Tunnel Disintegration and Neutron Emission Probability

Toyu TANI [1] and Yukio KOBAYASHI [2]

1 Nagase 1194-13, Moroyama-cho, Iruma-gun, Saitama 351-03, JAPAN

2 Frontier Research Program, The Institute of Physical and Chemical Research (RIKEN), Hirosawa 2-1, Wako, Saitama 351-01, JAPAN (Present address : Department of Information Systems Science, Faculty of Engineering, Soka University, 1-236 Tangi-cho, Hachioji-shi, Tokyo 192, JAPAN)

ABSTRACT

It is shown that the main features of the so-called cold fusion, that is, poor reproducibility, high t/n ratio and the energy spectrum of neutrons, can be explained by the "tunnel disintegration" of a deuterium and the subsequent "dipole disintegration" of a deuteron. Especially, the 2.45-MeV peak found in the energy spectrum, which has been considered to be owing to the d-d nuclear fusion, is explained by this mechanism, and therefore the observation of 2.45-MeV neutrons may not be a direct verification of the d-d nuclear fusion.

1. Introduction

Cold nuclear fusion in condensed matter, one of the recent scientific topics which have startled the world, seems to find its reasons in the instability of the deuterium molecule. According to Van Siclen and Jones[1], Koonin and Nauenberg[2] and others, two deuterons in a free deuterium molecule tunnel mutually through the Coulomb barrier to initiate fusion at rates of 10^{-64} to 10^{-74} s^{-1}. However, these estimates of the d-d fusion rate in a free deuterium molecule appear to be not supported by quantum mechanics. First of all, it must be pointed out that the adiabatic approximation, under which estimates of the d-d fusion rate have been made, is not justified at shorter internuclear distances. Second, the electron motion is not correctly taken into consideration in estimating the d-d fusion rate. It is hard to suppose that the electron motion cannot be affected by the tunnel effect. In addition, recent experiments have revealed strange and incomprehensible results from the point of view of the d-d nuclear fusion: That is, high t/n ratio[3] and the neutron energy spectrum showing peaks at about 2.45 and 3 ~ 7 MeV[4]. Theory should be able to explain these experimental results as well as poor reproducibility.

Based on quantum mechanics, one of the authors has shown that the probability of fusion of two nuclei in a composite system, such as a free diatomic molecule, is exactly zero[5]. This implies that as a quantum-mechanical system the composite system should turn into a different system as soon as the two nuclei exceed the range classically forbidden to approach each other to zero separation. The change considered will be disintegration. From this it has been concluded that when a diatomic molecule interacts so strongly with a metal, such as palladium or titanium, in its surface region that the two nuclei approach each other to exceed the classically forbidden range, it will disintegrate with the transition of the electrons to the states of the continuous spectrum according to the reaction scheme

$$\text{(Dia. Mol.)} + \text{(Metal)} \rightarrow A + B + ne + \text{(Metal)}, \tag{1}$$

where A and B denote the two nuclei of the diatomic molecule, and n is the number of electrons contained in the molecule. We shall call this disintegration "the tunnel disintegration". If this is the case, it is expected that simultaneously with the tunnel disintegration, collective modes will be intensively excited to build up instantaneous strong localized electric fields because the energy released by the tunnel disintegration of a deuterium molecule is of the order of 30 eV. The deuteron is a quite loosely bound nucleus. If, therefore, an isolated deuteron is placed in a strong external electric field, there is a chance that dipole oscillations will be excited between the proton and neutron in the deuteron. If the localized electric field induced by the tunnel disintegration of deuterium ions D_2^+ is relatively slowly varying one (as compared with the characteristic period ($\sim 10^{-21}$s) of the nuclear motion), then it is possible that the deuteron ground state is prepared by the electric field for "dipole disintegration". In the present paper we calculate the probability of dipole disintegration of the deuteron, assuming for the localized electric field a pulse-like variation of the form

$$f(t)=\varepsilon_0 \lambda t(2-\lambda t)\exp(-\lambda t) \tag{2}$$

with $\varepsilon_0 = 1.0 \cdot 10^{20}$ (V/m) and $\lambda = 1.0 \cdot 10^{17} (s^{-1})$.

2. Tunnel Disintegration

Consider a diatomic molecule with n electrons. Hereafter, a representation in which its center-of-mass coordinates are separated from the other coordinates will be referred to as the center-of-mass representation, and a representation in which the coordinates of the constituent particles are separated from each other will be referred to as the particle representation. It will be a natural requirement that the center-of-mass representation and the particle representation should be equivalent over the whole region of configuration space. It, however, can be shown that we can pass from the center-of-mass representation to the particle representation if and only if the Hamiltonians H_A and H_B of the nuclei A and B of the diatomic molecule are separately Hermitian. In the center-of-mass representation the Hamiltonians H_A and H_B are given by

$$H_A = \frac{p_R^2}{2M_A} + \frac{1}{2} M_A V^2 + \mathbf{P}_R \cdot \mathbf{V} \tag{3}$$

$$H_B = \frac{p_R^2}{2M_B} + \frac{1}{2} M_B V^2 - \mathbf{P}_R \cdot \mathbf{V} \tag{4}$$

where

$$\mathbf{V} = \frac{\mathbf{P}_1}{M_A+M_B} + \frac{\mathbf{P}_2}{M_A+M_B+m} + \dots + \frac{\mathbf{P}_n}{M_A+M_B+(n-1)m} \tag{5}$$

In Eqs. (3), (4) and (5) $\mathbf{P}_R$ is the relative momentum of the nucleus B with respect to the nucleus A with M_A and M_B the respective masses of the nuclei A and B and with m the electron mass, and $\mathbf{P}_i$ the relative momentum of the ith electron with respect to the center of mass of a subsystem consisting of the two nuclei and the 1st, 2nd,..., (i-1)th electrons. We can show that if the wave function describing the nuclear relative motion has a tail which penetrates to the interior of the classically forbidden range, then the Hamiltonians H_A and H_B will cease to be Hermitian separately. Therefore, in such a case, we cannot pass from the center-of-mass representation to the particle representation; in other words, we cannot define any unitary operator connecting the wave functions in both the representations. From the equivalency requirement of both the representations it has been concluded that when the diatomic molecule interacts so strongly with a metal in its surface region that two nuclei approach each other to exceed the classically forbidden range, one should expect the disintegration of the molecule as a quantum-mechanical system. This is what we called "the tunnel disintegration".

3. Dipole Disintegration of a Deuteron and Far-distant Interaction

The tunnel disintegration of deuterium ions is expected to lead to the occurrence of an intense localized electric field in condensed matter. In what follows we shall consider a deuteron from a collapsed ionized deuterium molecule. The localized electric field will act on the proton of the deuteron. If the localized electric field varies quickly, we cannot expect any nuclear phenomenon from this electric action. If it, on the contrary, varies slowly compared with the characteristic period of the nuclear motion, then the deuteron will be capable of absorbing energy from the localized electric field, hence we can expect nuclear phenomena. Considered are nuclear dipole oscillations excited between the proton and neutron in the deuteron. When the localized electric field is relatively slowly varying one, the amplitude of dipole oscillations will be gradually increased, as a result of which there will happen a chance of disintegrating.

For simplicity we assume that the localized electric field is in the z-direction. The Schrödinger equation for the deuteron under the action of the localized electric field is then

$$i\hbar\frac{\partial\Psi}{\partial t} = H_r\Psi \tag{6}$$

with
$$H_r = H_0 - \frac{eM_n}{M} f(t)\, z, \tag{7}$$

where H_0 is the unperturbed Hamiltonian with a spin-dependent square-well potential, and the second term represents a time-dependent perturbation due to the localized electric field with z the z-component of the distance $\mathbf{r}$ between the nucleons, f(t) being given by Eq.(2), M being the total mass with M_n the neutron mass, and e being the elementary charge. In the first approximation the solution of Eq.(6) is given by

$$\Psi(\mathbf{r},t) = e^{-\frac{i}{\hbar}E_0 t}\,\psi_0^{(0)}(\mathbf{r}) + \sum_k a_k^{(0)}(t)\, e^{-\frac{i}{\hbar}E_k^{(0)}t}\,\psi_k^{(0)}(\mathbf{r}) \tag{8}$$

where $H_0\psi_0^{(0)}(\mathbf{r}) = E_0\psi_0^{(0)}(\mathbf{r})$ and $H_0\psi_k^{(0)}(\mathbf{r}) = E_k^{(0)}\psi_k^{(0)}(\mathbf{r})$. $\psi_0^{(0)}(\mathbf{r})$ represents a $^3S_1$ state and $\psi_k^{(0)}(\mathbf{r})$ ^3P states. At t=T at which the amplitude of dipole oscillations reach a maximum, the "dipole disintegration" of the deuteron is initiated. The Hamiltonian describing this decaying process is given by

$$H_r = \overline{H_0} + V_{res}(r) - \frac{eM_n}{M}f(t)\, z, \tag{9}$$

where $\overline{H_0}$ is a self-consistently constructed Hamiltonian. We here must point out that a "far-distant" interaction $V_{res}(r)$, which has been hitherto neglected, should be taken into account under the action of the localized electric field. For t > T we expand the solution of Eq.(6) in the form

$$\Psi(\mathbf{r},t) = e^{\frac{-i}{\hbar}E^{(1)}(t-T)}\psi_0^{(1)}(\mathbf{r}) + \sum_{l,m}\int a_{Elm}(t)e^{\frac{-i}{\hbar}E(t-T)}\psi_{Elm}^{(0)}(\mathbf{r})dE, \tag{10}$$

where $\overline{H_0}\,\psi_0^{(1)}(\mathbf{r}) = E^{(1)}\psi_0^{(1)}(\mathbf{r})$,

$$\psi_0^{(1)}(\mathbf{r}) = N\left(\psi_0^{(0)}(\mathbf{r}) + \sum_k a_k^{(0)}(T)\, e^{\frac{-i}{\hbar}(E_k^{(0)}-E^{(1)})T}\psi_k^{(0)}(\mathbf{r})\right), \tag{11}$$

and $\overline{H_0}\,\psi_{Elm}^{(0)}(\mathbf{r}) = E\,\psi_{Elm}^{(0)}(\mathbf{r})$ $\quad (E > 0)$. (12)

The probability that the neutron is ejected with energy between E and E + dE by nuclear dipole oscillations is

$$\sum_{lm} |a_{Elm}(\infty)|^2\, dE \tag{13}$$

4. Results and Conclusions

As is seen above, our theory reasonably explains the poor reproducibility of the phenomena observed.

Taking, with a view to investigate the validity of the theory, for the Hamiltonian $\overline{H_0}$ spin-dependent square-well potentials with E_0, $E_k^{(0)}$ and the well depths as parameters, and assuming for $V_{res}(r)$ a potential of δ-function type of the form

$$V_{res}(r) = V\,\delta(r - a) \qquad (a \sim 30\text{ fm};\ V = 1.0\text{ MeV}), \tag{14}$$

we calculated the probability of dipole oscillations, i.e., the neutron emission probability. Figure 1 shows a result of calculations. From this we find that the neutron emission probability has three peaks at C.M. energies of about 0.01 MeV, 4.9 MeV and ~ 12 MeV, which correspond to laboratory energies of about 0.005 MeV, 2.45 MeV and ~ 6 MeV, respectively. Especially, the ratio of the emission probability at the extremely low energies to that at 4.9 MeV is of the order of 10^5, which will explain the large t/n ratio reported. We therefore conclude that the main features of the observed phenomena can be reasonably explained by the theory of dipole disintegration.

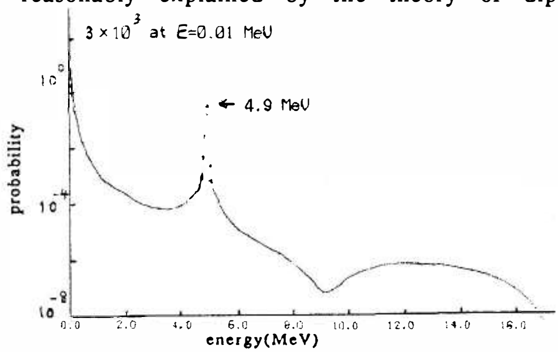

Figure 1. Neutron emission probability by the dipole disintegration.

5. References

1. Van Siclen, C. Dew. and Jones, S. E., 1986, J. Phys. G 12, 213.
2. Koonin, S. E. and Nauenberg, M., 1989, Nature, 690.
3. Proc. 1st Annual Conf. Cold Fusion, 1990, Salt Lake City.
4. Takahashi, A. et al., 1990, J. Nucl. Sci. and Technol. 27, 663.
5. Tani, T., 1990, unpublished paper.