A new approach to achieving D–D fusion reactions

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The attractive prospects for using thermonuclear energy sources are stimulating searches for new methods of designing controlled nuclear fusion reactions. After the recent noisy "uproar" concerning cold fusion, one must expect a definite skepticism in regard to any attempt to discuss approaches even remotely reminiscent of cold fusion or that differ from the traditional and intensively developed methods of controlled thermonuclear fusion.

Nevertheless, in the present note we would like to call attention to a recent paper[1] in which it seems an effect of "warm" (by analogy with the term cold) D–D fusion was observed.

The experiments carried out in Ref. 1 and subsequently may be associated with a unique achievement of a fairly old idea[2] of creating the conditions for setting off fusion reactions by means of colliding large particles that have been accelerated to high velocities. As is well known, the strong compression and heating of matter in the shock wave which arises upon the collision of a large particle with an obstacle (or with a similar particle) can guarantee creation of conditions for the occurrence of fusion reactions. The last detailed discussion of this problem in the pages of "Uspekhi Fizicheskikh Nauk" occurred in 1981,[3] and serious difficulties in achieving the necessary collision velocities were noted.

In the work discussed below, which was done at Brookhaven National Laboratory (U.S.A.), singly ionized heavy water clusters $(D_2O)_N D^+$ (from now on $(D_2O)_N$) which were accelerated in a linear Cockroft–Walton type accelerator (see Fig. 1) to energies of the order of 300 keV (i.e., to velocities ~ 100 km/sec) were used as the colliding particles. A plate of deuterized (to a high degree of saturation) titanium (TiD) was used as the bombardment target. Size selection of the clusters was done by means of a quadrupole mass spectrometer placed at the entrance to the accelerator section. Its resolution provided a controlled range of the number of molecules in a cluster from several tens to thousands ($25 \leqslant N \leqslant 1{,}300$). Typical currents of beams of accelerated clusters of specified size were from 1 nA to 10 nA. For the indicated values of N and a nominal beam energy of 300 keV, the specific energies per deuteron $E(D)$ varied in the range $0.12 \leqslant E(D) \leqslant 6$ keV.

The fusion channels of interest correspond to the reactions

$$^2H + {}^2H \begin{cases} \rightarrow {}^1H(3\ \text{MeV}) + {}^3H(1\ \text{MeV}) \\ \rightarrow {}^3He(0.8\ \text{MeV}) + n(2.45\ \text{MeV}). \end{cases}$$

A semiconductor detector was used to detect the energetic products ^1H, ^3H, and ^3He in Ref. 1, and a typical spectrum of the output signal amplitudes from the semiconductor detector is shown in Fig. 2. Calibration of the semiconductor detector (the scales of a multichannel analyzer) was done with α-particle sources (^{241}Am, ^{148}Gd), and one can reliably identify a line that is recorded in the 3 MeV region with the output of energetic protons from a fusion reaction. However, control measurements with the semiconductor detector covered with an aluminum layer 48 mg/cm^2 thick were made for an additional verification of this. Slowing down of the products in the absorbing aluminum layer led to a shift of the observed lines that is predicted based on the known tabulated values of the material's slowing-down capability. Thus, the fact of the recording of energetic protons of thermonuclear origin which originate during the bombardment of a TiD target by accelerated $(D_2O)_N$ clus-

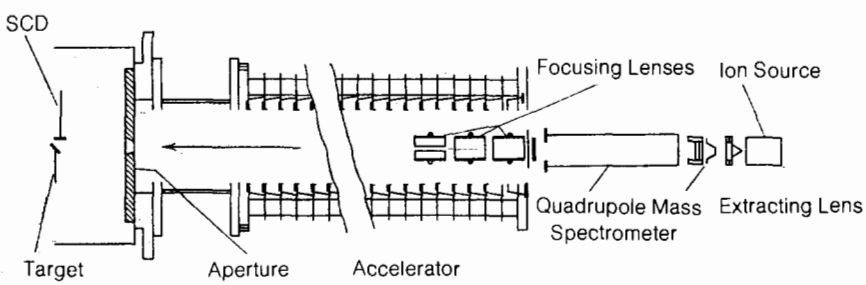

FIG. 1. Layout of the experimental facility of Ref. 1. Charged clusters that are carried out by a gas dynamical jet towards the extracting lens are formed in the ion source by means of a corona discharge in a mixture of water vapor and helium. The extracting lens collimates and accelerates the charged clusters into a quadrupole mass spectrometer, isolating a beam of clusters of a specified size. The focused cluster beam is accelerated in the accelerator section to a nominal energy, goes through a restricting aperture, and falls onto a TiD target. The target is placed at a 45° angle; SCD, the semiconductor detector, intercepts the emerging energetic fusion reaction products.

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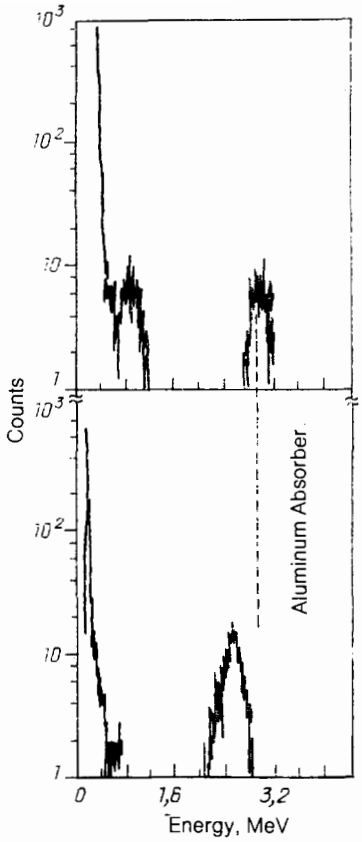

FIG. 2. The amplitude distributions of the output signals from the semiconductor detector that are recorded during bombardment of the target by heavy water clusters. The lower spectrum corresponds to the semiconductor detector covered by an aluminum layer (48 mg/cm^2). A shift of the lines caused by slowing-down of the reaction products in the shielding layer and which agrees with calculation is evident.

ters appears to be convincingly demonstrated. The makeup of the bombarding beam was analyzed by means of the same semiconductor detector shielded by a thin ($50\,\mu$g/cm^2) aluminum layer to eliminate the trivial explanation of the appearance of products by the presence in the beam of fragments (for example, D^+, OD^+, and D_2O^+) with total energies of hundreds of keV. The thickness of this layer is sufficient for "stopping" the atoms of the accelerated clusters, but it transmits with slight slowing-down the high energy (D^+, OD^+, and D_2O^+) fragments. This control experiment enabled one to estimate the possible contribution of the admixtures of energetic fragments to be at a level of no more than 0.3% of the value of the output that is recorded for the case of bombardment of the target by a beam of accelerated clusters.

The complete elimination of parasitic contributions to the measured yield, however, requires additional control experiments. Thus, in a recent note,[4] attention was called to one more possible source of "self-poisoning" of a beam in the course of an experiment. Besides the beam itself, there is a second potential source of admixtures. Sputtering of the target material inevitably occurs during bombardment of deuterated targets. The secondary products (their ionized component of type D^+ and D_2^+) that enter the first part of the acceleration interval can contaminate the beam with an admixture of fast deuterons. If one considers the sharp dependence of the reaction cross-section on energy, even a trace of admixtures can produce the recorded output. In response to this note, the Brookhaven group excluded this possibility on the basis of the small amount of the total current of the bombarding beam. However, direct experimental verification of the absence of this admixture, for example, by means of spatial separation of the light and heavy (cluster) components of the beam will obviously be the best answer here.

Along with TiD, the authors used deuterated zirconium and polydeuteroethylene[5] as targets.[1]

It is also relevant to mention additional control experiments that have been done in this work. Thus, in one series of experiments, a beam of normal water clusters $(H_2O)_N$ was used to bombard a TiD target, and in another series, a TiH target was bombarded by $(D_2O)_N$ clusters. In neither case was there an output of MeV energy protons. Except for the trivial explanation connected with significantly smaller cross sections for H–D reactions in comparison with the cross sections for D–D reactions, the absence of signals in the case of substituting D for H in the beam or target enables one to draw an even more reliable conclusion. The reason for this is that the fusion reactions which were observed obviously cannot be localized either in the impactor material nor in the target material, that are presumably compressed and heated by shock waves. Within the discussion of a possible mechanism with impact compression, it is relevant to notice that, for the hydrodynamic picture of the collision, the compressed impactor and target materials will be separated by the contact surface and, having different temperatures, will coexist in a certain sense without interacting with each other. Consequently, the need for direct "contact" of the D atoms in the beam and target as a condition for achieving a reaction appears to be an important consequence of the control experiments under discussion. Actually, such "contact" could have been attained in a process of primary collisional interaction which corresponds to an atomic and not to a macroscopic level of hydrodynamical treatment.

By using the well-known expression for a fusion reaction cross section[6]

$$\sigma(E) = \frac{S(E)}{E}\exp(-A/E^{1/2}) = \frac{S(E)}{E}\cdot 10^{-B/E^{1/2}}, \qquad (1)$$

where E is the relative collision energy ($S(E) = 0.55\cdot 10^{-22}$ cm^2 keV, $A = 31.28$ keV$^{1/2}$, and $B = 13.58$ keV$^{1/2}$), one can make estimates of the fusion reaction yield that is caused by direct collisions. According to Eq. (1), the cross section decreases sharply with a decrease of energy in the sub-keV range, and the yield of the reactions is exceptionally sensitive to the collision energy.

However, the results obtained in Ref. 1 (see Figs. 3 and 4) sharply contradict these expectations. The dependence of the yield of the products (3 MeV protons) normalized to the beam current on the size of clusters which were accelerated to the same nominal energy (300 keV) is shown in Fig. 3. The variation of N from 25 to 1,300 will be accompanied by a variation of the specific (per D_2O molecule or D atom) energy by 50 times. However, the variations of the yield in Fig. 3 fit into at most an order of magnitude. Furthermore, an increase in yield is seen at first (with a maximum at $N \approx 10^2$) with a decrease of specific energy. Here the measured yield exceeds that expected from an estimate for D–D collisions by 10 or more orders of magnitude. The result of measuring the dependence of the yield on energy for a beam of clusters

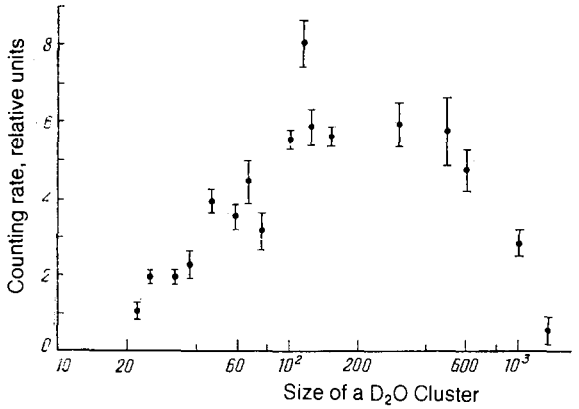

FIG. 3. The dependence of the yield (normalized to the beam current) of reaction products on the cluster size N with a nominal energy of 300 keV.

of fixed size ($N = 150$) that is shown in Fig. 4 also appears to be no less paradoxical. The relation for $\sigma(E)$ enables one to make an estimate of the possible output variations while varying the beam energy by 1.25 times (from 225 keV to 300 keV). Thus, if one assumes that the output is connected with fragmentary D^+ ions in the beam, then $\sigma(300)/\sigma(225) \approx 1$. But if one assumes that the output variation is connected with variations of the specific energies of the D atoms in the cluster, then $\sigma(0.20)/\sigma(0.15) \approx 10^4$. Thus, we have complete disagreement with the measurements for both cases. One can estimate the effective energy which, according to Eq. (1), provides a variation of output by 10 times. The value of E_{eff} turns out to be ~ 6 keV for the case where the specific energy $E(D) = 0.2$ keV.

These unexpected results initiated experimental[7] and theoretical[8] efforts directed towards confirming and explaining the observations. A group of French researchers from the Institute of Nuclear Physics in Lyon attempted to detect the products of nuclear fusion by bombarding a target of deuterated titanium with beams of clusters of D_2 (and also of N_2) molecules. The results of experiments with specific energies of D atoms in a beam $E(D) \lesssim 1$ keV turned out to be negative. However, one must notice that this result is apparently entirely regular and could be predicted before the measurements. The group plans to repeat the experiment in the future using beams of heavy water clusters.

An attempt at a quantitative explanation of the observations of Ref. 1 based on an impact mechanism for heating matter was presented in Ref. 8. In it, in essence (by postulating an anomalously high (500 eV) temperature of matter during collision), the calculated reaction rate values and the energy dependence of the yield have been fitted to the observations due to the contribution of the high energy "tail" of the Maxwell–Boltzmann distribution. The arbitrariness of the fitting is evident from the fact, for example, that, in the $N = 1{,}000$ case, the specific energy $E(D_2O)$ of a molecule entering into a cluster equals 300 eV, 80% of which is associated with the oxygen atom. As a result of collision with the target, the energy is redistributed between the atoms of the impactor and target material, and it is completely improbable to obtain average energies (temperatures) above 100 eV under these conditions. But one cannot successfully explain the yield which was observed in Ref. 1 at temperatures < 100 eV.

One must expect that, because of the mass ratio, the collisional "pumping" of energy from the oxygen atoms to the deuterium atoms of the impactor and target is very inefficient. One cannot succeed in achieving equipartition of energy since, according to an estimate, the characteristic path length ($L \sim 20$ Å) for such energy transfer is comparable with the linear dimensions ($R_{\text{cl}} = 10$ to 40 Å) of the clusters. Thus, the problem of the quantitative explanation of the anomalous yield remains even after the publication of Ref. 8.

Because of the low efficiency of direct collisional energy transfer, one must look for channels for increasing it. A simple possibility for "pumping" the relative energies of D–D collisions up to a level that provides a significant increase in yield is considered below. One of the possibilities may be based on the obvious consideration of the structural features of the target and of the cluster and the molecules which form it (see Fig. 5). The presence of structure provides for the realization of correlated collisions, and specifically, of collisions in a linear chain of atoms arising from an impacting D–O molecule fragment and an impacted Ti–D target fragment. The difference of the masses of O and D atoms obvi-

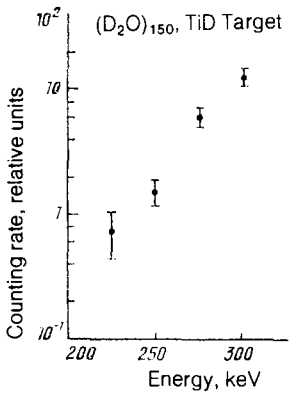

FIG. 4. Dependence on energy of the yield of products during bombardment of the target by clusters of fixed ($N = 150$) size.

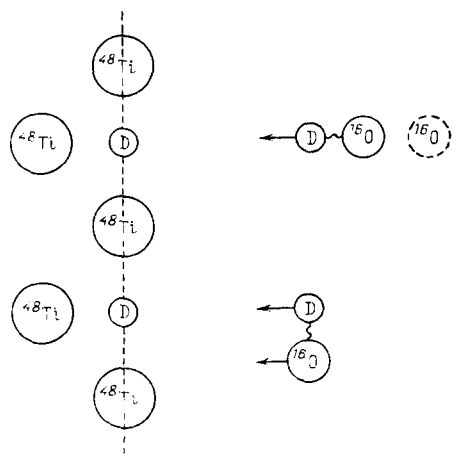

FIG. 5. Schematic representation of the collinear and orthogonal configurations of a collision complex of target fragments (Ti–D) and of a water molecule (O–D).

ously increases the efficiency of "pumping" energy from O to D in such a chain. Actually, the collision of the D atoms in a chain occurs as if between a "hammer" (an O atom) and an "anvil" (a Ti atom), and the closest approach distance R_{D-D} of the atoms will be determined by the total energy E(O–D) of the fragment. By solving the equations of motion for the atoms of a chain in the classical mechanical approximation that is justified here, one can find the closest approach distance R_{D-D} for D atoms, which determines the tunneling transition probability. The tunneling exponential $P = \exp(-31.28/E)^{1/2} = 10^{-13.58/E^{1/2}}$ can be easily converted to the form $P = 10^{-11.33R_{D-D}^{1/2}}$, where R_{D-D} is in units of 0.01 Å. In the numerical calculations, the interatomic interactions were described by the Coulomb repulsion potential for the deuterons and by the potentials from Refs. 9 and 10 for the other pairs. A time trace is shown in Fig. 6 for a typical trajectory of the relative motion of D atoms in a chain (the case of an impact with $N = 100$ and $E_{cl} = 300$ keV was modelled). (The calculations were carried out by Dr. Ts.-S. Van). Multiple collisions with attainment of the minimum R_{D-D} after the third or fourth oscillation, when the relative energy of collision turns out to be close to half of the initial kinetic energy E(O–D) of the fragment, are a typical feature of such trajectories.

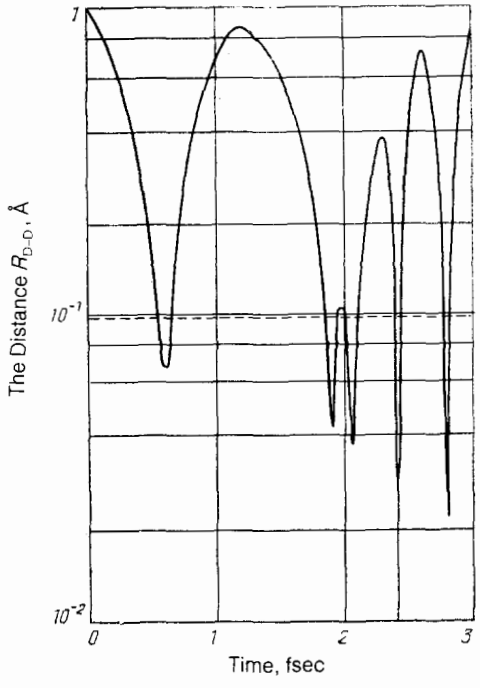

FIG. 6. A time trace of a classical collision trajectory in a linear Ti–D–D–O chain. A D–O fragment strikes a Ti–D fragment with velocity $1.7 \cdot 10^7$ cm/sec. Due to an increase of the relative energies of the collisions, a multiple D–D collision leads to an increase of the probability for a tunneling passage through the reaction energy barrier. The closest approach distance R_{D-D} for a collision with an energy E(D) corresponding to the velocity $1.7 \cdot 10^7$ cm/sec is shown by the dashed line.

The calculations show that the gain in the probability P for a tunneling transition that is attainable here can amount to from 10 to 30 orders of magnitude for N in the $25 \leqslant N \leqslant 1{,}000$ range in comparison with the values calculated for E(D). Thus, collinear collisions in a chain actually provide an efficient energy "pumping" by increasing the reaction probability. The question as to whether this is sufficient for a quantitative description of the observations remains open. To a significant degree, the efficiency of such a mechanism will be determined by the geometric structure of the cluster.

Certain indications as to the nature of the distribution of the molecular axes in water clusters can be found from Ref. 11. A predominance of the O–H bonds oriented radially in a spherical cluster with the hydrogen atoms "looking" outward has been noted in Ref. 11.

The problems of the present note and the limited amount of available experimental data make a more detailed discussion of possible mechanisms premature.

In conclusion, I would like to call attention to the statement made in Ref. 1 that "a new approach to studying nuclear fusion reactions ... and, possibly, a new path to obtaining thermonuclear energy" has been developed by the authors, and also the intention stated in Ref. 5 of conducting analogous experiments using a more powerful (5 MW) accelerator and large clusters.

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