JAERI-M
89-093

FRACTO-FUSION
—MECHANISM OF COLD FUSION—

July 1989

Tatsuoki TAKEDA and Tomonori TAKIZUKA

日本原子力研究所
Japan Atomic Energy Research Institute

JAERI-Mレポートは，日本原子力研究所が不定期に公刊している研究報告書です。

入手の問合わせは，日本原子力研究所技術情報部情報資料課（〒319-11茨城県那珂郡東海村）あて，お申しこしください。なお，このほかに財団法人原子力弘済会資料センター（〒319-11 茨城県那珂郡東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

JAERI-M reports are issued irregularly.

Inquiries about availability of the reports should be addressed to Information Division Department of Technical Information, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan.

編集兼発行　日本原子力研究所
印　　　刷　㈱高野高速印刷

Fracto-Fusion
- Mechanism of Cold Fusion -

Tatsuoki TAKEDA and Tomonori TAKIZUKA

Department of Thermonuclear Fusion Research
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

(Received June 29, 1989)

As a cold fusion mechanism we investigated a fracto-fusion by which reacting particles are accelerated by the electric field generated between the crack surfaces in a crystal and the beam fusion occurs. By assuming the possible magnitude of the potential difference we calculated the fusion rate and energy multiplication factor. These results are consistent with cold fusion experiments. On the basis of a simple model it is conjectured that necessary electric potential difference to accelerate particles can be generated even in a metal crystal with rather low resistivity, and we conclude that the fracto-fusion mechanism can explain the cold fusion phenomena successfully.

Keywords: Fracto-Fusion, Cold Fusion, DD-Reaction, DT-Reaction, Metal Crystal, Crack-Generated Electric Potential

フラクト・フュージョン
−低温核融合の機構−

日本原子力研究所那珂研究所核融合研究部
竹田　辰興・滝塚　知典

（1989年6月29日受理）

低温核融合の機構としてフラクト・フュージョンについて調べた。この現象は，結晶に生じた亀裂に発生する電位差によって粒子が加速されて核融合が起こるものである。発生可能な電位差の大きさを仮定し，核融合反応率とエネルギー増倍率を計算した。これらの結果は，低温核融合実験で得られているものと矛盾がない。簡単なモデルに基づいて，粒子を加速するのに必要な電位差はかなり抵抗率の低い金属結晶中に於てさえ発生可能であることを理論的に推定し，フラクト・フュージョン機構が低温核融合をうまく説明できることが結論づけられた。

那珂研究所：〒311−01　茨城県那珂郡那珂町大字向山801−1

Contents

目　　次

1. Introduction

Since the claims of discovery of the cold fusion by Fleischmann & Pons[1] and Jones et al.[2], various kinds of experiments to reconfirm their results have been carried out by many groups. The key points for the confirmation of the cold fusion are observations of excess heat generation, neutron emission due to the $D(d,n)He^3$ branch of the DD fusion, tritium production due to the $D(d,p)T$ branch, and γ-ray emission from the subsequent reactions by the produced neutrons. Some of the groups[3-6] reported to have succeeded in above observations partly, and most groups could not observe any indication of existence of the cold fusion phenomena. By taking into account of both the successful and unsuccessful results the remarkable features of the cold fusion experiments are summarized as follow: (1)Enormous heat generation is observed in some experiments but it is difficult to divide the heat into those of the nuclear origin and the chemical origin, (2) neutron emission seems a direct proof of the fusion reactions and from the magnitude of the neutron flux the fusion rate is conjectured as 8×10^{-22} fusion/d/s (d: deuteron) at maximum, (3) neutron emissions are irregular in general, i.e., neutrons are emitted at random in time or they are emitted in bursts, and (4) reproducibility is extremely bad and experimental results are different each other according to the difference of samples and difference of the experimentalists or the institutions.

In parallel with the experimental efforts to confirm the cold fusion there have also been carried out a lot of theoretical studies to explain the observed phenomena. Negative explanations were that the origins of the excess heat were energies of chemical reactions[7] or of stresses in a crystal[8]. Theoretical models from the affirmative viewpoints are roughly classified into three groups, i.e., (1) fusion reaction due to tunneling effects by screening of the Coulomb barrier by some unconfirmed effects[9], (2) fusion by high energy particles produced in a local hot spot[10] or accelerated by high potential difference produced at a crack in a crystal[11,12], and (3) completely new fusion reaction unknown up to now. The possibility to explain the phenomena by the muon catalyzed fusion induced by muons in cosmic rays was pointed out, but Nagamine et al.[13] denied it experimentally by using intense muon beam from an accelerator. In order to construct a theoretical model of the cold fusion it seems very important to explain the whole cold fusion phenomena including an explanation why the phenomena were observed in such a capricious manner. In this letter we investigate a theoretical model of the cold fusion due to high energy deuterons accelerated by a crack-generated electric field (a fracto-fusion mechanism) and conclude that this model is very plausible.

2. Electric potential difference generated at a crack

2.1 Survey of experiments

As is well known, fresh surfaces produced by cracking of a crystal have capability to emit charged particles. This phenomenon is usually attributed to the fact that highly concentrated energy is deposited into a small volume of material during the crack-formation and then imbalance of electric charges between the two crack-walls causes an intense electric field with the growth of the crack. In this intense electric field, electrons and ions are accelerated to high energy. In the experiments of crack-formation, one can observe a various kinds of emissions, i.e., positive ion affirmative viewpoints are roughly classified into three groups, i.e., (1) fusion reaction due to tunneling effects by screening of the Coulomb barrier by some unconfirmed effects[9], (2) fusion by high energy particles produced in a local hot spot[10] or accelerated by high potential difference produced at a crack in a crystal[11,12], and (3) completely new fusion reaction unknown up to now. The possibility to explain the phenomena by the muon catalyzed fusion induced by muons in cosmic rays was pointed out, but Nagamine et al.[13] denied it experimentally by using intense muon beam from an accelerator. In order to construct a theoretical model of the cold fusion it seems very important to explain the whole cold fusion phenomena including an explanation why the phenomena were observed in such a capricious manner. In this letter we investigate a theoretical model of the cold fusion due to high energy deuterons accelerated by a crack-generated electric field (a fracto-fusion mechanism) and conclude that this model is very plausible.

2. Electric potential difference generated at a crack

2.1 Survey of experiments

As is well known, fresh surfaces produced by cracking of a crystal have capability to emit charged particles. This phenomenon is usually attributed to the fact that highly concentrated energy is deposited into a small volume of material during the crack-formation and then imbalance of electric charges between the two crack-walls causes an intense electric field with the growth of the crack. In this intense electric field, electrons and ions are accelerated to high energy. In the experiments of crack-formation, one can observe a various kinds of emissions, i.e., positive ion emission, photon emission, electron emission, and neutral particle emission. These phenomena are called the fracto-emission.

There are a lot of experimental evidences of the fracto-emissions, which could be attributed to generation of high potential difference at a crack in a crystal. For example, Linke and Wollbrandt observed electron emission with an energy spectrum which has a peak at 20 keV and the maximum energy of 120 keV[14]. As for photon emissions Klyuev et al. observed X-ray with energy of several tens keV[15], and even very high energy γ-ray as 4 MeV was observed by Sobolev et al.[16]. Emissions of positive ions were almost the same as that of electrons in number and energy[17]. Unfortunately these high energy emissions were observed only in cases of cracks of insulators as alkali-halide crystals[14,16,17] or adhesive bonds between a polymer and a metal plate[15], and the generation of the high electric potential difference in a metallic crystal such as Pd and Ti has not been observed quantitatively. Klyuev et al., however, reported an experiment to confirm the possibility of fusion due to the crack-generated electric field by giving a strong impact on a LiD single crystal by using a 0.05 kg bullet with speed of 200 m/s[11]. The authors claimed that about 10 neutrons were emitted per single shot in the average of 75 shots-experiment, which suggests that about 20 fusion reactions occurred in the LiD crystal by the high energy deuterons accelerated by the crack-generated electric field.

2.2 Theoretical consideration

One of the most interesting problems from the viewpoint of the cold fusion is to determine theoretically whether such a high electric potential difference can exist or not in metal hydrides as PdD_x or TiD_x, and if the potential difference lasts long enough to accelerate the deuterons to high energy. Concerning the question Mayer et al.[18] suggested that sufficient electric potential difference could be generated if the surface density of unbalanced electric charge of about 0.1 per lattice existed for some reason.

We analyzed this problem by assuming that a crack of wedge shape with the vertex angle of θ ($\theta \ll 1$) propagates with the velocity of U (m/s)(Fig.1). If the crack is modelled by a parallel plate condenser with a gap width of δ(m), the potential difference of V(V) is calculated from the charge density, σ(C/m^2), at the crack-walls as

$$V = \frac{\sigma\delta}{\varepsilon_0}\ , \tag{1}$$

where ε_0 is the dielectric constant of the vacuum. The electric charge originates from the charge imbalance at the propagation vertex of the crack, which is apt to disappear due to the current flow to the vertex along the crack surface. We should, therefore, find a condition by which the unbalanced electric charges are sustained on the surfaces and the high potential difference is generated with the increasing gap width. We consider the ohmic law at the point X of Fig.1, as

$$E = \rho j = \rho e n_e \mathrm{v}_e\ , \tag{2}$$

where $E = V/l$ is the electric field strength along the surface, j the current density, l the length between the vertex and the point X, and ρ, n_e, and v_e are the resistivity, electron density, and the average electron speed along the surface, respectively. From Eq.(2)

we can obtain the condition that the unbalanced charge does not flow away to the vertex as

$$v_e = \frac{V}{en_e l\rho} = \frac{V\theta}{en_e \delta\rho} << U \quad . \tag{3}$$

If the crack propagation speed is sufficiently large and the above condition is satisfied, the charge density distribution on the crack-walls is sustained almost constant in time during the growth of the crack(Fig.2) and the potential difference obtained by the parallel plate condenser model gives a good approximation.

To give an idea of magnitude of the parameters several examples of potential difference and average electron speed are shown in Table 1. In this Table the charge density is represented by a number density of electrons, Σ (= σ/e)(m^{-2}), and resistivity of pure Ti (ρ = 4.0×10^{-7} Ωm), θ = 10^{-2}, and n_e = $10^{29}m^{-3}$ are employed. If the gap width, δ(m), of the crack is large enough, high potential difference can be attained by rather small number of unbalanced charges as $\Sigma \approx 10^{14} \sim 10^{15}$ m^{-2}. For these conditions the average electron speed, v_e(m/s), can also become smaller in comparison with crack propagation speed, which assures the formation and sustainment of the high electric potential difference.

3. Number of fusion reactions per deuteron

Taking into account of the above data and investigations we can presume that the high electric potential difference can be generated at cracks in Pd or Ti crystals used in the present cold fusion experiments. These cracks can be formed easily by packing the deuterons strongly into the crystal lattice in the case of the we can obtain the condition that the unbalanced charge does not flow away to the vertex as

$$v_e = \frac{V}{en_e l \rho} = \frac{V\theta}{en_e \delta \rho} << U \quad . \qquad (3)$$

If the crack propagation speed is sufficiently large and the above condition is satisfied, the charge density distribution on the crack-walls is sustained almost constant in time during the growth of the crack(Fig.2) and the potential difference obtained by the parallel plate condenser model gives a good approximation.

To give an idea of magnitude of the parameters several examples of potential difference and average electron speed are shown in Table 1. In this Table the charge density is represented by a number density of electrons, Σ (= σ/e)(m^{-2}), and resistivity of pure Ti (ρ = 4.0×10^{-7} Ω m), θ = 10^{-2}, and n_e = $10^{29}m^{-3}$ are employed. If the gap width, δ(m), of the crack is large enough, high potential difference can be attained by rather small number of unbalanced charges as $\Sigma \approx 10^{14} \sim 10^{15}$ m^{-2}. For these conditions the average electron speed, v_e(m/s), can also become smaller in comparison with crack propagation speed, which assures the formation and sustainment of the high electric potential difference.

3. Number of fusion reactions per deuteron

Taking into account of the above data and investigations we can presume that the high electric potential difference can be generated at cracks in Pd or Ti crystals used in the present cold fusion experiments. These cracks can be formed easily by packing the deuterons strongly into the crystal lattice in the case of the electrolytic cold fusion, or by rapidly cooling/heating the crystal in the case of the high pressure cold fusion. On the basis of this consideration, we estimate the number of fusion events in a crystal by assuming the magnitude of the potential difference between the crack walls or the energy of an accelerated deuteron. In the following investigation we consider only the DD and DT fusion reactions which are represented as

$$D + D \dashrightarrow T + P + 4.0\ \mathrm{MeV} \tag{4}$$

$$D + D \dashrightarrow He^3 + n + 3.3\ \mathrm{MeV} \tag{5}$$

$$D + T \dashrightarrow He^4 + n + 17.6\ \mathrm{MeV} \tag{6}$$

First we have to calculate the fusion cross sections corresponding to the above reactions, σ_{DDp}, σ_{DDn}, and σ_{DT} in respective order. These are generally expressed[19] as

$$\sigma(E) \cong \frac{S}{E} \exp\left(-\frac{A}{\sqrt{E}}\right), \tag{7}$$

where E is the deuteron energy, S and A are the constants given in Table 2, and the total cross section of the DD fusion reaction σ_{DD} is expressed as a sum of σ_{DDp} and σ_{DDn}.

Next, it is necessary to calculate the energy loss of an accelerated deuteron. There are many possibilities of the energy losses and among them we evaluate the magnitude of the losses due to the following important processes, i.e., the large angle elastic scattering by which the fast ion is back-scattered from the crystal, the ionization-excitation collision, and the small angle scattering Coulomb collision. Since the energy loss by an ionization-excitation collision, E^*, is several eV, the energy decay rate of a fast ion with energy E becomes smaller by (E^*/E) times than the ionization-excitation collision frequency. The result of the evaluation is summarized in Table 3. In this Table we can easily see that the Coulomb collision with electrons is the dominant process for the energy loss in the parameter range of our concern, and, hereafter, we consider only the Coulomb collision as the energy loss process in the crystal. The energy loss due to this process is represented by using the slowing down time τ_S of the accelerated deuteron as

$$\frac{dE}{dt} = -\frac{E}{\tau_s}, \tag{8}$$

$$\tau_s = 1.4 \times 10^{13} \frac{E^{1.5}}{n_e} = \tau_0 \left(\frac{E}{E_0}\right)^{1.5}, \tag{9}$$

where n_e is the electron density in unit of m^{-3}, E is the deuteron energy in keV, and the Coulomb logarithm is assumed to be 10. Subscript 0 denotes the state with maximum energy just before entering the crack surface.

Using the above equations we can calculate the number of the fusion reactions per single deuteron, f, as

$$f = \int_0^\infty n_t \sigma v \, dt, \tag{10}$$

where n_t is the density of the target particles (D or T) of order of $10^{29} m^{-3}$ and v $(= 3.1 \times 10^5 \sqrt{E}$ m/s) is the velocity of the accelerated deuteron. Since σv is approximately expressed as a power of the incident particle energy, $\sigma v \approx [\sigma v]_0 (E/E_0)^\beta$, the integration of Eq.(10) is carried out analytically as

$$f \cong n_t[\sigma v]_0 \frac{\tau_0}{\beta} . \tag{11}$$

As for the energy multiplication factor, Q, input energy is rather difficult to determine, but by employing the deuteron acceleration energy E_0 as the input energy we can define the maximum limit of the Q-values. Figure 3 shows the number of the fusion reactions per deuteron, f_{DD}, and the Q-values, Q_{DD}, as functions of the accelerated deuteron energy, where the ratio of n_e and n_t is assumed to be $n_e/n_t=2$. Figure 4 shows the case of DT fusion. The attainable Q-values for both cases are found to be much smaller than unity. In order to estimate the fusion rate we need the time scale, t_f, of the overall process governed by the characteristic time of the crack-formation, and the ratio, ε, of the deuterons usable for the acceleration. We assume as $t_f \approx 1$ month $\approx 3\times10^6$ s and $\varepsilon \approx 10^{-3}$. Then the rate for the DD fusion is derived as $1\times10^{-23} \sim 6\times10^{-20}$ fusion/d/s for the crack voltage of 10 ~ 30 keV. Under this condition energy loss of a deuteron is calculated as 0.03 ~ 0.1 $\mathrm{MWm^{-3}}$, which is larger than the fusion output energy by more than the factor of 10^8. These values as well as the irreproducibility of the crack-formation are consistent with experiments.

4. Conclusions and discussion

In the present investigation we assumed the existence of the high electric field in a crack of the metal deuterides such as PdD_x and TiD_x. And we also assumed a sufficiently long life time of the electric field for the fusion process as about 10^{-10} second. These assumptions are not confirmed experimentally up to now. But the

$$f \cong n_t[\sigma v]_0 \frac{\tau_0}{\beta} . \qquad (11)$$

As for the energy multiplication factor, Q, input energy is rather difficult to determine, but by employing the deuteron acceleration energy E_0 as the input energy we can define the maximum limit of the Q-values. Figure 3 shows the number of the fusion reactions per deuteron, f_{DD}, and the Q-values, Q_{DD}, as functions of the accelerated deuteron energy, where the ratio of n_e and n_t is assumed to be n_e/n_t=2. Figure 4 shows the case of DT fusion. The attainable Q-values for both cases are found to be much smaller than unity. In order to estimate the fusion rate we need the time scale, t_f, of the overall process governed by the characteristic time of the crack-formation, and the ratio, ε, of the deuterons usable for the acceleration. We assume as $t_f \approx$ 1 month $\approx 3\times10^6$ s and $\varepsilon \approx 10^{-3}$. Then the rate for the DD fusion is derived as $1\times10^{-23} \sim 6\times10^{-20}$ fusion/d/s for the crack voltage of 10 ~ 30 keV. Under this condition energy loss of a deuteron is calculated as 0.03 ~ 0.1 $\mathrm{MWm^{-3}}$, which is larger than the fusion output energy by more than the factor of 10^8. These values as well as the irreproducibility of the crack-formation are consistent with experiments.

4. Conclusions and discussion

In the present investigation we assumed the existence of the high electric field in a crack of the metal deuterides such as PdD_x and TiD_x. And we also assumed a sufficiently long life time of the electric field for the fusion process as about 10^{-10} second. These assumptions are not confirmed experimentally up to now. But the existence of the high electric potential difference is consistent with the theoretical analysis based on a simple model of the crack propagation even in a metal crystal with rather low resistivity. We can conclude, (1) the fracto-fusion mechanism seems consistent with the cold fusion experiments so far carried out, and (2) the fracto-fusion reactor does not seem promising as an energy source.

Acknowledgments

The authors would like to thank Dr. M. Tanaka and Prof. G Miyamoto for stimulating discussions and continuing encouragement.

existence of the high electric potential difference is consistent with the theoretical analysis based on a simple model of the crack propagation even in a metal crystal with rather low resistivity. We can conclude, (1) the fracto-fusion mechanism seems consistent with the cold fusion experiments so far carried out, and (2) the fracto-fusion reactor does not seem promising as an energy source.

Acknowledgments

The authors would like to thank Dr. M. Tanaka and Prof. G Miyamoto for stimulating discussions and continuing encouragement.

References

1. M. Fleischmann, S. Pons and M. Hawkins, J. Electroanal. Chem. **261** (1989) 301.
2. S.E. Jones et al., Nature **338** (1989) 737.
3. H.O. Menlove et al., "The measurement of neutron emission from Ti plus D_2 gas," Los Alamos National Laboratory Report LA-UR-89-1570 (1989).
4. A. De Ninno et al., "Neutron emission from a titasnium-deuterium system," Workshop on Cold Fusion Phenomena, 1989, Santa Fe.
5. A.J. Appleby et al., "Evidence for excess heat generation rates during electrolysis of D_2O in LiOD using a palladium cathode - A microcalorimetric study," ibid.
6. K.L. Wolf et al., "Neutron emission and the tritium content associated with deuterium loaded palladium and tritium metals," ibid.
7. L. Pauling, Nature **339** (1989) 105.
8. A.F. AbuTaha, "Cold fusion - heat mechanism," Workshop on Cold Fusion Phenomena, 1989, Santa Fe.
9. C D. Van Siclen and S.E. Jones, J. Phys. G: Nucl. Phys.**12** (1986) 213.
10. R. Seitz, Nature **339** (1989) 185.
11. V.A. Klyuev et al., Sov. Tech Phys. Lett. **12** (1986) 551.
12. J.S. Cohen and J.D. Davies, Nature **338** (1989) 705
13. K. Nagamine et al., "Evidence against condensed matter fusion induced by cosmic-ray muons," Workshop on Cold Fusion Phenomena, 1989, Santa Fe.

14. E. Linke and J. Wollbrandt, "Emission of high energy electrons by mechanical treatment," 4th International Symposium on Exoelectropn Emission and Dosimetry, Liblice 1973, INIS-mf-1597 (Feb. 1974).
15. V.A. Kluev et al., Dokl. Phys. Chem. **279** (1984) 1027.
16. G.A. Sobolev et al., Dokl. Acad. Nauk **276** (1984) 583.
17. J.T. Dickinson, E.E. Donaldson and M.K. Park, J. Mater. Sci. **16** (1981) 2897.
18. F.J. Mayer, J.S. King and J.R. Reitz, "Nuclear fusion from crack-generated particle acceleration," Workshop on Cold Fusion Phenomena, 1989, Santa Fe.
19. B.H. Duane et al., "Fusion cross section theory," Battelle Pacific Northwest Laboratory. Report BNWL-1685 (1972).

Table 1 Examples of dependence of electric potential difference, V, at a crack, and electron flow speed, v_e, along the crack surface, on the gap width, δ, and the charge density, Σ, on the crack-wall. Resistivity, ρ, vertex angle, θ, and electron density, n_e, are assumed as 4.0×10^{-7} Ωm, 10^{-2}, and 10^{29} m^{-3}, respectively.

V(V)	δ(m)	Σ(m^{-2})	v_e(ms^{-1})
10^4	10^{-3}	5.5×10^{14}	1.7×10^1
10^4	10^{-4}	5.5×10^{15}	1.7×10^2
10^5	10^{-3}	5.5×10^{15}	1.7×10^2
10^5	10^{-4}	5.5×10^{16}	1.7×10^3

Table 2 Coefficients S and A in the formula of the fusion cross sections.

	σ_{DDp}	σ_{DDn}	σ_{DT}
S(m^{2}keV)	1.5×10^{-26}	2.0×10^{-26}	2.3×10^{-24}
A(keV$^{1/2}$)	46	48	46

Table 3 Comparison of collision frequencies relating the energy losses of accelerated deuteron.

Large-angle elastic scattering	Ionization-excitation collision	Small-angle scattering Coulomb collision
$\nu_R \sim n_{cry} \sigma v$	$\nu_{eff} < (E^*/E_0) v / d_e$	$\nu = 1/\tau_s$
$\sigma \sim 10^{-28} m^2$ $v \sim 10^6 ms^{-1}$ $n_{cry} \sim 10^{29} m^{-3}$ $\nu_R \sim 10^7 s^{-1}$	$E^* \sim 10eV$ $E_0 \sim 10keV$ $d_e \approx n_e^{1/3} \sim 10^{-10} m$ $\nu_{eff} \sim 10^{13} s^{-1}$	$E_0 \sim 10keV$ $\nu \sim 8 \times 10^{14} s^{-1}$ $E_0 \sim 100keV$ $\nu \sim 2.5 \times 10^{13} s^{-1}$

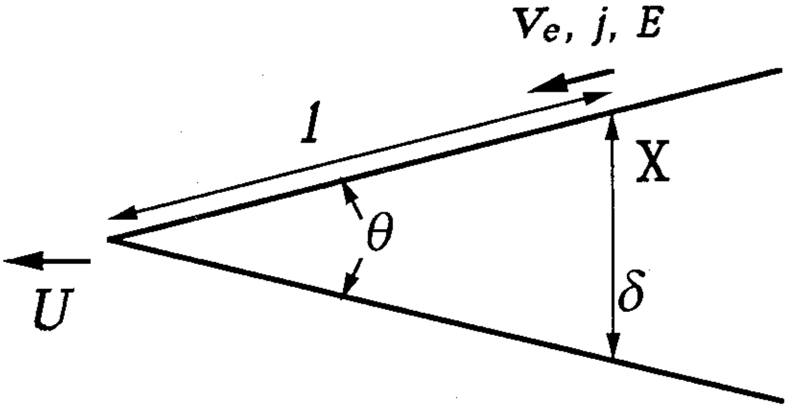

Fig.1 Crack propagation process.

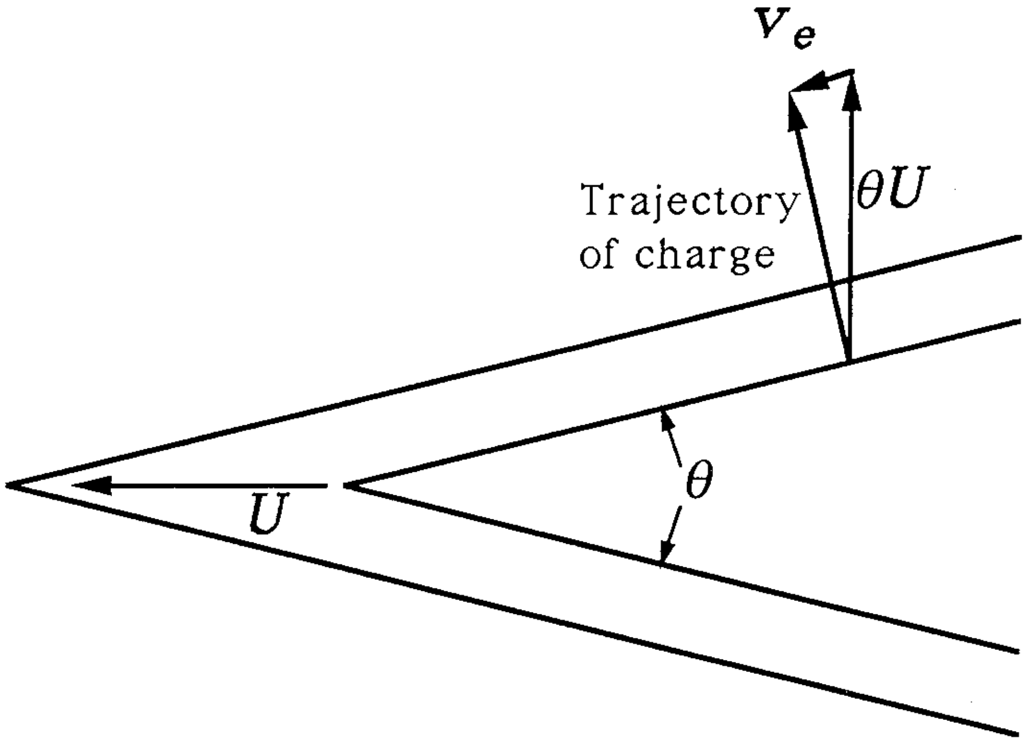

Fig.2 Motion of unbalanced charges during the growth of the crack.

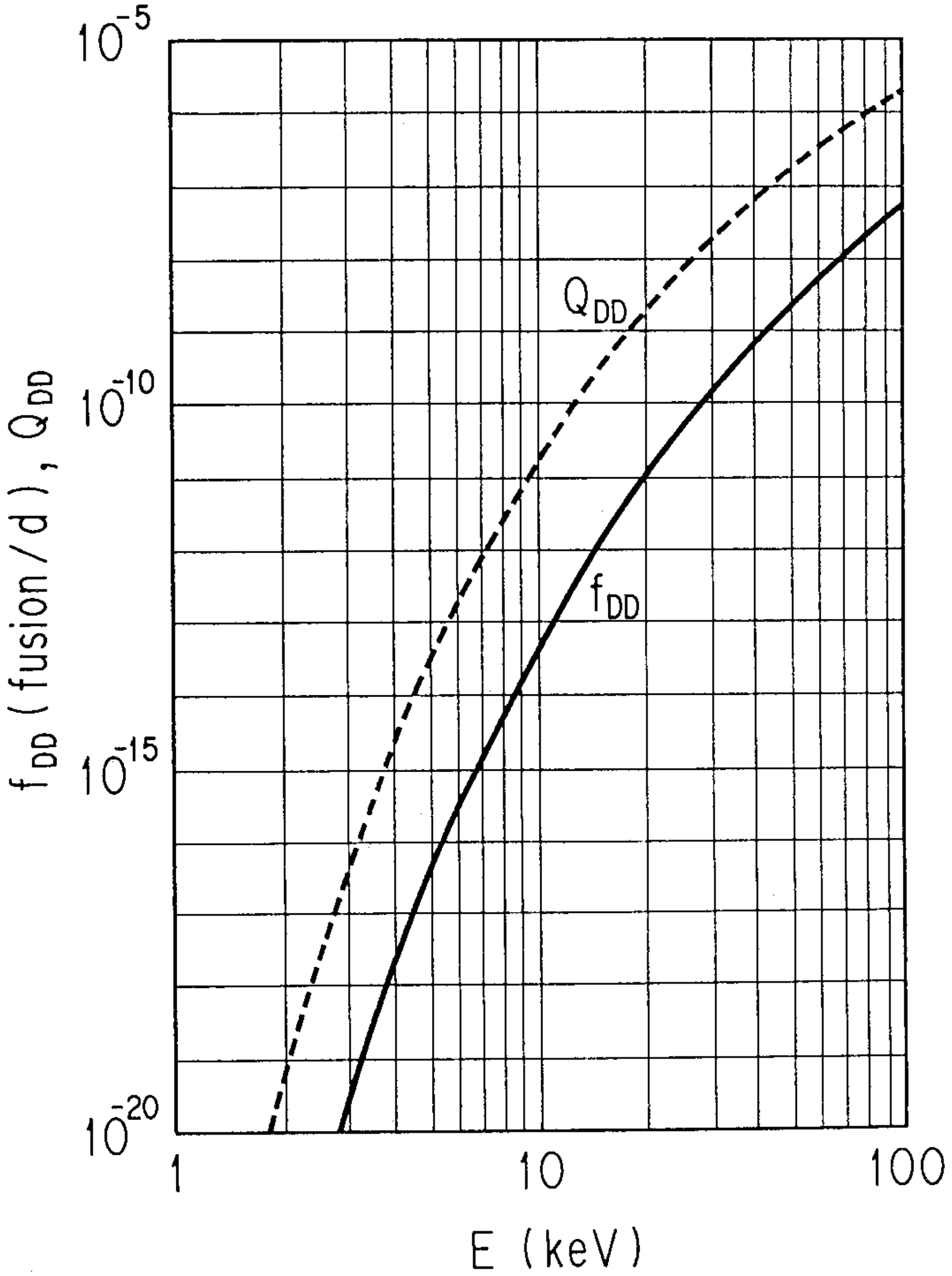

Fig.3 Number of DD fusions per deuteron, f_{DD}, and energy multiplication factor, Q_{DD}, versus energy, *E*, of a deuteron accelerated by the crack-generated electric field.

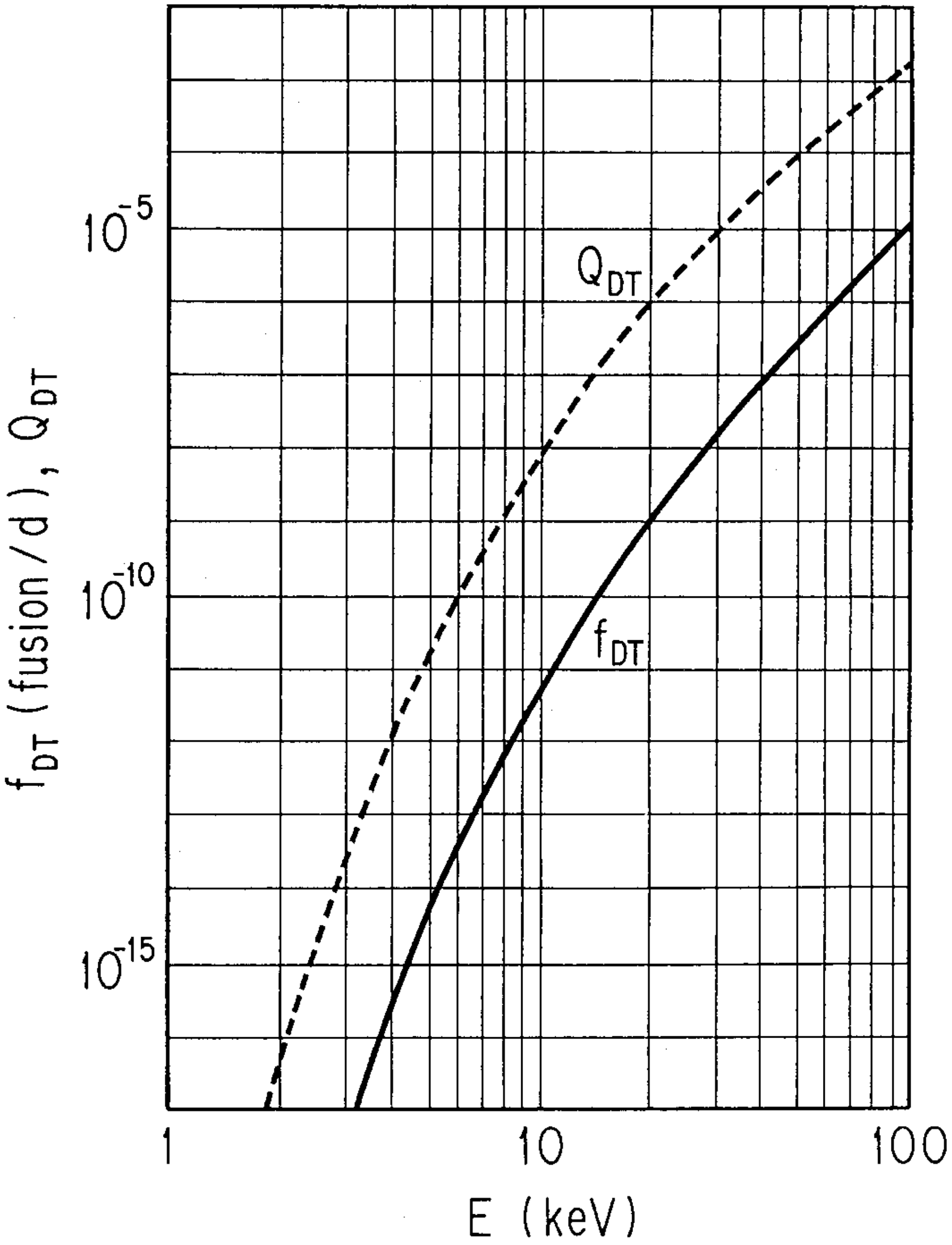

Fig.4 Number of DT fusions per deuteron, f_{DT}, and energy multiplication factor, Q_{DT}.