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

J. Kasagi

Research Center for Electron Photon Science

Tohoku University

Cold Fusion in condensed matter

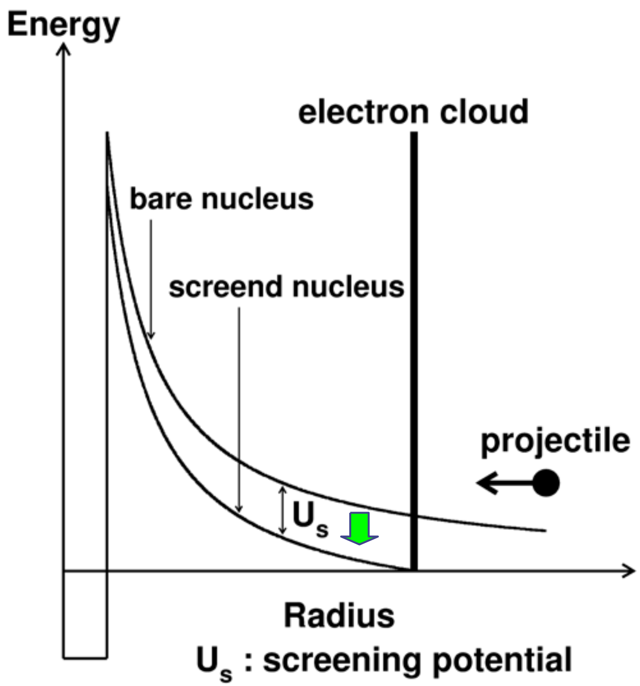
Is EH effect really due to a nuclear reaction?
$D+D \rightarrow {}^4He + 23.85$ MeV
To get 1W power（Q value ~20MeV）
$R = 1/(20 \times 10^6 \times 1.6 \times 10^{-19}) = 3 \times 10^{11}$ reactions/sec
note: $D+D \rightarrow p+T$ (50%), $n+{}^3He$ (50%)
$\rightarrow {}^4He+\gamma$ ($\sim 10^{-6}$)

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

$$\sigma_b(E) = \frac{S(E)}{E}\exp(-2\pi\eta), \eta = \frac{Z_1 Z_2 e^2}{h\nu}$$

Gamow factor

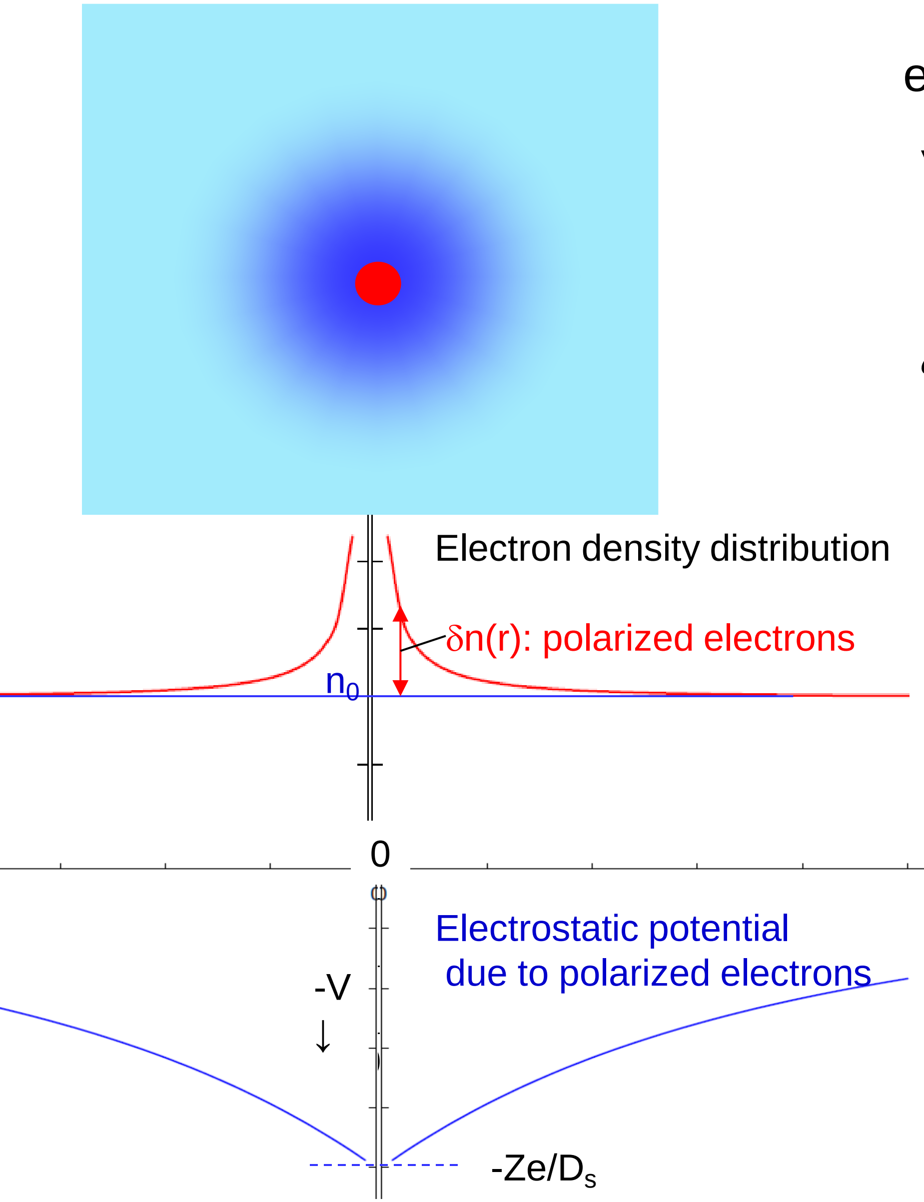
$$E \rightarrow E + U_{screening}$$

$$\sigma_s(E) \sim \sigma_b(E + U_{screening})$$

Gamow factor for DD at room temperature

U_{screen}	$\exp(-2\pi\eta)$
0 eV	10^{-2760}
13.6 eV	3.0×10^{-117}
50 eV	1.7×10^{-61}
300 eV	1.5×10^{-25}
600 eV	2.9×10^{-18}

Screening due to conduction electrons (Thomas-Fermi screening)



e^- density distribution $n_0 \rightarrow n(r)$

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

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

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

$$U_s = \frac{ZZ_p e^2}{D_s}$$ Screening Potential energy

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

E_F: Fermi energy of electron

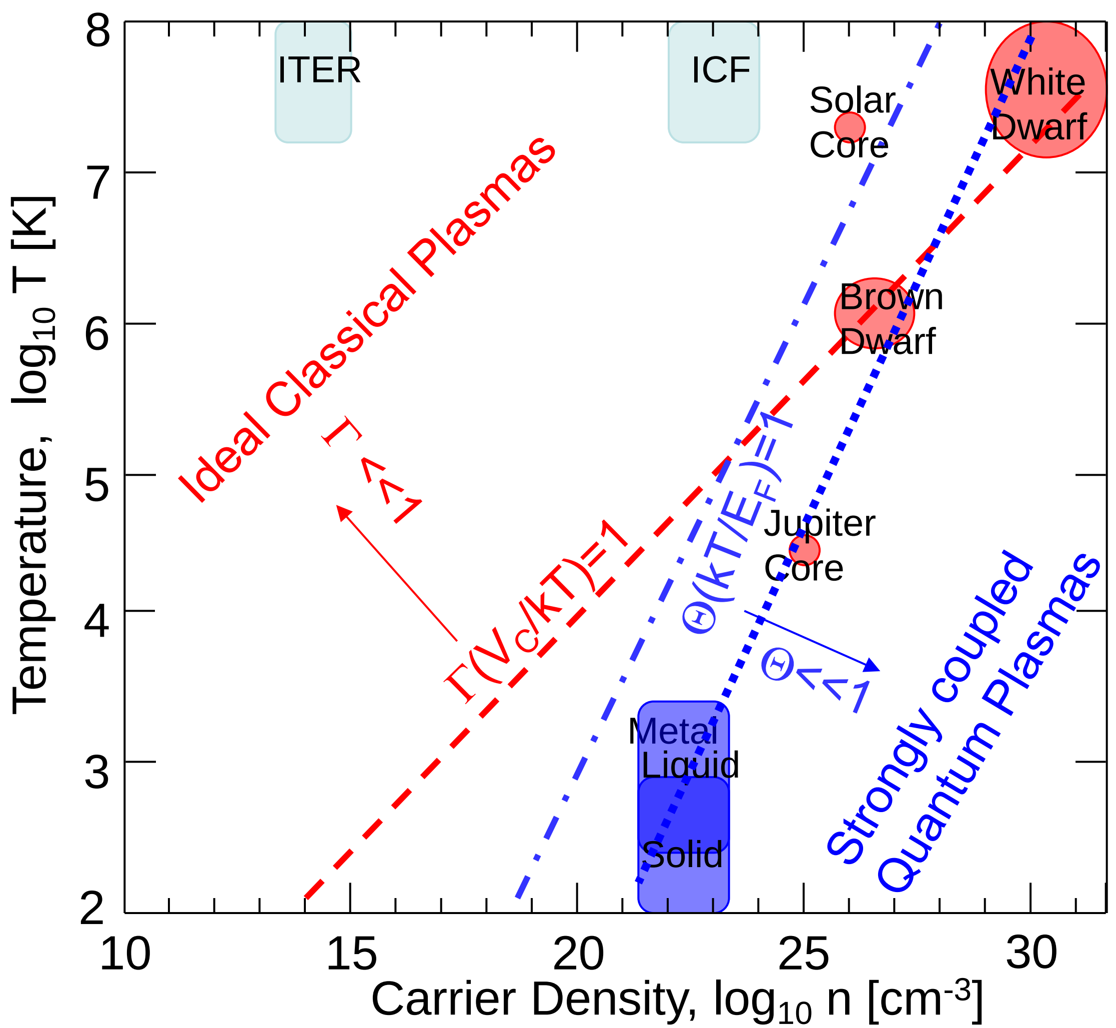
N_e: density of conduction electron

T-F U_s in metal

$U_s \sim 24$ eV $> U_s$(bound electron)

for $E_F \sim 5$ eV, $N_e \sim 5\times10^{22}$ cm^{-3}

Nuclear reactions in various plasmas



Hot Fusion on earth (ITER)
High T, Low density
$\Gamma < 0.1$, $\Theta > 10$
Ideal 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 Liquid/Solid Metals
$\Gamma > 1$, $\Theta < 1 \rightarrow \Gamma < 1$, $\Theta > 1$
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

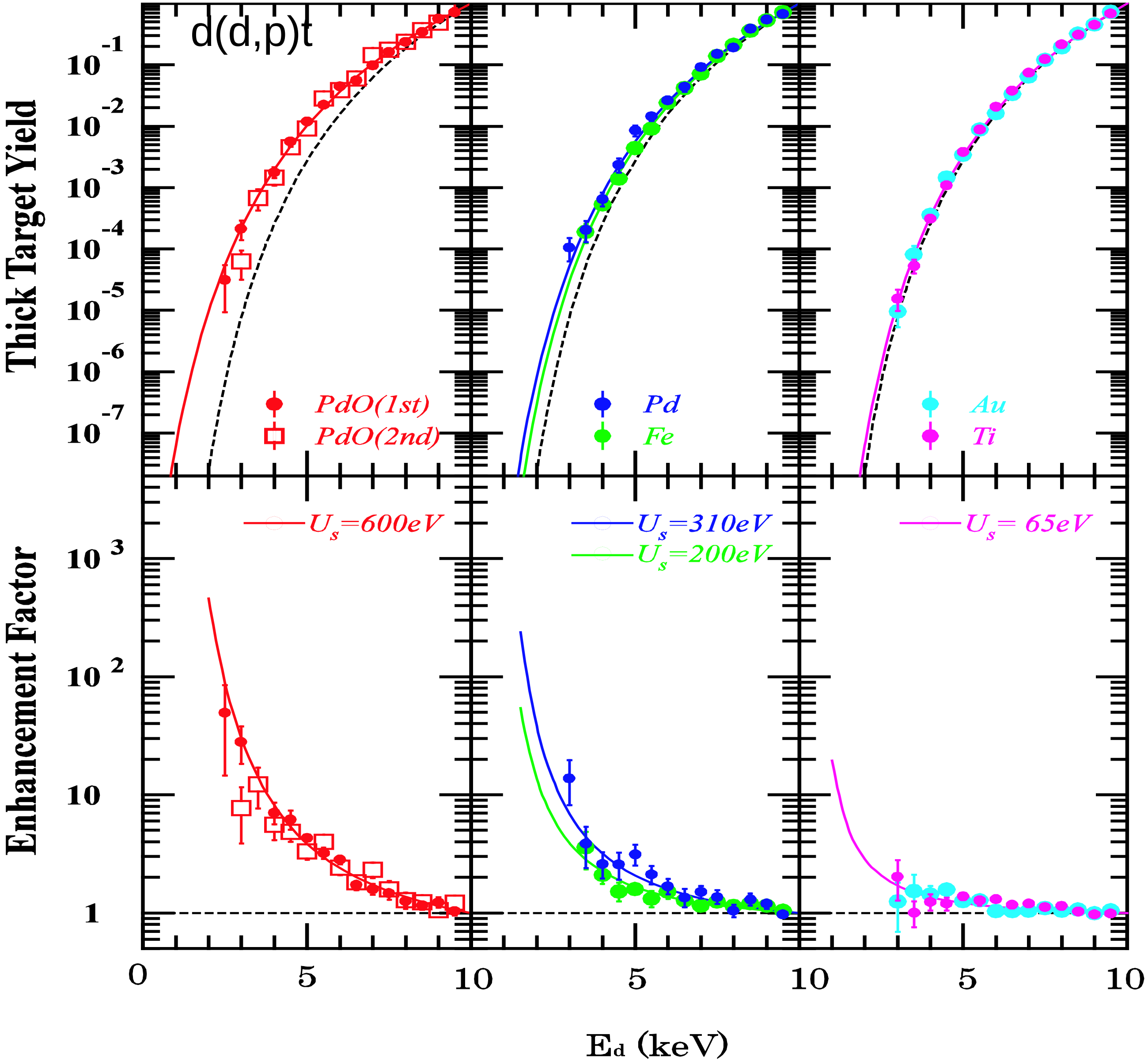
Rough values reported so far by us, Rolf's group and Czerski's group.
(simple estimation)

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

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 Us?
Previous measurements of Us

Comparisons of experimental Y(Ed) to calculated yield with Us



$Y(E) \propto N_b N_T \sigma(E)$

N_b: beam d

N_T: target d

$\sigma(E)$: cross section

$\sigma(E) = \sigma_{bare}(E)\, F(E,U_s)$

$U_s = 0$ (for σ_{bare})

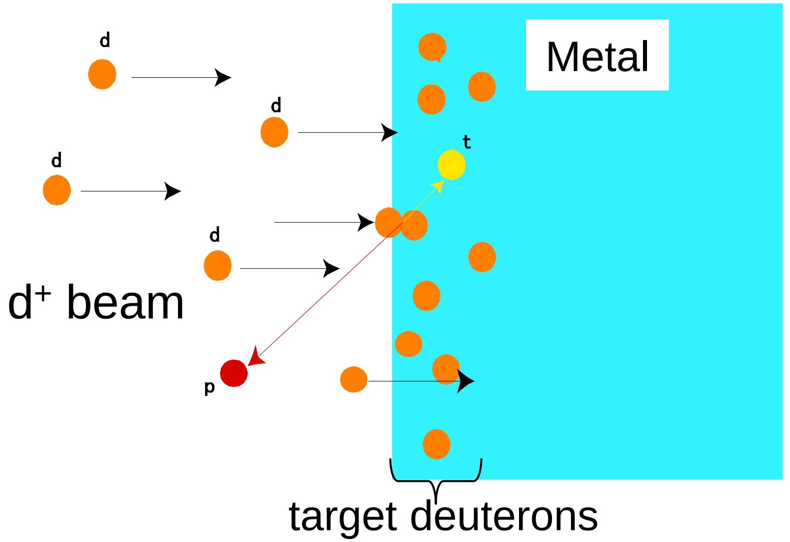
Enhancement Factor (for $F(E,U_s)$)

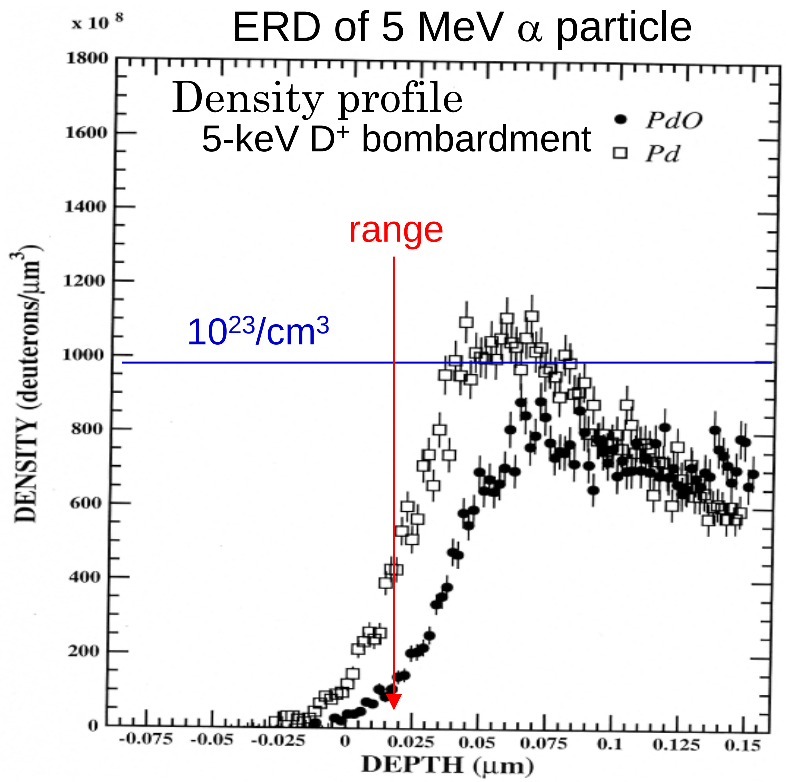
$F(E,U_s) = \sigma(E)/\sigma_{bare}(E)$
$= \exp(\pi\eta U_s/E)$

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 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 Us.

New measurement of Us

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

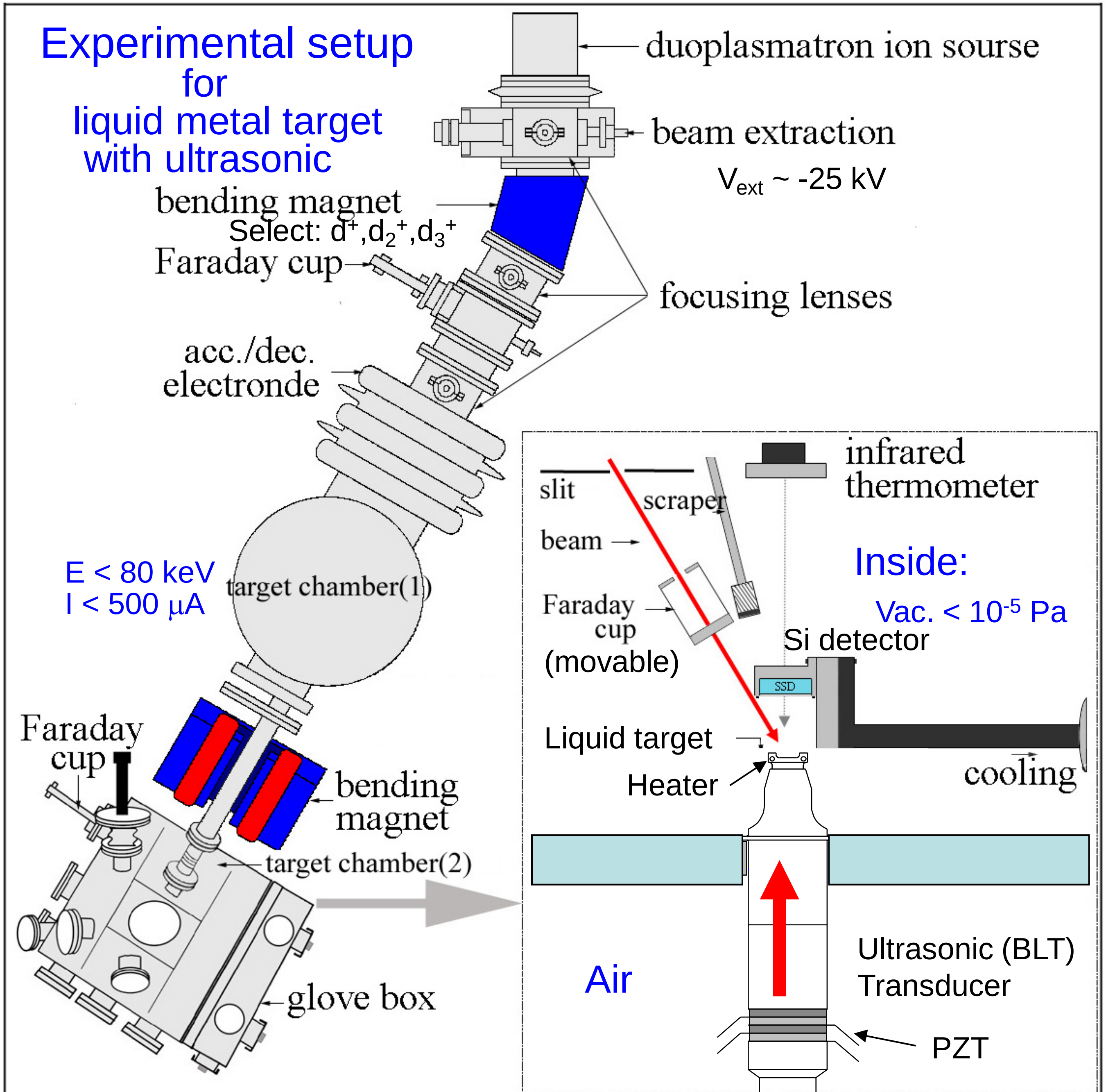
d-d colliding in metal; i.e., not fixed target.

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



Experiment:

d+d in liquid Indium

Deuteron beam

d_3^+, 15–60 keV

E_d = 5~20 keV

$I_{current}$ = 10 ~ 100 μA

Liquid Indium

T~190°C (T_m=157°C)

Si Detector

Area: 450 mm^2,

Thickness: 100μm

Al (2μm) absorber foil

~50 mm from target

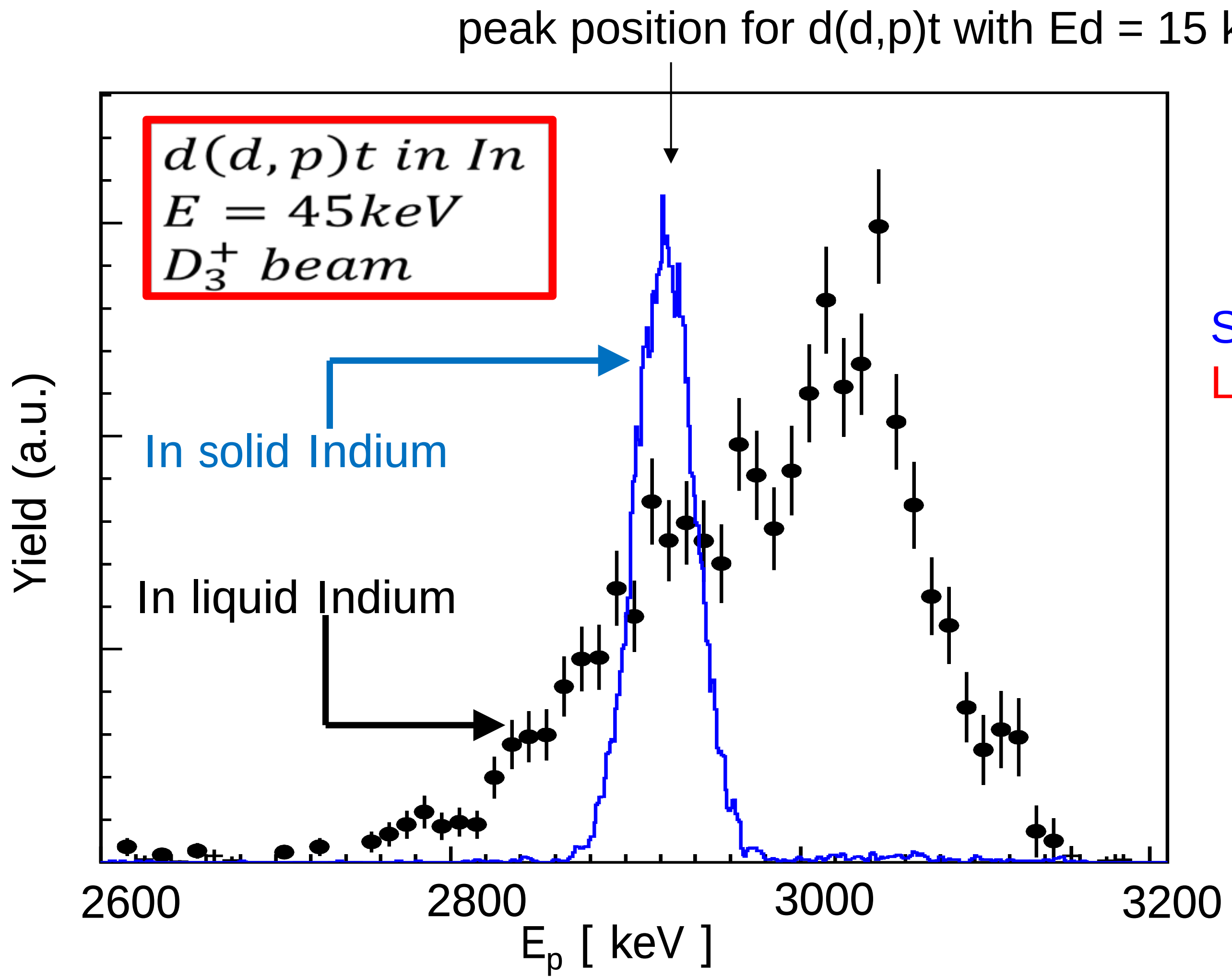
Θ = 124°, 142°

Ultrasonic

repeat on/off

no effects

① Mysterious proton spectra in liquid In



Solid In: quite normal

Liquid In: anomalous

① peak shift

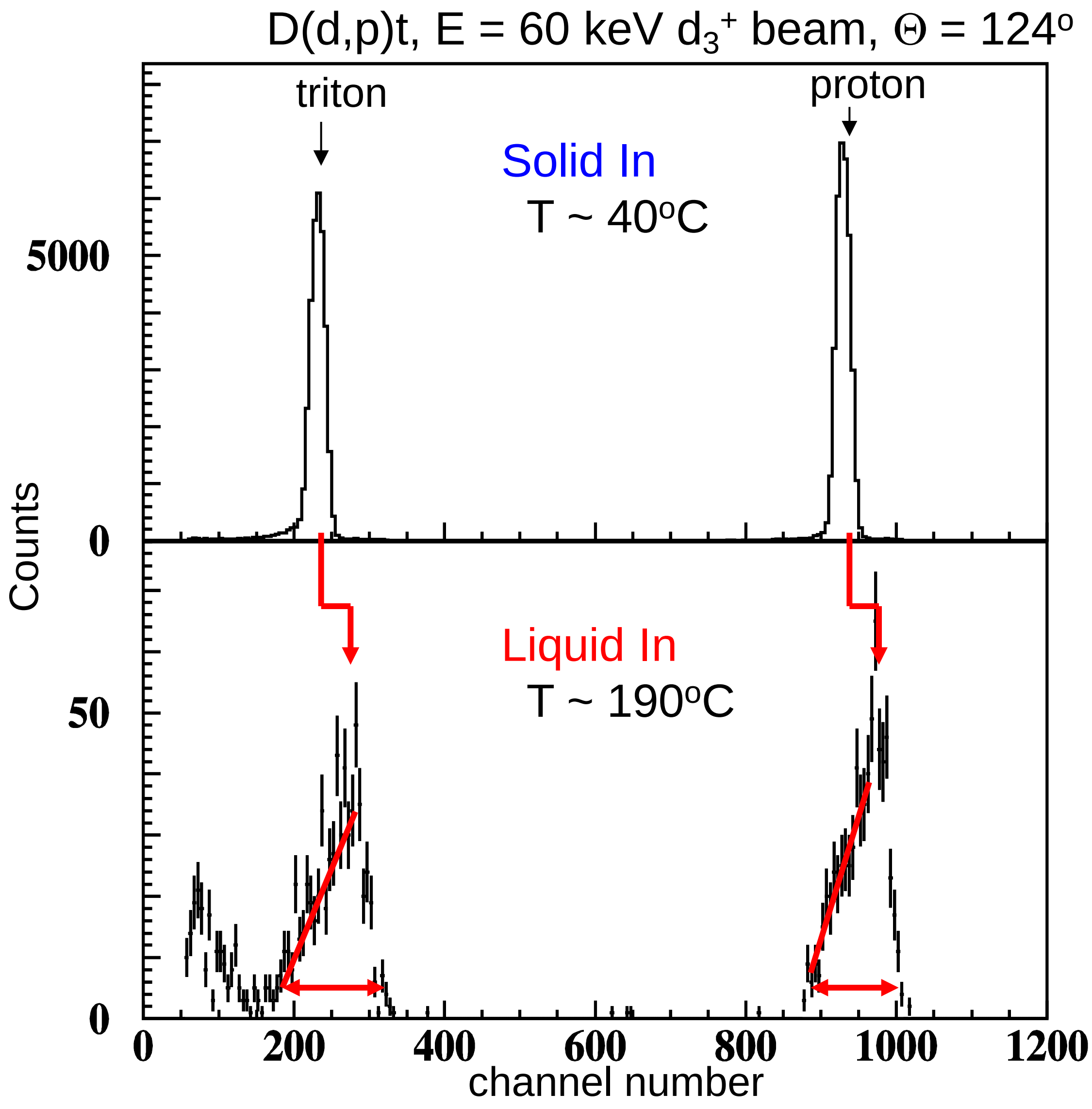
② broader width

③ asymmetric distribution

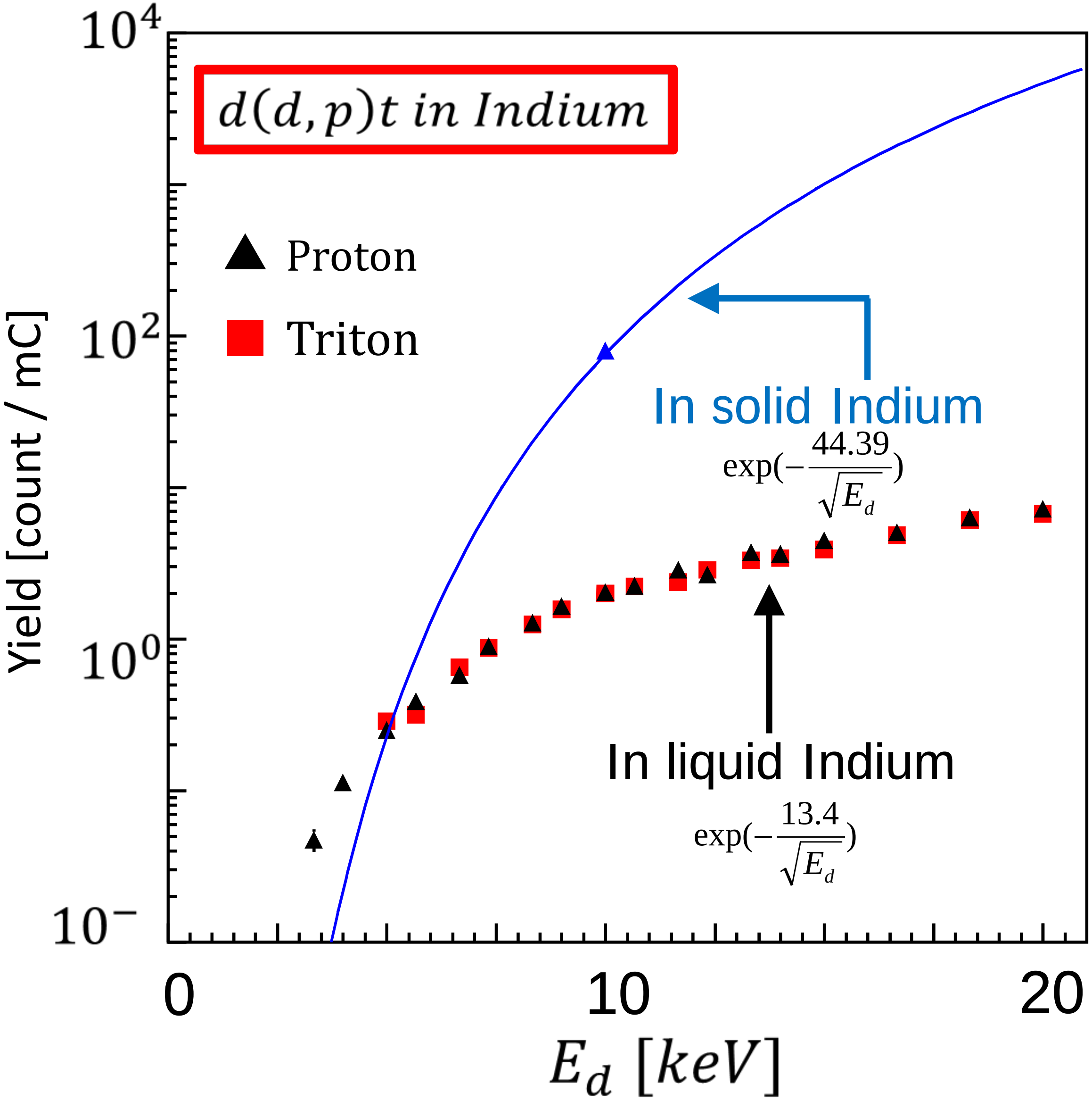
The reaction is not a simple two-body reaction.

Target Ds are not at rest; they have finite momentum.

proton/triton spectra in liquid In



② Anomalous excitation function in liquid In



Thick target yield

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

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

$$\equiv \frac{A}{E} \exp(-\frac{B}{\sqrt{E}})$$

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

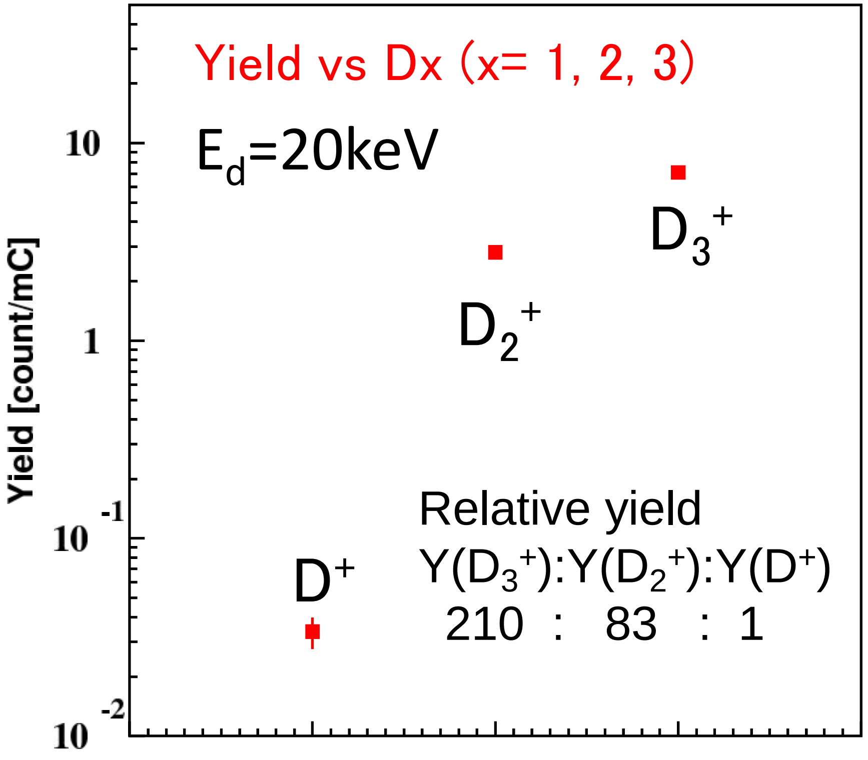
$$Y_{thick} \propto \frac{2A}{kB} \exp(-\frac{B}{\sqrt{E_d}})$$

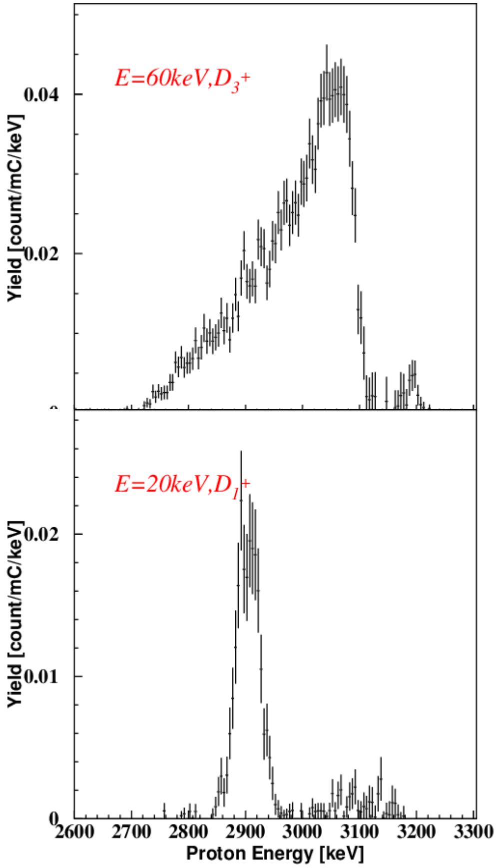
For D(d,p)t reaction
B = 44.39: sold In
quite normal

liquid In; B = 13.4??
$E_{eff} \sim 10E_d$?

Target Ds are not at rest;
they have finite momentum.

Yield vs number of deuterons number in molecule



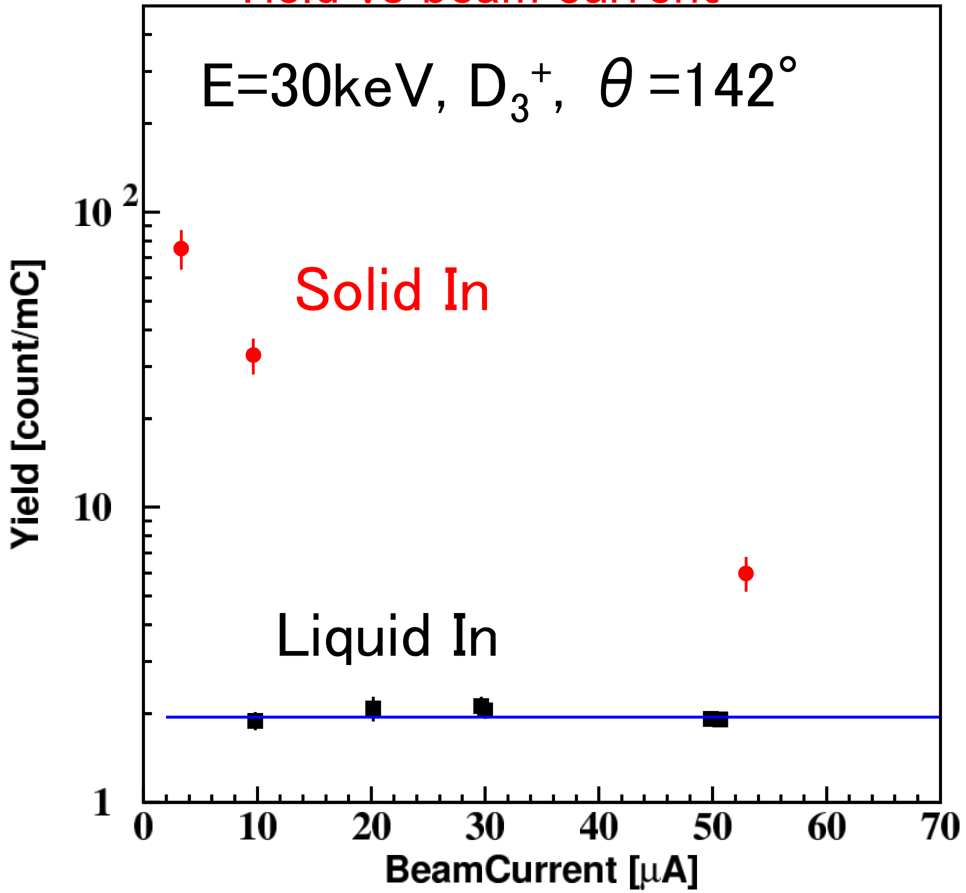


The d(d,p)t reaction occurs almost only with molecular (d_2^+/d_3^+) beam.
Yield for d_3^+ beam is larger than for d_2^+; $Y(d_3^+)/Y(d_2^+)$ ~ 2.5.
Atomic beam gives scarce yield; almost no deuterons are accumulated in liq. In.

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

Other features

Yield vs beam current



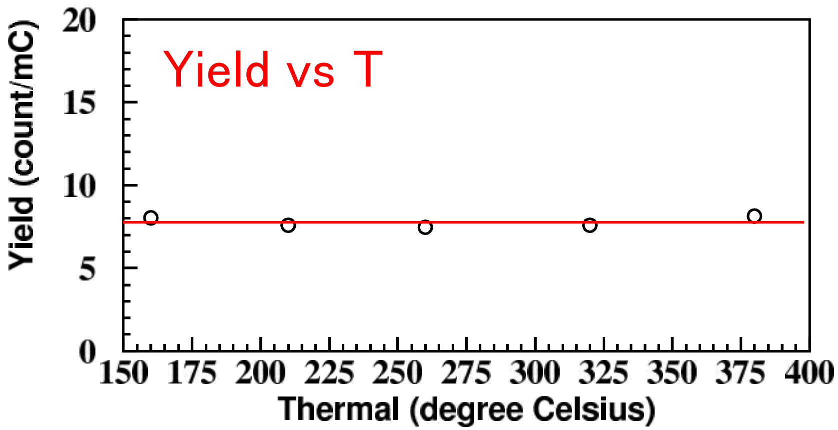
Solid In: large current dependence

change of density of target d

Liquid In: no current dependence

no temperature dependence

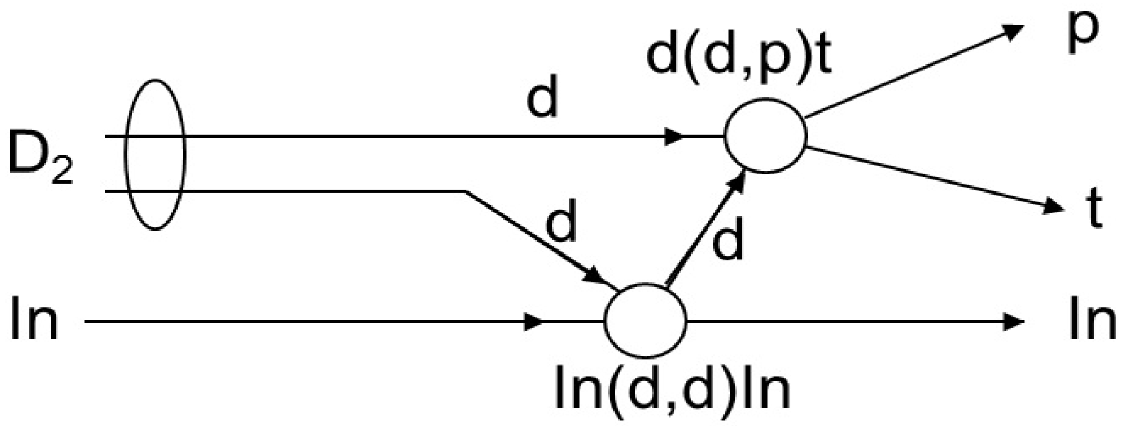
stable density of target d



very stable reaction; no N_b dependence, no T dependence

target d and beam d are from same molecule

Cooperative Colliding Process



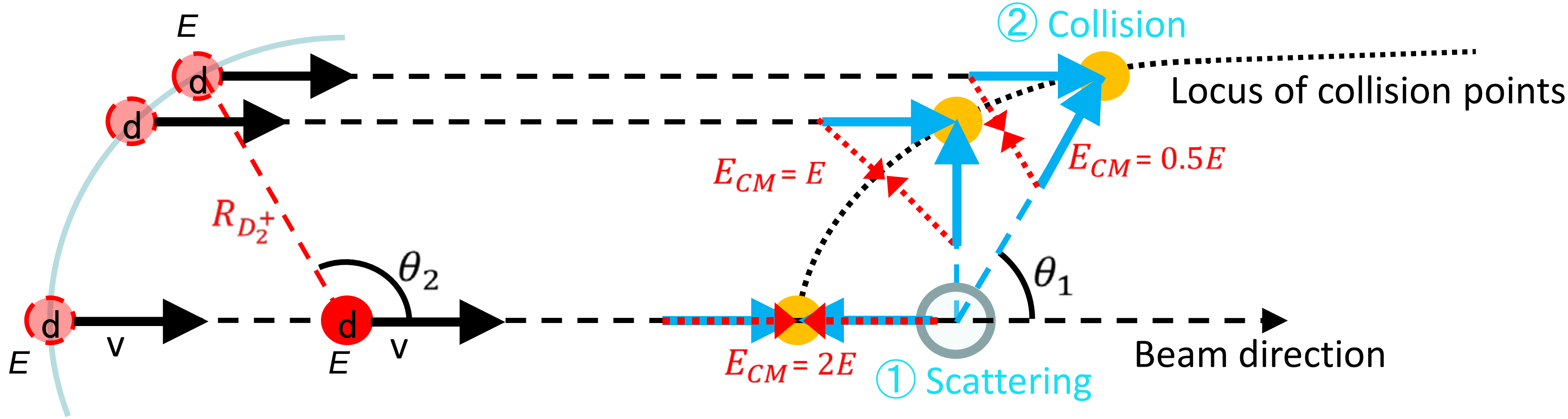
Two-step reaction

First step: In(d,d)In, 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

Kinematics of cooperative colliding



Unique kinematics; relation between d1 and d2

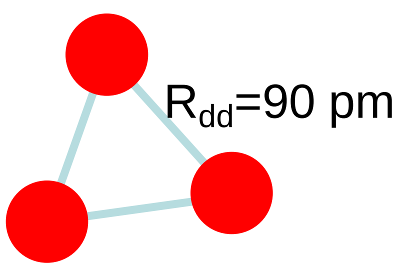
initial position of the partner depends only on the scattering angle θ_1

$\theta_2 = \theta_1/2 + 90^o$; collision point depends only on θ_1

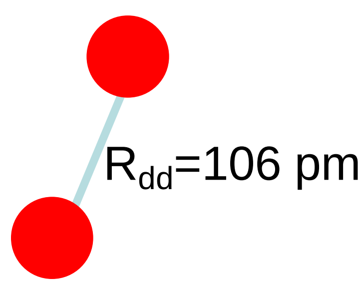
d-d colliding energy depends only on θ_1

$E_{cm} = E\,(1-\cos\theta_1)$

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



D_3^+

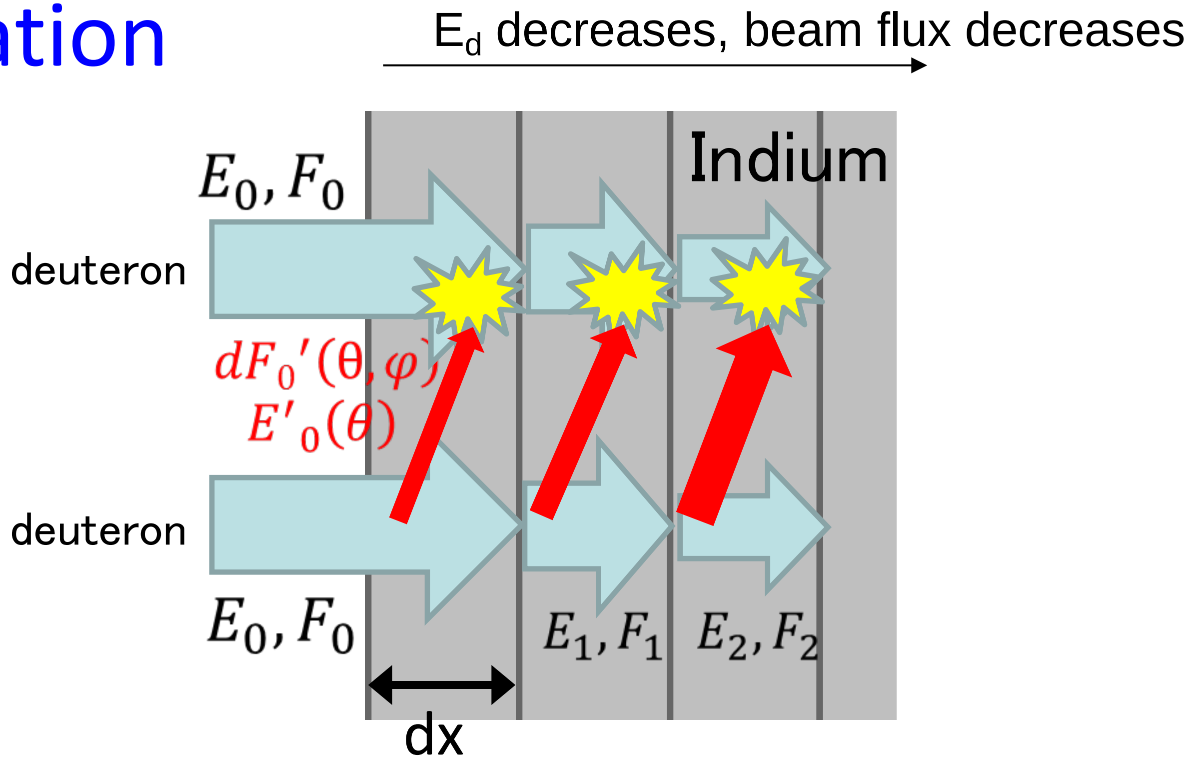


D_2^+

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

X=2, 3 for D_2, D_3

Calculation



In each layer:

In(d,d)In scattering:

$$dF_n'(E_n,\theta) = F_n \cdot \rho_{In}\, dx \cdot \left(\frac{d\sigma(E_n,\theta)}{d\Omega}\right)_{Ruthe} \Delta\Omega(\theta,\phi)$$

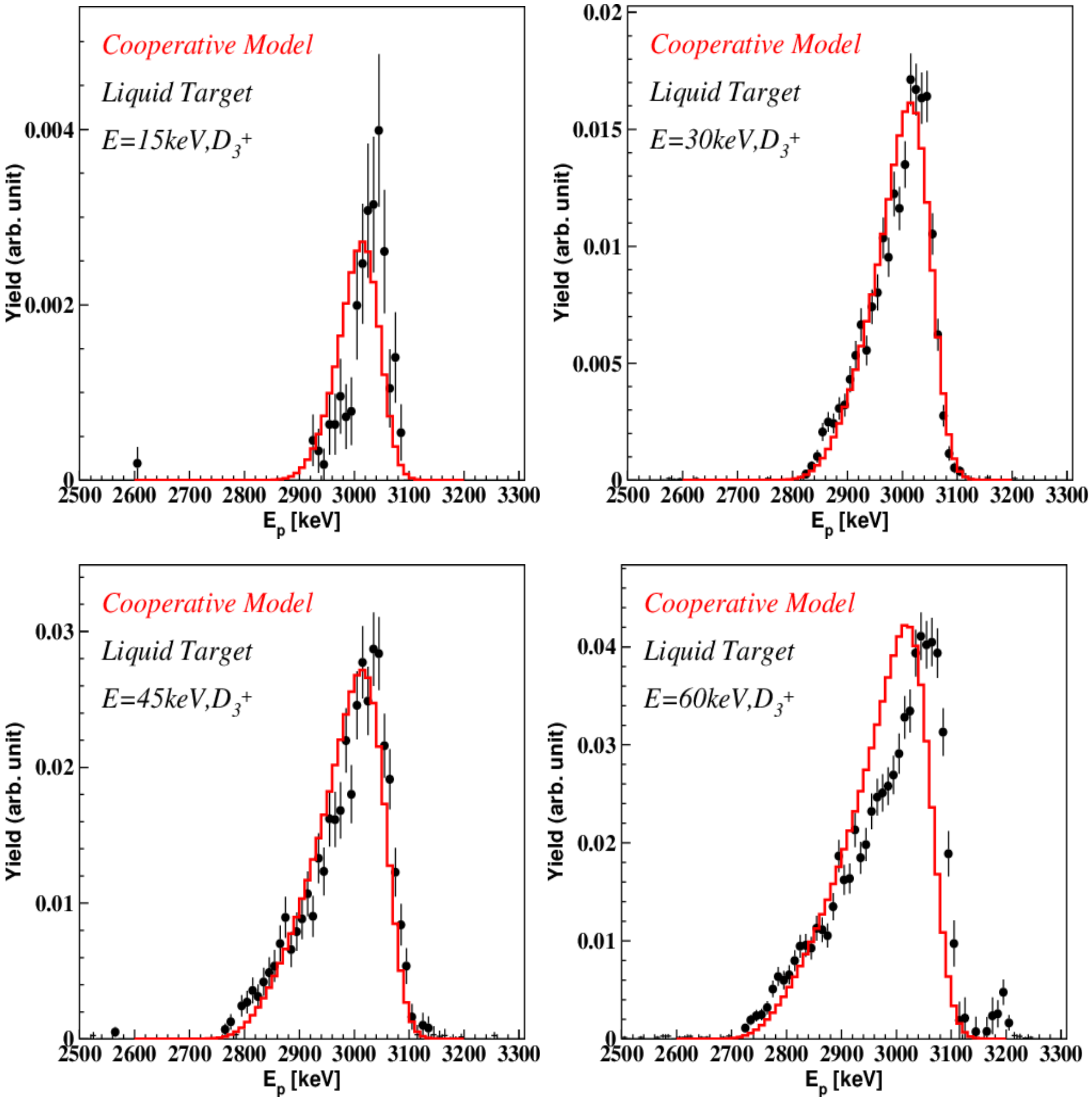
incident Flux (F_n) density of In ($\rho_{In}\, dx$)

d(d,p)t reaction:

$$d^2Y_n(E_n,\theta,\Theta) = dF_n' \cdot F_n\rho_d \cdot \left(\frac{d\sigma(\mathrm{E_n},\mathrm{E_n'},\Theta)}{d\Omega}\right)_{d+d} \Delta\Omega'(\Theta,\Phi)$$

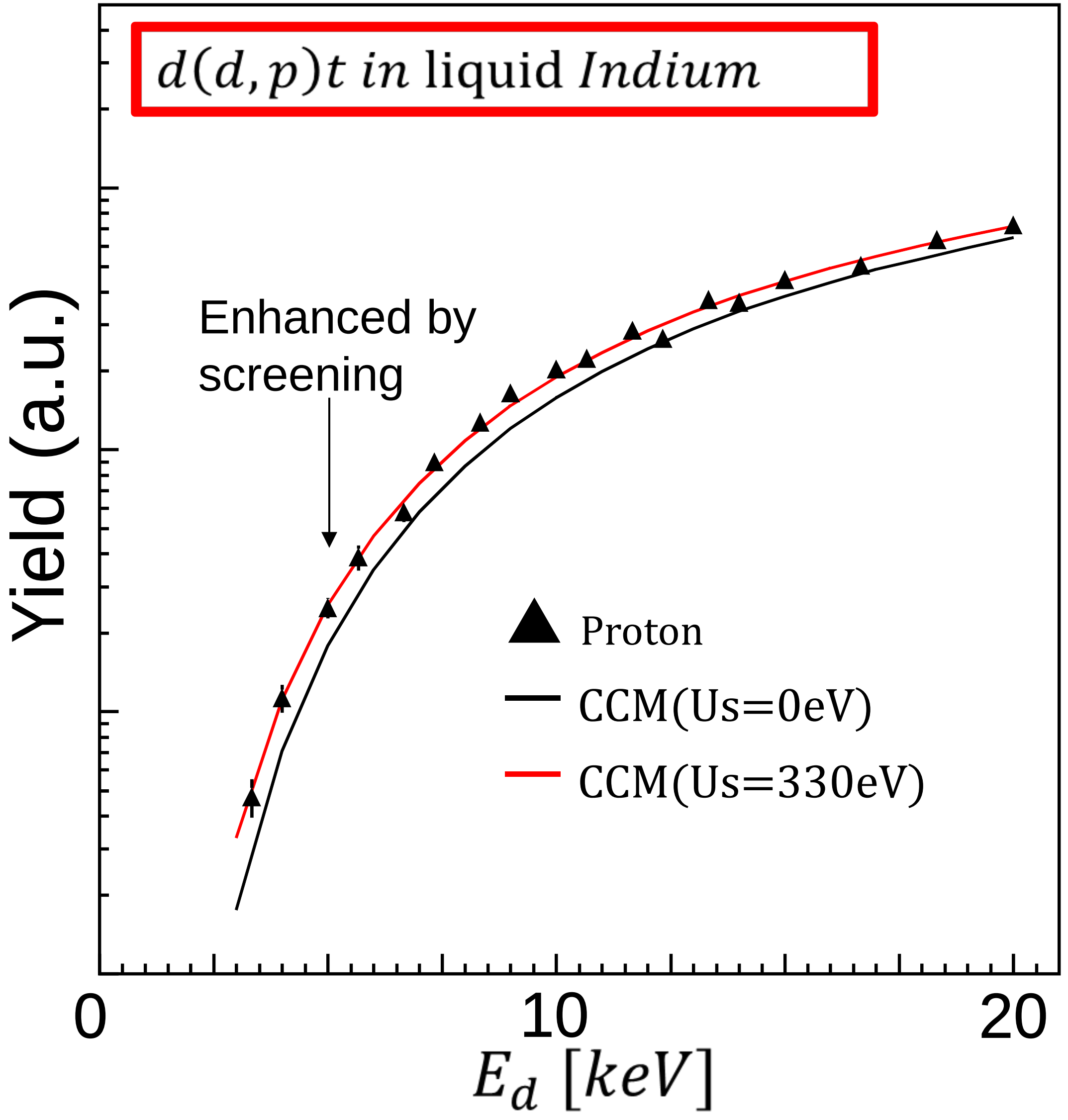
D density

spectrum shape



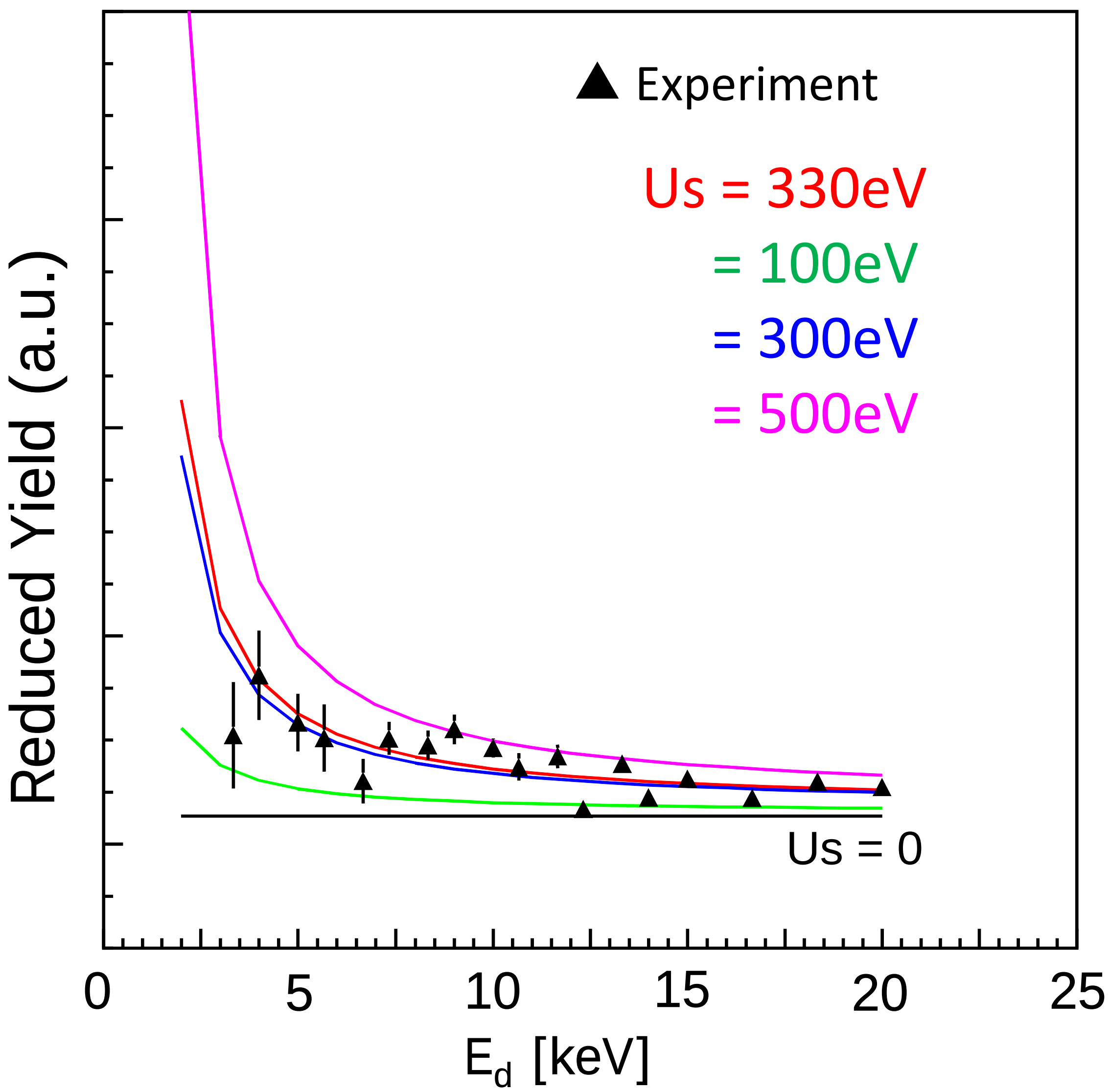
Calculations reproduce observed spectra very well.

Yield vs Ed: comparison with calculations



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

Enhancement



Present value
U_s = 330 +/- 50 eV

c.f.
U_s = 520 +/- 50 eV
(experiment by Raiola et al.)

calculations
U_s = 30 eV
(Thomas-Fermi screening)
U_s = 40 eV
(Kato and Takigawa)
U_s = 130 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

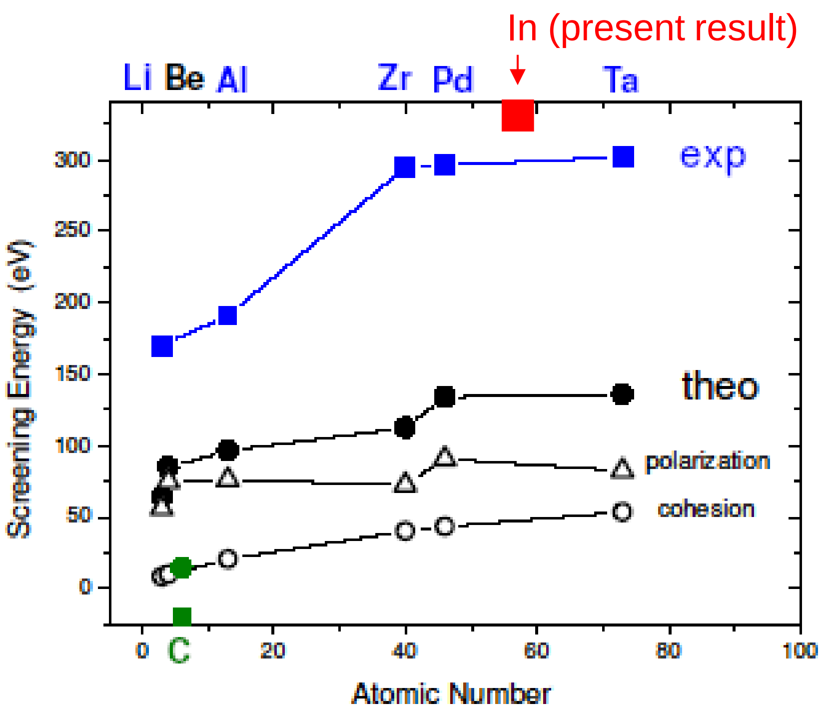


Fig. 2. Experimental and theoretical electron screening energies.

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^*)

$V_{d\text{-}env}+V_{d\text{-}env} > V_{\alpha^*\text{-}env}$

$U_{theo} < U_{exp}$; need another effect

Czerski et al.,Eur. Phys. J. A 27, s01, 83 (2006)

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

D+D→p+t reaction
Assume $\rho \sim 7 \times 10^{22}$/cc

U_s(eV)	rate(/cc/sec)	σ(b)
300	2×10^{-1}	10^{-27}
600	2×10^{10}	10^{-16}
1000	2×10^{14}	10^{-12}

Li+D→α+α reaction
Assume $\rho \sim 5 \times 10^{22}$/cc

U_s(eV)	rate(/cc/sec)	σ(b)
1000	10^{-3}	10^{-29}
1500	10^{3}	10^{-23}
2000	10^{6}	10^{-20}

D+D in metal
Us = 300 ~ 350 eV

Li + D in liquid Li
Us ~ 500 eV for normal density

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

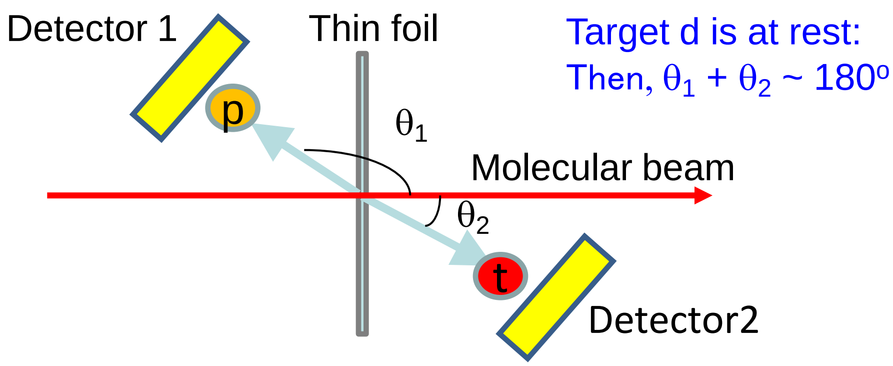
However, heat production
300 eV→1pW/cc, 600 eV→0.1W/cc

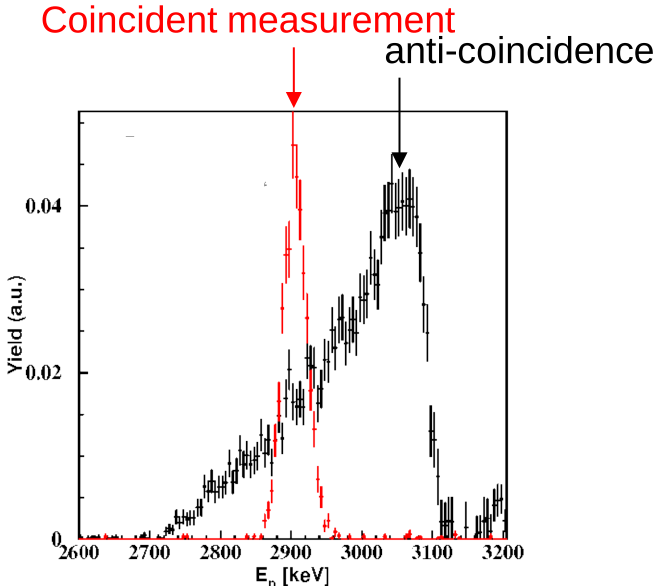
One needs U_s > 800 eV; 1000 eV→kW/cc

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 Us 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=15.3x10^{22}), Hg (n_e=8.2x10^{22}), Bi(n_e=6.0x10^{22}); In (n_e=11.5x10^{22})
The measurement can be applied to solid metal target, also.
Use thin foil.
Kinematical selection with two detectors.





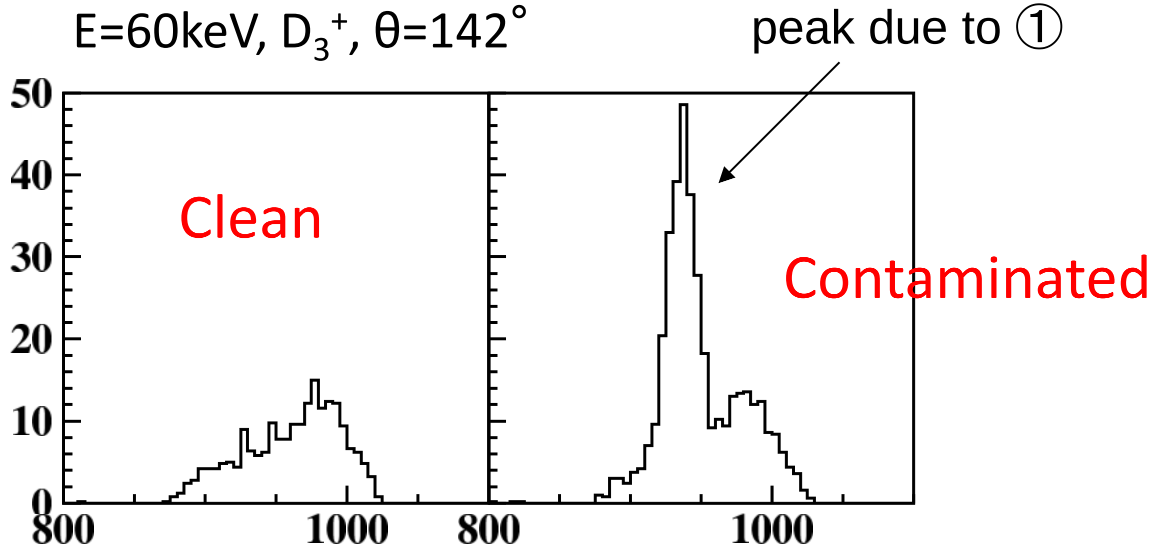
Possible events from the d(d,p)t reaction other than in liquid In

① reaction with D accumulated in surface contaminants

metal surface should be kept completely clean

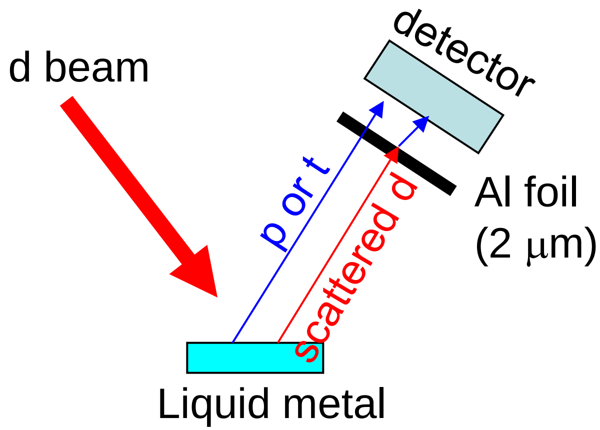
Cleaning up

Skim off contaminants by a scraper



② reaction with D accumulated in Al foil

unavoidable; should be identified and subtracted



Change distance between Al and det.
Calculate spectrum shape