotope is produced. A similar reaction produces energy from cold fusion of protons with nickel, however ^{4}He instead of tritium [24] is produced:

$$^{62}_{28}\mathrm{Ni}+\mathrm{p}={}^{54}_{27}\mathrm{Co}+{}^{4}\mathrm{He}+0.3048\ \mathrm{MeV} \tag{8}$$

again arriving at the only stable cobalt isotope whereas nickel with its magic number of protons has many stable isotopes. It should be further underlined that the effects of the interfaces may be involved in continuous cold fusion reactions as first happening in the experiments of Liaw et al. [25] where the palladium was melted to an iron support and the high temperature of a molten salt electrolyte may have caused a strong cold fusion reaction at the interface between the palladium and the iron.The reactions with nickel or that of cerium or thorium may be less complicated than that of palladium with its phase transitions. The latter seems to be the reason why a reaction produced increase of temperature may stop the cold fusion, as observed in ref. [3], the continuous reaction resumes only after the palladium has cooled down. If the plasma and swimming electron layer model continues to be successful in understanding the cold fusion reaction, it should be noted that the increase in temperature normally (in the absence of phase transitions) would increase the cold fusion reactions. This is simply because the Boltzmann factor (6) and the classical plasma collision frequency (5) gives a temperature dependence determined by the factor

$$T^{3/2}\exp(-E/kT)\,. \tag{9}$$

The factor F of the increase of the reaction rate as a function of temperature up to 800°C is shown in fig. 2.

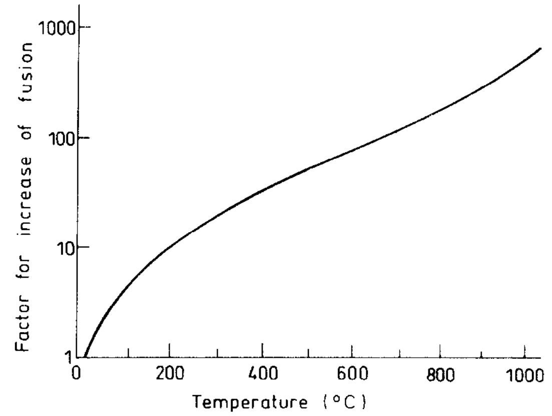

Fig. 2. Thermal increase of cold fusion, if exclusion of phase transitions and of similar effects can be made.

5. Conclusions

The recent experimental results by Yamaguchi and Nishioka [2] have emphasized that there are two different categories of cold fusion experiments, (a) those associated with phase transitions in the palladium metal plates which cause jumps in temperature, with mechanical deformations, and with bursts of released gas, but not necessarily cold fusion reactions, though they may do so under special circumstances; (b) continuous and reproducible production of fusion neutrons and X-rays, with spectra showing 8.1 MeV peaks. To explain this high energy peak we extended the model of plasma and swimming electron layers to evaluate the screening needed to reproduce the repulsion of deuterons that would allow separations of the 3 pm necessary for the observed cold fusion reaction rates. It turns out that the screening factor has to be about 14 to reduce the Coulomb repulsion sufficiently. This rather high screening seems to coincide with an evaluation of the Preparata plasmon model where the screening is implicitly taken into account. Our results based on the power law of eq. (2) for reaction rates depending on the nuclear densities and reliable experiments in cold fusion [3,4] resulted in a reaction distance of 3 pm in agreement with the 2.5 pm derived from a different model of Vigier and Rambaut [20]. Further conclusions of the ^{4}He production are given by a mechanism leading to the only stable isotopes of Co from Ni or of Rh from Pd.

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