New measurement of screening potential by ‘cooperative colliding process’ for the d+d reaction in metallic electron environment

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Cold Fusion in condensed matter

Is EH effect really due to a nuclear reaction?
D+D→⁴He+23.85 MeV
To get 1W power (Q value ~20MeV)
\[ R = \frac{1}{(20 \times 10^6 \times 1.6 \times 10^{-19})} = 3 \times 10^{11} \text{ reactions/sec} \]
note: D+D→p+T(50%), n+³He (50%)
\[ \rightarrow {}^4\text{He}+\gamma (\sim 10^{-6}) \]

Two miracles are needed (initial and final state)
1. Huge \( \sigma(E) \): fusion cross section
   D+D (initial state) \( \rightarrow {}^4\text{He}^* \) (intermediate state)
   how to overcome the Coulomb barrier?
2. New branch of the final state
   \( {}^4\text{He}^* \rightarrow {}^4\text{He}+x(\sim 100\% \text{ thermal energy}) \) (final state)

What we are asking by low-energy beam experiment is;
Can \( \sigma(E) \) be enhanced very much in metal?
Screening potential playing an important role in low energy reactions

Reaction rates at very low energies:
very much enhanced due to screening provided by surrounding conditions

\[ \sigma_b(E) = \frac{S(E)}{E} \exp(-2\pi \eta), \eta = \frac{Z_1 Z_2 e^2}{\hbar v} \]

\[ E \rightarrow E + U_{\text{screening}} \]

\[ \sigma_s(E) \sim \sigma_b(E + U_{\text{screening}}) \]

Gamow factor for DD at room temperature

<table>
<thead>
<tr>
<th>( U_{\text{screen}} ) (eV)</th>
<th>( \exp(-2\pi \eta) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 eV</td>
<td>10^{-2760}</td>
</tr>
<tr>
<td>13.6 eV</td>
<td>3.0 \times 10^{-117}</td>
</tr>
<tr>
<td>50 eV</td>
<td>1.7 \times 10^{-61}</td>
</tr>
<tr>
<td>300 eV</td>
<td>1.5 \times 10^{-25}</td>
</tr>
<tr>
<td>600 eV</td>
<td>2.9 \times 10^{-18}</td>
</tr>
</tbody>
</table>
Screening due to conduction electrons
(Thomas-Fermi screening)

\( \nabla^2 \varphi(r) = -4\pi e [Z \delta(r) - \delta n(r)]; \) Poisson equation

\( \delta n(r) = n(r) - n_0 \approx \frac{3}{2} n_0 \frac{e \varphi(r)}{\varepsilon_F}; \) conduction electrons

\( \varphi(r) = \frac{Ze}{r} \exp\left(-\frac{r}{D_s}\right); \) Screened electrostatic Potential

\( U_s = \frac{Z^2 e^2}{D_s} \) Screening Potential energy

\( D_s = \left(\frac{6\pi e^2 N_e}{E_F}\right)^{-1/2} \)

\( E_F: \) Fermi energy of electron

\( N_e: \) density of conduction electron

T-F \( U_s \) in metal

\( U_s \sim 24 \text{ eV} \quad > U_s(\text{bound electron}) \)

for \( E_F \sim 5 \text{ eV}, \) \( N_e \sim 5 \times 10^{22} \text{ cm}^{-3} \)

Electron density distribution

\( n_0 \rightarrow n(r) \)

Electrostatic potential due to polarized electrons
Nuclear reactions in various plasmas

- Nuclear reactions in stars
  - High T, Ultra-High density
    - $\Gamma \sim 1$, $\Theta < 1$
    - Border between Ideal plasma and Strongly-coupled-Degenerated plasma

- Nuclear reactions in various plasmas
  - $\Gamma > 1$, $\Theta < 1 \rightarrow \Gamma < 1$, $\Theta > 1$
  - another approach to NF

- Electron plasma; $\Theta \sim 0.1$

Simulations of screening in stars
Us for D+D and Li+d/p in various conditions

Rough values reported so far by us, Rolf’s group and Czerski’s group.
(simple estimation)

<table>
<thead>
<tr>
<th></th>
<th>atom/molec (bound e)</th>
<th>in metals (conduction e)</th>
<th>in solid Li</th>
<th>in liquid Li</th>
<th>liquid Li + ultrasonic cavitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>D+D</td>
<td>~25 eV (20 eV)</td>
<td>60~ 300 eV</td>
<td>~150 eV</td>
<td>190~350 eV</td>
<td>High-T plasma T ~ 6.8 × 10^6 K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>800 eV (Pd)</td>
<td>(25 eV)</td>
<td>(200 eV)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(30~70 eV)</td>
<td></td>
<td></td>
<td>[cf. Us ~ 2000 eV]</td>
</tr>
<tr>
<td>Li+D or Li+p</td>
<td>~290 eV (186 eV)</td>
<td>1200 eV (Pd)</td>
<td>~400 eV</td>
<td>480~550 eV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3800 eV (Pd)</td>
<td>(250 eV)</td>
<td>(670 eV)</td>
<td></td>
</tr>
</tbody>
</table>

In general, $U_s$(metal) > $U_s$(atom); conduction electrons!
$U_s$(liquid Li) > $U_s$(solid Li); mobile ions!
Experimental values are always larger than calculations.
Contribution of c.e. is much larger than expected.

However,
- different values are reported for same metal, often.
  - for ex., for Pd, ~800eV (Rolf’s G), ~300eV (ours and Czerski’s G)
  - for Zr, < 40 eV (Rolfs G), ~300 eV (Czerski’s G)

Problems of experimental method?
How can we determine values of $U_s$?

Previous measurements of $U_s$

Comparisons of experimental $Y(E_d)$ to calculated yield with $U_s$

\[ Y(E) \propto N_b N_T \sigma(E) \]

$N_b$: beam d

$N_T$: target d

$\sigma(E)$: cross section

\[ \sigma(E) = \sigma_{\text{bare}}(E) F(E, U_s) \]

\[ F(E, U_s) = \frac{\sigma(E)}{\sigma_{\text{bare}}(E)} = \exp\left(\frac{\pi \eta U_s}{E}\right) \]

$U_s = 0$

Enhancement Factor

$N_b$: from electric current

$N_T$?
target deuterons in solid metal

\[ Y(E) \propto N_b N_T \sigma(E) \]
- \( N_b \): beam d
- \( N_T \): target d
- \( \sigma(E) \): cross section

Density profile
5-keV D\(^+\) bombardment

range
10\(^{23}/\text{cm}^3\)

Density distribution near the surface:
saturation at the deep region
escape from the surface

surface cleanness? \( E_d \) dependence?
beam intensity dependence?
Ambiguity of \( N_T \) might give incorrect value of \( U_s \).
A new reaction process was found by chance. 
liquid Indium bombarded with deuteron molecular beam (d$_3^+$ beam)

We observed anomalous behavior of the d(d,p)t reaction. 
anomalous spectrum of p and t 
anomalous reaction yield vs Ed 
no reaction yield with atomic (d$^+$) beam bombardment

d-d colliding in metal; i.e., not fixed target. 
useful process to determine $U_s$ in metallic electron environment  
accurate value of $N_T$ 
easy check of surface cleanness
Experimental setup for liquid metal target with ultrasonic

Target chamber(1)
- Bending magnet
- Faraday cup
- Select: d⁺, d₂⁺, d₃⁺

Vac. < 10⁻⁵ Pa

Beam extraction

V_{ext} \approx -25 \text{ kV}

Focusing lenses

Target chamber(2)
- Faraday cup (movable)

Liquid target
- Heater

Ultrasonic (BLT) Transducer
- PZT

Inside:

Vac. < 10⁻⁵ Pa

Deuteron beam
- d⁺, 15–60 keV
- E_d = 5–20 keV
- I_{current} = 10 \sim 100 \mu \text{A}

Si Detector
- Area: 450 mm²
- Thickness: 100 \mu \text{m}
- Al (2 \mu \text{m}) absorber foil

~50 mm from target

Θ = 124°, 142°

Experiment:

d+d in liquid Indium

Liquid Indium
- T \sim 190°C (T_m=157°C)

Select: d⁺, d₂⁺, d₃⁺ (movable)

Deuterium beam
- d⁺, 15–60 keV
- E_d = 5–20 keV
- I_{current} = 10 \sim 100 \mu \text{A}

Si Detector
- Area: 450 mm²
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Ultrasonic repeat on/off
no effects
The reaction is not a simple two-body reaction. Target Ds are not at rest; they have finite momentum.
proton/triton spectra in liquid In

\[ \text{D(d,p)t, } E = 60 \text{ keV } d_3^+ \text{ beam, } \Theta = 124^\circ \]

Solid In
\[ T \sim 40^\circ \text{C} \]

Liquid In
\[ T \sim 190^\circ \text{C} \]
### Anomalous excitation function in liquid In

For the reaction $d(d, p)t$ in Indium, the thick target yield is given by:

$$Y_{thick} \propto \int_0^{E_d} \sigma(E) \cdot \left(\frac{dE}{dx}\right)^{-1} dE$$

where

$$\sigma(E) \approx \frac{S}{E} \cdot \exp(-2\pi Z_1 Z_2 \alpha \sqrt{\frac{\mu c^2}{2E}})$$

and

$$\frac{dE}{dx} \approx k\sqrt{E}$$

The yield equation for liquid In is:

$$Y_{thick} \propto \frac{2A}{kB} \exp\left(-\frac{B}{\sqrt{E_d}}\right)$$

For the $D(d, p)t$ reaction:

- $B = 44.39$: solid In; quite normal
- $B = 13.4$: liquid In; $E_{eff} \sim 10E_d$?

Target Ds are not at rest; they have finite momentum.
The d(d,p)t reaction occurs almost only with molecular (d$_2^+$/d$_3^+$) beam. Yield for d$_3^+$ beam is larger than for d$_2^+$; $Y(d_3^+)/Y(d_2^+) \sim 2.5$.

Atomic beam gives scarce yield; almost no deuterons are accumulated in liq. In.

Both target d and beam d are from same molecule; they collide cooperatively.
Other features

E=30keV, D$_3^+$, $\theta=142^\circ$

Solid In: large current dependence change of density of target d

Liquid In: no current dependence no temperature dependence stable density of target d

very stable reaction; no N$_b$ dependence, no T dependence

target d and beam d are from same molecule
Cooperative Colliding Process

Two-step reaction
First step: In(d,d)ln, d is elastically scattered by In
Second step: d(d,p)t with another d in the same molecule

d-d colliding with a partner
d-d colliding in a sea of conduction electrons
Unique kinematics; relation between d1 and d2
initial position of the partner depends only on the scattering angle $\theta_1$
$\theta_2 = \theta_1/2 + 90^\circ$; collision point depends only on $\theta_1$
d-d colliding energy depends only on $\theta_1$
$E_{cm} = E (1-\cos \theta_1)$

$N_T$ of the colliding reaction is determined by the bond length.

$$N_T = \frac{x-1}{4\pi R_{dd}^2} \quad (\text{atoms} / \text{cm}^2)$$

$X=2, 3$ for $D_2, D_3$
Calculation

\[ E_d \text{ decreases, beam flux decreases} \]

**Indium**

\[ E_0, F_0 \]

\[ d(d,p)t \text{ reaction:} \]

\[ d^2Y_n(E_n, \theta, \Theta) = dF'_n \cdot F_n \rho_d \cdot \left( \frac{d\sigma(E_n, E'_n, \Theta)}{d\Omega} \right)_{d+d} \Delta\Omega'(\Theta, \Phi) \]

\[ \text{dx} \]

**In each layer:**

\[ \ln(d,d)\ln \text{scattering:} \]

\[ dF'_n(E_n, \theta) = F_n \cdot \rho_{In} \text{ incident Flux } dx \cdot \left( \frac{d\sigma(E_n, \theta)}{d\Omega} \right)_{Ruthe} \Delta\Omega(\theta, \phi) \]
Calculations reproduce observed spectra very well.
Yield vs Ed: comparison with calculations

\[ \text{d}(d, p) t \text{ in liquid Indium} \]

\[ Y_{cal} = 2\pi \rho_{in} N_T \int \left( \frac{d\sigma_R}{d\theta_1}(E) \right) \sigma_{dd}(E_{cm} + U_s) \sin \theta_1 d\theta_1 \]

- ▲ Proton
- CCM(Us=0eV)
- CCM(Us=330eV)
Enhancement

Present value
\( U_s = 330 \pm 50 \text{ eV} \)

c.f.
\( U_s = 520 \pm 50 \text{ eV} \)
(experiment by Raiola et al.)
calculations
\( U_s = 30 \text{ eV} \)
(Thomas-Fermi screening)
\( U_s = 40 \text{ eV} \)
(Kato and Takigawa)
\( U_s = 130 \text{ eV} \)
(Czerski et al.)

Present result is not so large as reported so far. But definitely larger than theoretical predictions.
large screening for d+d due to electrons in metal is not fully understood

Czerski et al.: polarization charge of quantum e gas conduction e (Thomas-Fermi screening) bound e of host metal atom cohesive effects of d+d → (α*) $V_{d-env} + V_{d-env} > V_{\alpha^*-env}$ $U_{theo} < U_{exp}$; need another effect

Fig. 2. Experimental and theoretical electron screening energies.

Screening energy and Reaction rate at room temperature
(simple extraction of ~keV to < eV)

\[ D+D \rightarrow p+t \text{ reaction} \]
Assume \( \rho \sim 7 \times 10^{22}/\text{cc} \)

<table>
<thead>
<tr>
<th>( U_s (\text{eV}) )</th>
<th>rate (/cc/sec)</th>
<th>( \sigma (\text{b}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>( 2 \times 10^{-1} )</td>
<td>( 10^{-27} )</td>
</tr>
<tr>
<td>600</td>
<td>( 2 \times 10^{10} )</td>
<td>( 10^{-16} )</td>
</tr>
<tr>
<td>1000</td>
<td>( 2 \times 10^{14} )</td>
<td>( 10^{-12} )</td>
</tr>
</tbody>
</table>

\[ \text{Li}+\text{D} \rightarrow \alpha+\alpha \text{ reaction} \]
Assume \( \rho \sim 5 \times 10^{22}/\text{cc} \)

<table>
<thead>
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<th>( U_s (\text{eV}) )</th>
<th>rate (/cc/sec)</th>
<th>( \sigma (\text{b}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>( 10^{-3} )</td>
<td>( 10^{-29} )</td>
</tr>
<tr>
<td>1500</td>
<td>( 10^{3} )</td>
<td>( 10^{-23} )</td>
</tr>
<tr>
<td>2000</td>
<td>( 10^{6} )</td>
<td>( 10^{-20} )</td>
</tr>
</tbody>
</table>

D+D in metal
\( U_s = 300 \sim 350 \text{ eV} \)

Low level \((p,t,n,^3\text{He})\) emission may be observed.

However, heat production
300 eV \( \rightarrow 1 \text{pW/cc} \), 600 eV \( \rightarrow 0.1 \text{W/cc} \)

Li + D in liquid Li
\( U_s \sim 500 \text{ eV} \) for normal density

One needs \( U_s > 800 \text{ eV} \); 1000 eV \( \rightarrow \text{kW/cc} \)
Remarks and Future works

$U_s$ measurement by cooperative colliding is superior to the previous ones. Accurate $N_T$ (target deuteron density), clean surface.

It is clearly shown that the new $U_s$ value is, again, much larger than the present model calculations.

Why? Deep understanding is very important, not only for low-energy fusion in metal but also for reactions in stars.

We will proceed the measurement for other liquid metals. For ex., Ga ($n_e=15.3\times10^{22}$), Hg ($n_e=8.2\times10^{22}$), Bi($n_e=6.0\times10^{22}$); In ($n_e=11.5\times10^{22}$)

The measurement can be applied to solid metal target, also.

Use thin foil.

Kinematical selection with two detectors.

Target $d$ is at rest: Then, $\theta_1 + \theta_2 \sim 180^\circ$

**Diagram:**

- Detector 1
- Thin foil
- Molecular beam
- Detector 2
- $p$
- $t$
- $\theta_1$
- $\theta_2$

**Graph:**

- Yield (a.u.)
- $E_\gamma$ [keV]

Coincident measurement anti-coincidence
Possible events from the d(d,p)t reaction other than in liquid In

① reaction with D accumulated in surface contaminants
metal surface should be kept completely clean

Cleaning up

Skim off contaminants by a scraper

E=60keV, D$_3^+$, $\theta$=142° peak due to ①
(2) reaction with D accumulated in Al foil unavoidable; should be identified and subtracted

E = 60keV, D$_3^+$

θ = 124°

θ = 142°

Peaks due to (2)