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Nuclear fusion induced by a neutron flux in a crystal
Repulsive Coulomb potential

Kinetic energy

\[ E = kT \]

\( T \) (°K)

<table>
<thead>
<tr>
<th>Room</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>15 × 10^6</td>
</tr>
<tr>
<td>( V_{\text{max}} )</td>
<td>10^{10}</td>
</tr>
</tbody>
</table>

\( E \) (eV)

<table>
<thead>
<tr>
<th>Room</th>
<th>10^{-2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>1.3</td>
</tr>
<tr>
<td>( V_{\text{max}} )</td>
<td>1 MeV</td>
</tr>
</tbody>
</table>

Penetration

<table>
<thead>
<tr>
<th>Room</th>
<th>10^{-2600}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>10^{-10}</td>
</tr>
<tr>
<td>( V_{\text{max}} )</td>
<td>1</td>
</tr>
</tbody>
</table>

\( V_{\text{max}} \sim 1 \text{ MeV} \)

\[ V_c(r) = \frac{Z_1 Z_2 e^2}{r} \]

\[ P \sim \exp \left( -\frac{2\pi Z_1 Z_2}{137} \sqrt{\frac{mc^2}{2E}} \right) \]

Number of pp-pairs in the sun \( \sim 10^{57} \)
\[ N_A = 6.02214076 \times 10^{23} \text{ mol}^{-1} \]

<table>
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<th>whole crystal</th>
<th>single pair</th>
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<td>1 fusion/hour</td>
<td>( \frac{1}{N_A \cdot 3600 \text{ s}} \approx 10^{-27} \text{ s}^{-1} )</td>
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\[ N_A = 6.02214076 \times 10^{23} \text{ mol}^{-1} \]

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Electromagnetically induced fusion (in a crystal)

V. B. Belyaev, M. B. Miller, J. Otto, and S. A. Rakityansky
Nuclear fusion induced by x rays in a crystal

Exposing the solid compound LiD (lithium deuteride) to X rays for the duration of 111 h, we detect 88 events of nuclear fusion $d + ^6\text{Li} \rightarrow ^8\text{Be}^*$
Nuclear fusion induced by x rays in a crystal

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The nuclei that constitute a crystalline lattice oscillate relative to each other with a very low energy that is not sufficient to penetrate through the Coulomb barriers separating them. An additional energy, which is needed to tunnel through the barrier and fuse, can be supplied by external electromagnetic waves (x rays or synchrotron radiation). Exposing the solid compound LiD (lithium deuteride) to x rays for the duration of 111 h, we detect 88 events of nuclear fusion $d + ^6\text{Li} \rightarrow ^8\text{Be}$. Our theoretical estimate agrees with what we observed. One possible application of the phenomenon we found is in measurements of the rates of various nuclear reactions (not necessarily fusion) at extremely low energies inaccessible in accelerator experiments.

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I. INTRODUCTION

Fusion of two atomic nuclei is possible if they approach each other at a short distance ($\sim 10^{-13}$ cm). To come that close, they need to go through a Coulomb barrier of the height of a few MeV. The penetration probability for such a barrier at room temperature (energy of relative motion, $\sim 10$ meV) is practically 0 ($\sim 10^{-2600}$ [1]), but this probability rapidly increases when the kinetic energy of the nuclei increases. For example, for the $dd$ system at an energy of 30 keV the penetration probability becomes $\sim 10^{-3}$ [1]. Therefore, the obvious way to fuse the nuclei is to raise the temperature of their mixture. In this way so-called thermonuclear reactions occur in stellar bodies, in nuclear weapons, and in the TOKAMAK [2].

such a probability, one muon can help with fusion, i.e., can catalyze the fusion of many nuclear pairs before it decays (muon lifetime, $\sim 2 \times 10^{-6}$ s). Muon-catalyzed fusion has been observed and well studied both experimentally and theoretically (see, for example, Refs. [6] and [7]) but turned out to be inefficient as a new source for energy production.

In the present paper, we suggest and experimentally explore yet another possible approach to fusion of light nuclei. The idea is to make a crystal out of the atoms whose nuclei we want to fuse. In this crystal, the nuclei sit next to each other at an atomic distance and oscillate around the equilibrium positions. A crystal is just a huge molecule, and of course the probability of spontaneous fusion of neighboring nuclei is negligible, the same as in ordinary molecules. An experiment aimed at observing spontaneous fusion in the lithium deuteride...
\[ d^6\text{Li} \rightarrow \alpha + \alpha + 22.3726 \text{ MeV} \]

**Barrier penetration**

**d\(^6\text{Li}\) -- system**

\[ 2^+(22.2 \text{ MeV, } \Gamma \approx 800 \text{ keV}) \]

\[ \begin{align*}
22.2808 \\
21.688 \\
21.380 \\
18.8997 \\
17.2551 \\
-0.0918
\end{align*} \]

- \(d + ^6\text{Li}\)
- \(t + ^5\text{Li} + 0.5928 \text{ MeV}\)
- \(^3\text{He} + ^5\text{He} + 0.9008 \text{ MeV}\)
- \(n + ^7\text{Be} + 3.3811 \text{ MeV}\)
- \(p + ^7\text{Li} + 5.0257 \text{ MeV}\)
- \(\alpha + \alpha + 22.3726 \text{ MeV} \quad 96\%\)
LiD - crystal

\[ V_d(x) = \frac{Z_1 Z_2 e^2}{R_0 - x} + \frac{Z_1 Z_2 e^2}{R_0 + x} \]

\[ V_{\text{max}} \approx \frac{Z_1 Z_2 e^2}{r_1 + r_2} \approx 0.922 \text{ MeV} \]

\[ V_{\text{min}} = \frac{2Z_1 Z_2 e^2}{R_0} \approx 42.35 \text{ eV} \]

\[ r_1 = 2.1424 \text{ fm} , \quad r_2 = 2.5432 \text{ fm} \]
"dents" due to the electron clouds

$\approx 30 \text{ eV}$

$0.922 \text{ MeV}$

$20(r_1 + r_2) \approx 94 \text{ fm}$

$R_0 \approx 2 \times 10^5 \text{ fm}$

$V_d (\text{MeV})$

$V_{\text{max}}$
\[ E_n = \frac{\pi^2 \hbar^2 n^2}{8 \mu_d R_0^2}, \quad \psi_n(x) = \frac{1}{\sqrt{R_0}} \sin \frac{\pi n (R_0 + x)}{2R_0}, \quad n = 1, 2, 3, \ldots \]

\[ E_1(d) \approx 0.6 \text{ meV} \]

\[ E_1(\text{Li}) \approx 0.2 \text{ meV} \]
d
12,746 levels

Li6
22,030 levels

Avogadro number of nuclei $\sim 10^{23}$

100 keV

LiD - crystal

Boltzmann distribution

$$P_n = \frac{\exp \left( -\frac{E_n}{k_B T} \right)}{\sum_{j=1}^{\infty} \exp \left( -\frac{E_j}{k_B T} \right)}$$

$$\langle E \rangle_d = \sum_{n=1}^{\infty} E_n P_n \approx 14.2 \text{ meV}$$

$$\langle E \rangle_{Li} \approx 13.6 \text{ meV}$$

$T = 300 \text{ °K}$
At $T = 300 \, ^\circ \text{K}$, the energy level population is given by:

\[
\langle E \rangle_d = \sum_{n=1}^{\infty} E_n P_n \approx 14.2 \, \text{meV}
\]

\[
\langle E \rangle_{\text{Li}} \approx 13.6 \, \text{meV}
\]

Population of the energy levels

**Boltzmann distribution**

\[
P_n = \frac{\exp \left(-\frac{E_n}{k_B T}\right)}{\sum_{j=1}^{\infty} \exp \left(-\frac{E_j}{k_B T}\right)}
\]

12,746 levels

100 keV

22,030 levels

\[E_n = 100 \, \text{keV} \rightarrow P_n \sim 10^{-1700000}\]

Occupation probabilities of the square-well levels:

\textit{deuterons}, $T = 300 \, ^\circ \text{K}$
Avogadro number of nuclei $\sim 10^{23}$

Under the X-ray radiation the distribution is changing

Master equation

$$\frac{dP_m}{dt} = \sum_{n\neq m} p_{mn}P_n - \sum_{n\neq m} p_{nm}P_m + \sum_{n>m} p_{mn}^{sp}P_n - \sum_{n<m} p_{nm}^{sp}P_m$$

New distribution over the levels that depends on the spectrum of the X-rays
We only need the **stationary distribution**:

\[
0 = \sum_{n \neq m} p_{mn} P_n - \sum_{n \neq m} p_{nm} P_m + \sum_{n > m} p_{nm}^{sp} P_n - \sum_{n < m} p_{nm}^{sp} P_m
\]

**Normalization condition**

\[
\sum_{n} P_n = 1
\]

This linear system can be solved iteratively.

Occupation probabilities of the square-well levels under the influence of X-rays.

\[P(100 \text{ keV}) \sim 10^{-44}\]
Avogadro number of nuclei $\sim 10^{23}$

New distribution over the levels that depends on the spectrum of the neutron flux
Similarly, the rate can be found if the size of the cell is $2R_0$ and the velocity of the nucleus is $v$, then the attempts are repeated with the period $t = \frac{4R_0}{v}$ and the frequency $\nu = \frac{v}{4R_0}$.

The penetration probability is given by:

$$T(E) = \frac{2\pi \eta}{\exp(2\pi \eta) - 1} \xrightarrow{E \to 0} 2\pi \eta \exp(-2\pi \eta)$$

The Sommerfeld parameter is:

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar} \sqrt{\frac{\mu}{2E}}$$

The period of collisions is:

$$t = \frac{4R_0}{v}$$

The fusion rate is:

$$W_d(E) = T\nu = \frac{T(E)}{4R_0} \sqrt{\frac{2E}{\mu_d}}$$

Similarly, the rate $W_{Li}(E)$ can be found.
Average rates for the ensemble

\[ \langle W_d \rangle = \sum_{n} W_d(E_n^{(d)}) P_d(E_n^{(d)}) \]

\[ \langle W_{Li} \rangle = \sum_{n} W_{Li}(E_n^{(Li)}) P_{Li}(E_n^{(Li)}) \]

\[ \langle W_d \rangle \approx 2.4 \times 10^{-26} \text{ s}^{-1}, \quad \langle W_{Li} \rangle \approx 4.6 \times 10^{-27} \text{ s}^{-1} \]

``Bulk’’ rate for the sample

\[ R = \frac{6M}{m} N_A f_2 f_6 \left( \langle W_d \rangle + \langle W_{Li} \rangle \right) \]

molar mass

\[ m = f_1 \text{1 g} + f_2 \text{2 g} + f_6 \text{6 g} + f_7 \text{7 g} \]

\[ f_2 = 0.98, \quad f_6 = 0.0759, \quad M = 0.61 \text{ g} \]

\[ R \approx 5.2 \times 10^{-4} \text{ s}^{-1} \]

Exposure time \( t = 111 \text{ hours} \)

Expected events: \( N = 207 \)

Experiment: \( N > 88 \)
Experiment

85 detector plates
1 cm x 1 cm

Etching:
6.25 mol/L NaOH
70 °C
8 hours

$E > 6$ MeV

Background: $n + ^6\text{Li} \rightarrow \alpha + t + 4.78$ MeV
**Experiment**

**Etching:**
- 6.25 mol/L NaOH
- 70 °C
- 8 hours

**Background:**

\[ n + ^6\text{Li} \rightarrow \alpha + t + 4.78 \text{ MeV} \]
Low-energy tracks

$E > 6 \text{ MeV}$
Efficiency of detecting

We cannot register all the fusion events because the α-particles slow down when passing through the material.

Theory: $N = 207$

Experiment: $N > 88$

$88 \approx 40\% \rightarrow N \approx 220$
SUMMARY

• Neutrons can excite the oscillations of the nuclei relative to each other in a crystal

• Low fusion probabilities are magnified by the macroscopic number of the pairs

• Such a phenomenon could be used to study the low-energy nuclear reactions
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