Emission of Neutrons as a Consequence of Titanium-Deuterium Interaction.

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Summary. — The interaction of deuterium gas with titanium has produced a
flow of neutrons in the experiment reported here. This seems to show that it
is not necessary to use electrolysis in order to obtain a low-temperature
fusion reaction between deuterium nuclei. The experiment confirms also that
nonequilibrium conditions are necessary in order to produce such a
phenomenon.

PACS 25.00 - Nuclear reactions and scattering; specific reactions.
PACS 64.00 - Equations of state, phase equilibria and phase transitions.

The experiments recently reported by Jones and coworkers (i) (J) and by
Fleischmann and Pons (ii) (FP) are concerned with the production of fusion
reactions in an electrolytic cell containing heavy water, using a cathode made out
of palladium. In the case of J (who used both palladium and titanium as an
electrode) neutrons were observed from the cell, with an energy spectrum which

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condensed matter, to be published; J. Raffelski, M. Galda, D. Harley and S. E. Jones: Theoretical limits on cold fusion in condensed matter, to be published.
peaked around 2.4 MeV, the energy of neutrons produced in the fusion reaction
\[ D + D \rightarrow ^{3}\text{He}(0.82 \text{ MeV}) + n(2.45 \text{ MeV}). \]

In the case of FP there were two kinds of evidence: the energy balance of the system, obtained by a calorimetric method, showed an intense energy production that could not be accounted for in terms of chemical reactions, up to a few watts per cubic centimeter of palladium, as well as the emission of neutrons and gamma-rays. In terms of the more common reactions, the level of radiation emitted is much too low, by a factor \( \approx 10^4 \), to account for the energy produced. The authors suggest the possibility of other reactions, with by-products not detectable in their actual experimental arrangement.

Our approach to the problem was characterized by the interaction of deuterium gas with a metal; following consideration of the various metals that absorb hydrogen, we chose titanium.

In order to create nonequilibrium conditions, we decided to change the thermodynamic parameters of the system, in particular temperature and pressure; in this way we could create a dynamic condition for the process of absorption/desorption of deuterium in titanium.

Figure 1 shows a schematic drawing of the apparatus. About 100 grams of titanium, in the shape of shavings, are contained in a stainless steel cell. The cell was connected to a deuterium cylinder through valves. A manometer monitored the pressure in the cell, and a thermocouple in contact with the upper part of the titanium measured the temperature. A dewar could be placed around the cell, in order to change the cell temperature between room temperature and liquid nitrogen temperature. A BF\(_3\) neutron counter with high sensitivity was positioned quite close to the cell (typically 20 cm from centre to centre). The counter was interfaced with a computer, in order to read integral counts at regular intervals.

In a first prolonged run, after degassing the titanium, deuterium was admitted to the cell in steps of increasing pressure. At the same time the temperature was monitored, to check that there was not a relevant absorption reaction. This confirmed that only small amounts of deuterium were absorbed. A pressure around 20 bar (50 MPa) was reached. Then the temperature was lowered to 77 K by immersing the cell in a dewar full of liquid nitrogen. At this point the system was left to itself, at constant pressure, with the aim of obtaining changes of temperature both in time and space while the level of liquid nitrogen in the dewar was going down. The results of this run are shown in fig. 2, where a plot of

![Fig. 2. Diagram showing the time evolution of the neutron emission during the run lasting from 7 to 10 April, 1989. The values indicated are integral counts over periods of 10 minutes.](image)

the neutron counts is reported as a function of time over a period extending from the afternoon of Friday, April 7 to the late morning of Sunday, April 10, a total of more than 60 hours. The counts reported on the diagram are the integral values corresponding to time intervals of 10 minutes. The down-directed arrows indicate liquid nitrogen fillings. In the two refillings the liquid nitrogen level was quite low and most of the cell was out of the bath. The up-directed arrow shows the time when the liquid nitrogen dewar was taken away and the system was thus allowed to rise to room temperature. The correlation between the cooling cycle and the neutron emission is of particular note. Note also the almost quantized structure of the counts, as if they were coming in bunches of 20 (±4). A possible explanation for this behaviour is the saturation of the counter, because of the arrival of a large number of neutrons in a very short time interval. A better time resolution in the neutron detection will be required to confirm this
First Steps Toward an Understanding of -Cold- Nuclear Fusion.

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Summary. — We point out that the first steps in understanding the recent results reported on cold nuclear fusion can be made by considering the important role that the coherent interactions with the quantized e.m. field play in condensed matter. Indeed we find natural mechanisms to decrease the Coulomb repulsion and to suppress the usual nuclear fusion channel, with respect to the transfer of the excess energy directly to the electrons of the metal.

PACS. 25.70. Heavy particle induced reactions and scattering.
PACS. 71.55. Impurity and defect levels.
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Since the first announcement by Fleischmann and Pons (1) (hereafter referred to as FHP) of an electrochemically induced nuclear fusion of deuterium, several other reports have been given of analogous phenomena in different experimental conditions (2).

(2) S. E. Jones et al.: Brigham Young University preprint (1989).
(3) F. Scaramuzzi et al.: press report.
It is now rather clear that cold nuclear fusion is a real physical process. However, the evidence, given so far, can be classified in two distinct categories: FHP report about an electrolytical procedure for stocking deuterium ions inside palladium electrodes which lasts for prolonged times and includes a release of large quantities of heat, accompanied by a very modest release of neutrons (1 out of 10 estimated fusions). Other groups (1), on the other hand, seemingly have reported the observation of typical signals of nuclear fusion, such as neutrons in the relevant energy ranges, in experimental conditions which differ from those of FHP, both in duration and the flux of deuterium stocking and in the metal used as a catalyzer (titanium instead of palladium).

The great surprise and consequent scepticism that have ensued the results are easily understood in terms of the prevailing views about both condensed matter and nuclear physics. Indeed, the very fact that a metal can induce nuclear fusion on the absorbed deuterons means that energies and effects which were believed to be in the eV range turn out in fact to be in the MeV range (or, put differently, the distances involved are fm instead of Å). Furthermore the large amount of heat produced, without any large flux of neutrons or γ-rays of a few MeV, seems to indicate that the fusion process in the FHP set-up must take place in ways but have never been observed in vacuo.

It is the purpose of this paper to provide a few hints that might lead to a theoretical understanding of the fascinating phenomena that have been revealed in the last few weeks.

The problems that the generally accepted views on condensed matter and nuclear physics encounter in making sense of cold nuclear fusion are twofold:

i) why and how can the lattice of metals such as Pd and Ti "catalyze" a nuclear-fusion process;

ii) why and how the fusion process, under certain conditions, takes place differently than in vacuo, i.e. without the production of neutrons.

It is our view that one cannot overcome this dilemma without a major shift in our perception of the fundamental ways in which condensed matter organizes itself, while, of course, keeping the fundamental laws of electromagnetism and quantum mechanics, that have been corroborated in a countless number of observations.

This is just the basis of a research program that has been initiated a couple of years ago (2) which aims to describe, by the methods of quantum field theory (QFT), condensed matter in collective interactions through the quantized electromagnetic field (3).

The basic observation is that the charged particles existing in a lattice (electrons, absorbed hydrogen, etc.) can be looked at as comprising a plasma performing oscillations around their classical equilibrium positions with the typical plasma frequency (we shall set \(\hbar = c = 1\))

\[
\omega_p = \sqrt{\frac{4\pi n e^2}{m}} \left(\frac{N D}{N_1}\right) \frac{1}{\sqrt{1 + \frac{N_1}{D}}}
\]

where \(e\) is their charge, \(m\) their mass and \(N D\) their density. Quantum mechanically one can show that the classical equilibrium configuration is unstable when the coupling to the quantized electromagnetic field is brought into the picture. As a result the charged particles of the same kind will perform coherent oscillations with frequency and amplitude that depend on the appropriate parameters (4).

Let us look, in particular, to the \(Z\) electrons that oscillate coherently around the metal nuclei (5).

Calling \(d_{\text{r}}\) the minimum distance between two nuclei of the lattice, their plasma frequency is

\[
\omega_p = \sqrt{\frac{4\pi n e^2}{m}} \left(\frac{1}{d_{\text{r}}}\right)^{3/2} Z^{1/2} = 4.28 \cdot 10^7 Z^{1/2} \text{cm}^{-1}
\]

and the dispersion of the plasma oscillation is then given by

\[
\varepsilon = \frac{1}{(2\omega_p/\omega_0)^2} = 6.7 \cdot 10^{-7} Z^{1/2} \text{cm}.
\]

It should now be clear how these oscillations can exhibit a catalytic property. The "cloud" of \(Z\) electrons in a ball of radius \(\varepsilon\) investing two deuterons distort their Coulomb potential \(V(\varepsilon) = x/\varepsilon^2\) in the way

\[
V(\varepsilon) = \frac{2}{r^2} \left[1 - \frac{Z}{2} \frac{r^2}{\varepsilon^2}\right]
\]

\(^{(3)}\) G. Preparata: Lectures at Foggia INFN School (February 1989), to appear.

\(^{(4)}\) The first application of this program to free electron laser, water, and to high T\(_c\) superconductors \(^{(5)}\) appears now extremely promising.

\(^{(5)}\) Incidentally the electric dipoles generated by such coherent motion should have a major role in the cohesion of the crystal, as they lead to net attractions with a \(1/\varepsilon^2\) law instead of the typical \(1/\varepsilon^4\) behaviour of London-type forces.
and the classical turning point is then given by

\[ R_0 = \frac{z}{\sqrt{2}} \left( \frac{2}{Z} \right)^{1/3}. \] (5)

It is now a trivial exercise to compute the barrier penetration factor \( D \) between \( K \) and \( R_0 (\nu = 5 \text{ fm}) \) when the nuclear attraction overcomes the Coulomb repulsion. One obtains (\( \nu \) is the reduced mass)

\[ D \sim \exp \left[ - \frac{2(2\pi R_0)^{3/2}}{\nu^{1/2}} \left( \frac{1 - x^3}{x^2} \right) \right] = \exp \left[ - \frac{4(2\pi R_0)^{3/2}}{\nu^{1/2}} \right] \] (6)

Putting now the appropriate \( Z \), 46 and 22 for Pd and Ti respectively for dd, one computes \( D_{\text{Pd}} \sim 10^{-9} \) and \( D_{\text{Ti}} \sim 10^{-9} \), which must be compared with \( D_{\text{Pd}} \sim 10^{-8} \) that one computes for the \( \text{d}_2 \) molecule \( (Z = 2) \). However, due to the crudeness of our calculation we should not be surprised if our estimate of the argument in the exponent is in error of a few percent. Once the barrier gets penetrated (with probability \( D \)) the system will undergo a fusion process. Will fusion proceed as it does in \textit{vacuo}? The answer must be no for the following reasons. Once the deuterons reach equilibrium in the lattice they will also be subject to collective plasma oscillations with frequency

\[ \omega_{\text{pl}} = \frac{e}{m_{\text{d}} \sqrt{\left( \frac{N}{V} \right) \frac{f}{2}}} = 0.7 \cdot 10^{13} \text{ cm}^{-1}, \] (7)

where \( f \) is the number of deuterons per metal atom. The domain in which the deuterons will oscillate coherently has the linear size \( \lambda_{\text{pl}} = 2\pi c/\omega_{\text{pl}} = 9 \cdot 10^{-1} \text{ fm}^{-1} \). Inside the coherence domain the deuterons will act collectively and are described by a single quantum-mechanical wave function (the classical limit of the \textit{wave function} \( \psi \)).

The transition between the excited state \( ^3\text{He}^* \) (the compound nucleus of the fusing deuterons) and the ground state \( ^4\text{He} \) is the source of an oscillating electric field

\[ E = \frac{2e}{m_{\text{d}}} \exp[-i\omega t] \left( \frac{N}{V} \right)^{1/2} \frac{f}{2} D^{3/2}, \] (8)

where \( \omega = 24 \text{ MeV} \) is the energy difference between \( ^3\text{He}^* \) and \( ^4\text{He} \), and \( \nu \) is a typical velocity of the deuterons inside \( ^4\text{He}, |\nu| = 0.1 \). The important aspect of \( E \) (eq. (8)) is its independence from the space coordinate, within, of course, the coherence domain, within which all the plasma electrons are acted upon coherently. A simple calculation shows that the perturbative transition amplitude from the ground state of the electron plasma induced by the electric field (eq. (8)) is given by

\[ A(t) \sim \frac{\sin(\omega t)}{\omega} \frac{1}{2} \left( \frac{N}{V} \right)^{1/2} |D| \sim 2.35 \cdot 10^{-7} \text{ s}^{-1}, \] (9)

which must be compared with the nuclear rate \( \Gamma_n \) \( (\Gamma_n = 1 \text{ MeV}) \)

\[ \Gamma_n = f^2 D^{1/2} = f^2 D \cdot 10^{-7} \text{ s}^{-1}. \] (10)

We can now determine the specific power released in dd fusion from

\[ W = \Gamma_n \omega \left( \frac{N}{V} \right) = 3 \cdot 10^{10} f D \text{ W cm}^{-3}. \] (12)

We end this paper with a brief discussion of some of the experimental findings in the light of the present theoretical conclusions:

i) A comparison between eqs. (10) and (11) shows that the suppression factor of the nuclear channels is \( (f = 1) \) about nine orders of magnitude. This is in agreement with the findings of FHP.

ii) The mentioned suppression factor cannot apply when the stacking of deuterons is not in equilibrium. In this case the fusion must go through the nuclear channels. This might account for the observations in ref. \( f^{(2)} \).

iii) According to eq. (6) the fusion rate in Ti should be suppressed, with respect to Pd, by about 10 thus accounting for the very small heat rate reported in ref. \( f^{(3)} \).

iv) According to eq. (6) the reaction \( \text{pd} \rightarrow ^3\text{He} + 5.4 \text{ MeV} \) should be enhanced with respect to \( \text{dd} \rightarrow ^3\text{He} + 23.8 \text{ MeV} \) six orders of magnitude, being the relevant reduced mass a factor 23 smaller.

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