# Enhanced reaction rate of the Li+D reaction and the screening energy

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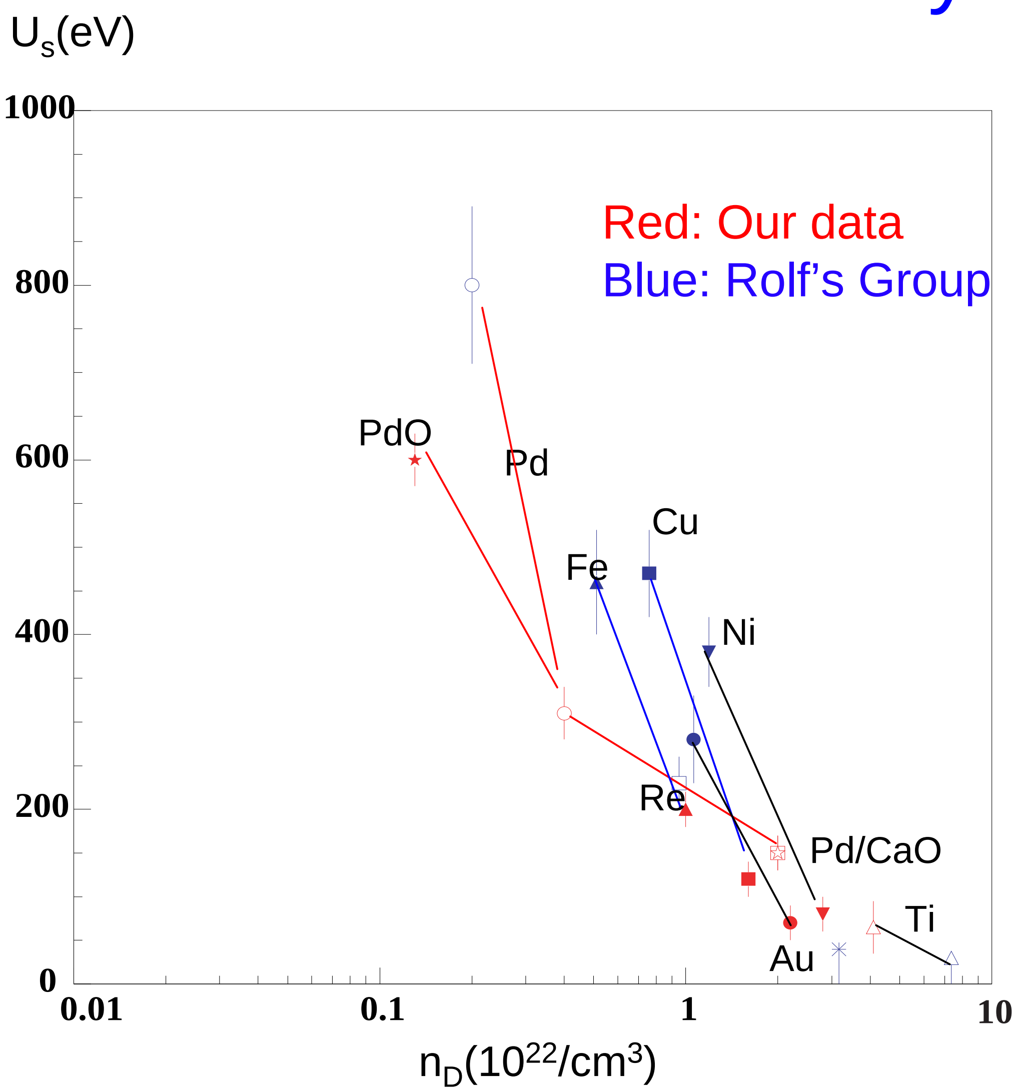
# What we have learned from DD reactions in metals at ~keV

- Reaction rate in metals can be strongly enhanced, in some cases, ~100 times larger @$E_{cm}$ = 1 keV.
- Enhancement can be explained by introducing a large screening energy, such as several hundreds eV.
- Extrapolation of the large screening energy predicts the fusion rate up to $10^9$ /cc/sec at 0 keV.
- There should be an important mechanism to enhance the DD reaction in metals.

# Correlation between screening energy and deuteron fluidity in metal ?



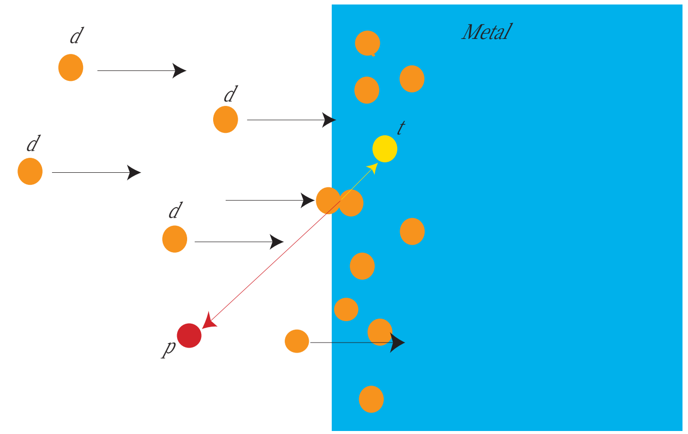

← Liquid like ?? Solid like →

Comparison: our data and Rolf's for the same metal

↓

Larger screening energy for lower deuteron density

Small density may correspond to large fluidity of deuteron in metal?

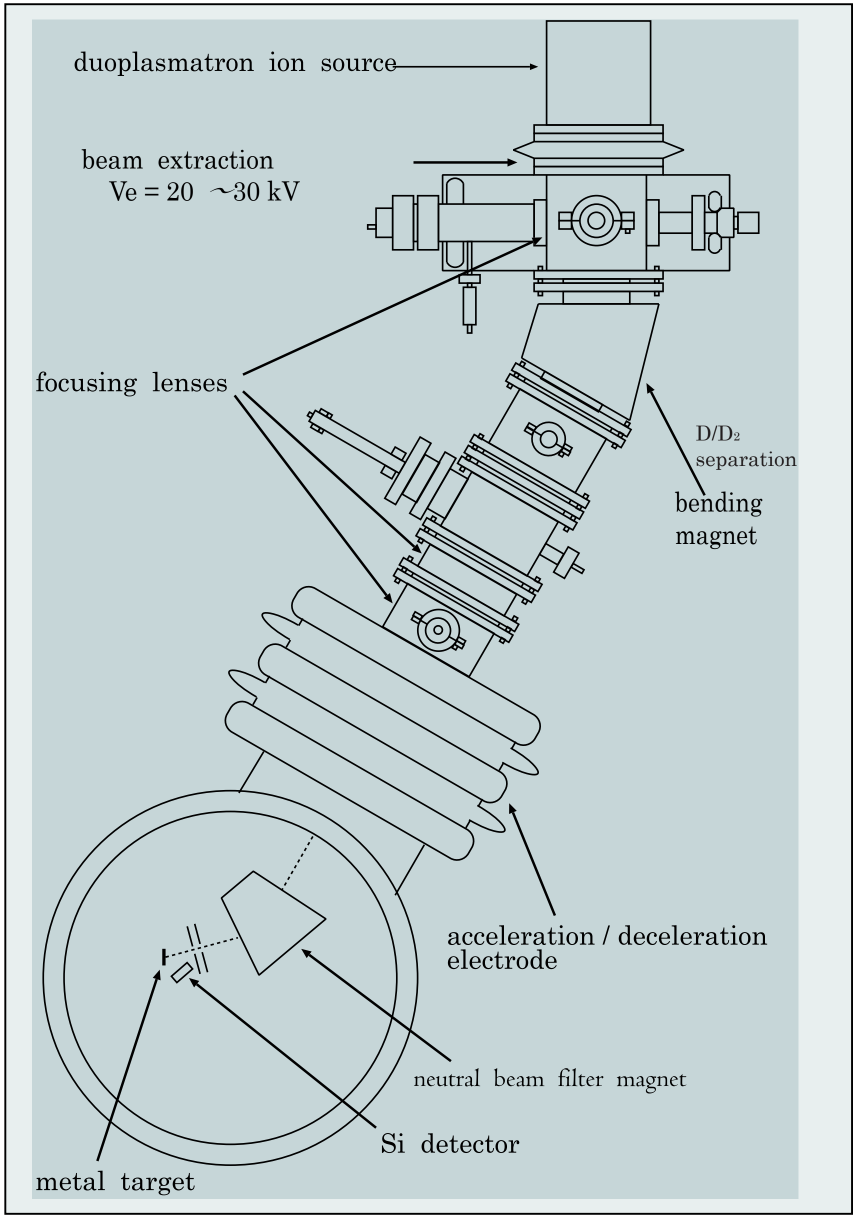


# Study of Li-D reactions in various conditions

- $Z_1Z_2$-dependence of the screening energy in the same host metal?
- Reaction rate vs deuteron density?
- Temperature dependence?
- Reaction in solid and liquid phase?

  $T_{melt}$ ~ 180 $^oC$

# Low-energy deuteron generator at LNS

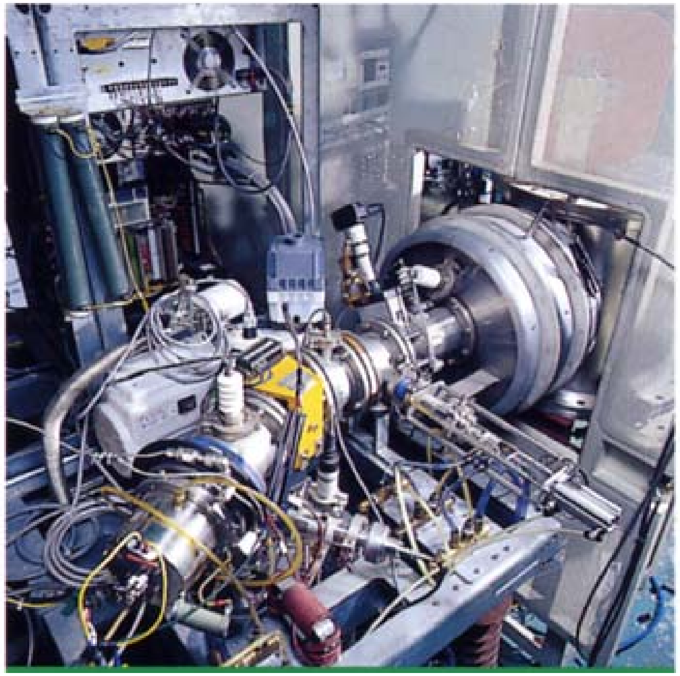



- $E_d = 2 \sim 100$ keV

  25 ~ 100 keV; acceleration mode

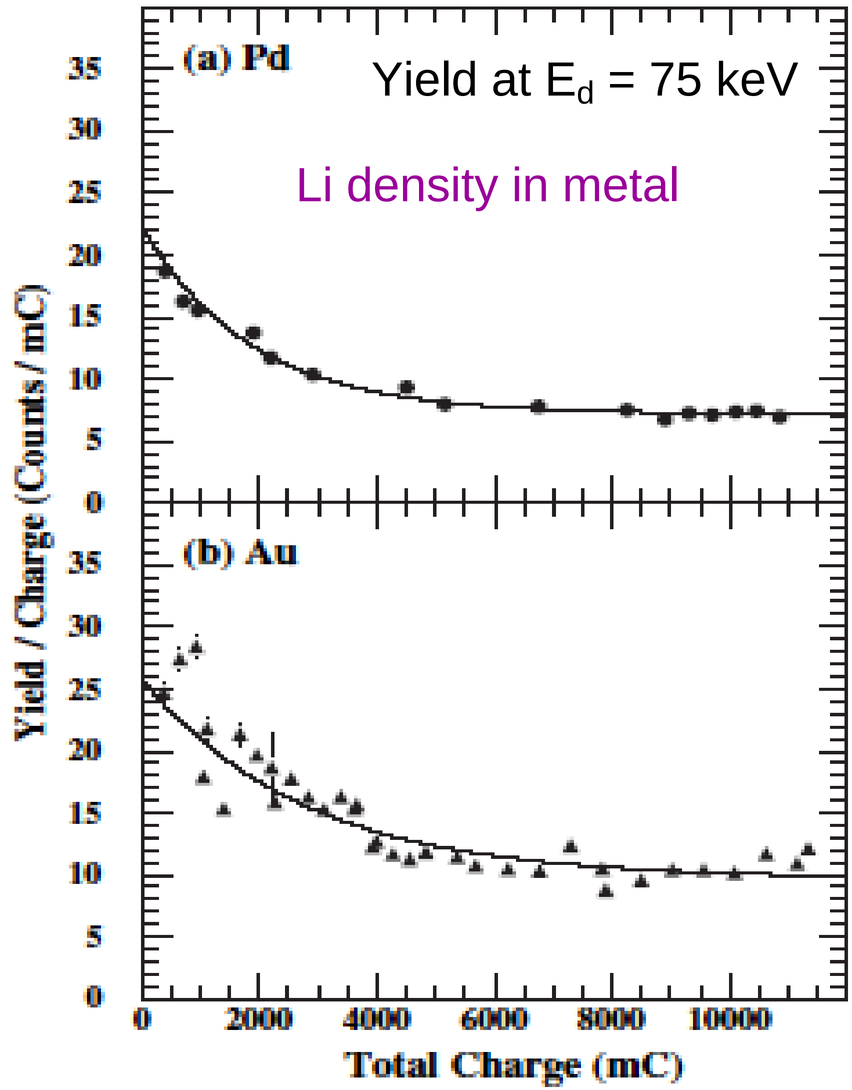
  2 ~ 25 keV; deceleration mode

- $I_d$ up to 500 μA

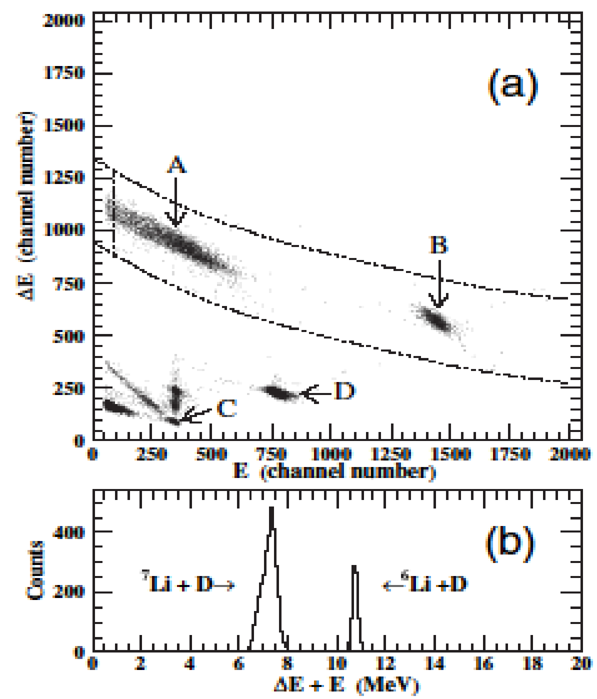


# Li+D reactions in Pd and Au

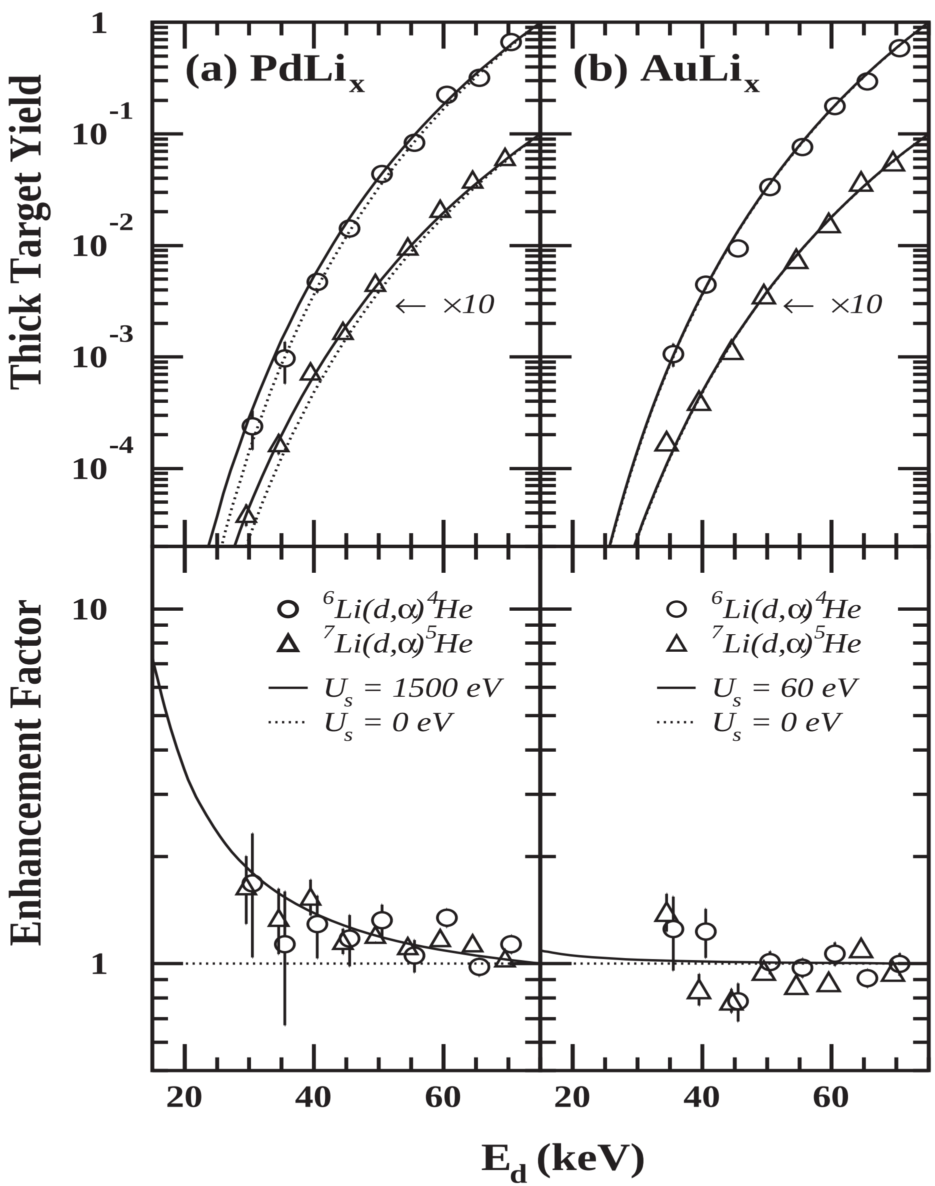
(Kasagi et al., J. Phys. Soc. Jpn. 73 (2004) 608)




Target: Pd-Li, Au-Li alloy
(several % of Li)
Cooled at -80 °C
ΔE-E silicon counter telescope
(30-100 μm thick Si)
Frequent measurements at 75 keV



# Screening energy for Li+D in Pd and Au




● Thick target yield normalized at 75 keV

$Y(E_d) \propto \int^{Ed} N_{Li}(x)\sigma(E)(dE/dx)^{-1}dE$

$N_{Li}(x)$: Number of target Li
cancelled (uniform distribution)

dE/dx: stopping power of d
Anderson-Ziegler

$\sigma(E)$: LiD reaction cross section
$\sigma_{bare}(E) = S(E)/E \exp(-2\pi\eta)$
S(E); $^6$Li+d; Engstler et al.

$\sigma_{enhance} = \sigma_{bare}(E+U_s)$
$U_s$; screening energy

# Comparison of screening energies in metals for Li+d and D+D reactions

Experimental values of Us (eV)

| Host | $U_s$(D+D) | $U_s$(Li+d) | 3×Us(D+D) |
|---|---|---|---|
| Pd | 310 ± 30 (ours) | 1500 ±310 (ours) | 930 |
| | 800 ± 90 (Rolfs) | | 2400 |
| Au | 70 ± 30 (ours) | 60±150 (ours) | 210 |
| | 280 ± 50 (Rolfs) | | 840 |

Ours: JETP Lett. 68(1998)823, JSPS 71(2002)2881, 73 (2004) 608
Rolfs: PL B547(2002) 193, PTP Supl. 154 (2004) 373

In Pd; Both Li+d and D+D reactions are enhanced strongly

Scaling ?

$\phi_s = Z_1 e/r \exp(-\kappa r) \sim Z_1 e/r\,(1-\kappa r)$

$U_s = Z_1 Z_2 e^2 \kappa$

$\rightarrow U_s(\text{Li+d}) = 3U_s(\text{D+D})$

# Li+D reaction in liquid phase

H. Ikegami (in Proc. FUSION03; Prog. Theor. Phys. Suppl. 154 (2004) 251)

In liquid phase, nuclear reaction might be enhanced for Li+D reaction

Reaction rate $\propto$ exp($-\Delta G/k_B T$),

$\Delta G$: Gibb's free energy for 7Li + D $\rightarrow$ 8Be + n

$\Delta G_r = \Delta G_f(\text{Be in Li}) - \Delta G_f(\text{Li}) - z_{eff}\Delta G_f(\text{LiD})$

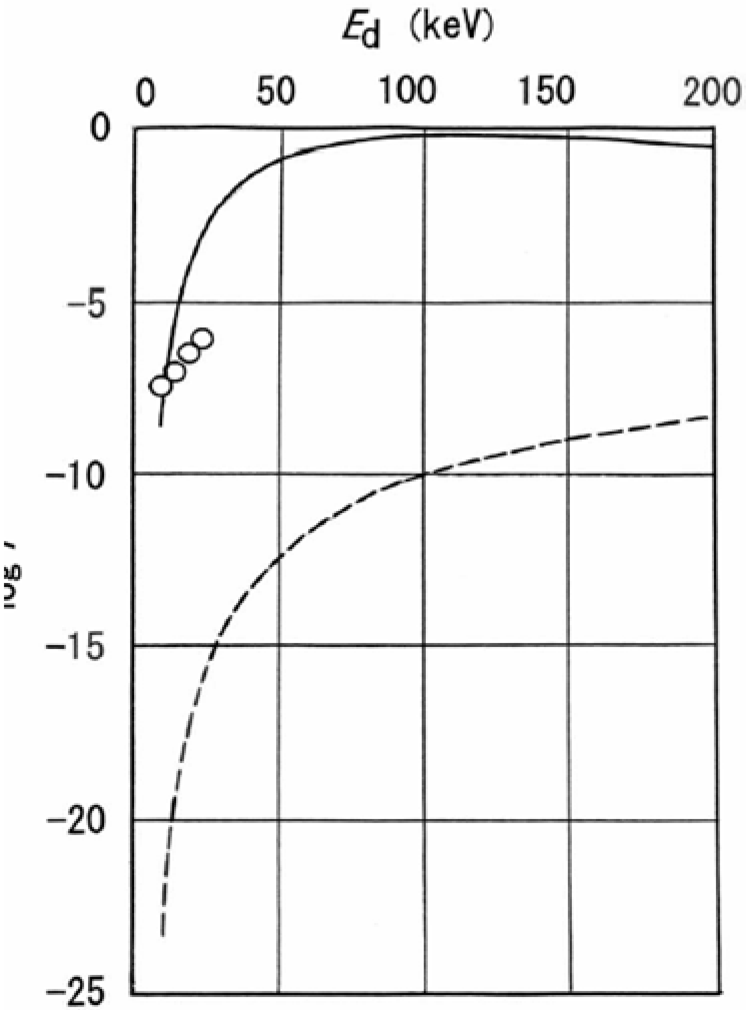
~ - 1.35 (eV)

Typical enhancement;

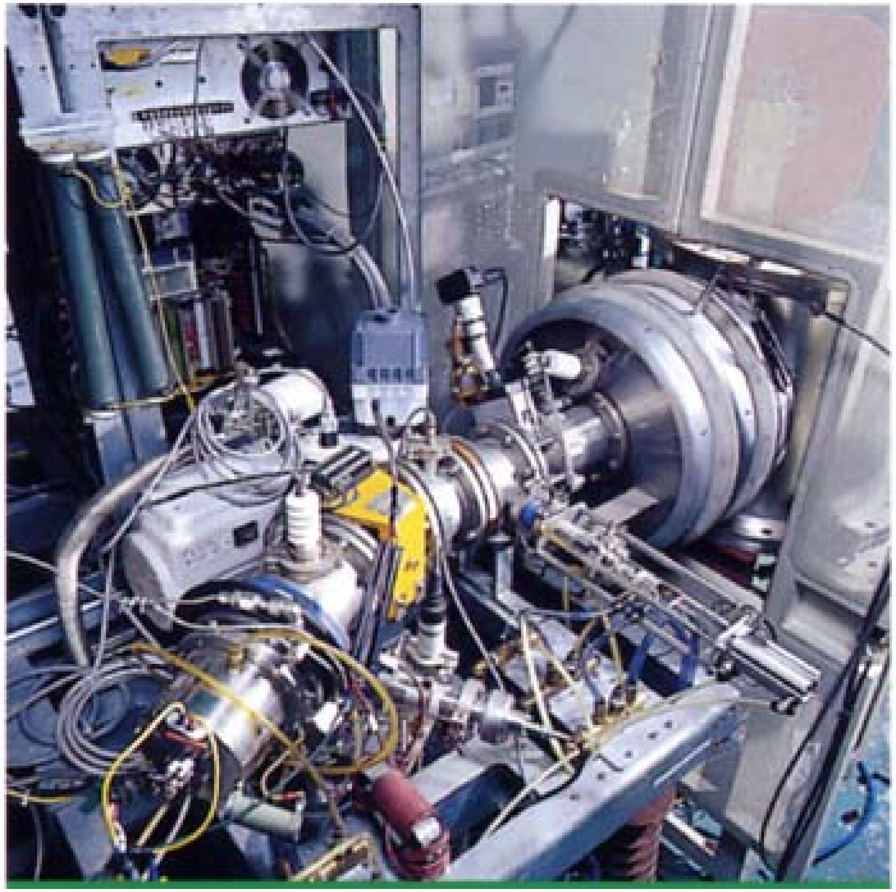
$2.4 \times 10^{14}$ at $E_d$ = 10 keV

$1.0 \times 10^{12}$ at $E_d$ = 20 keV

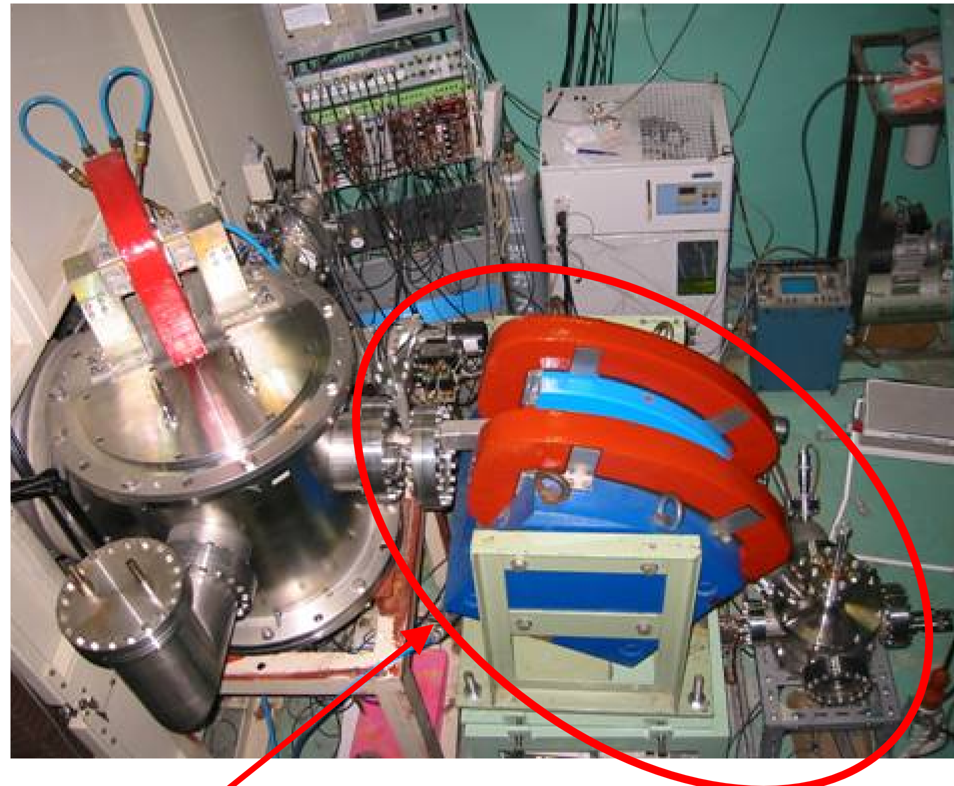
coherent emission of $\alpha$-particles



# Deuteron beam line for liquid target

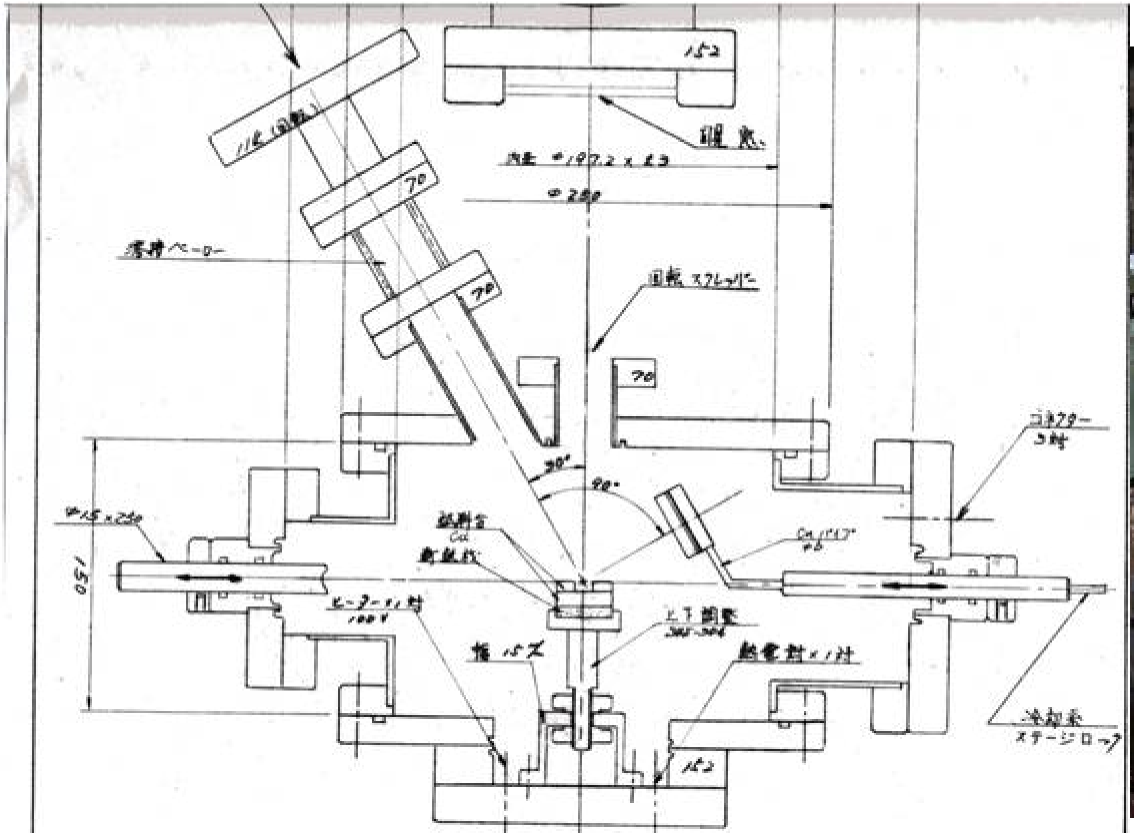


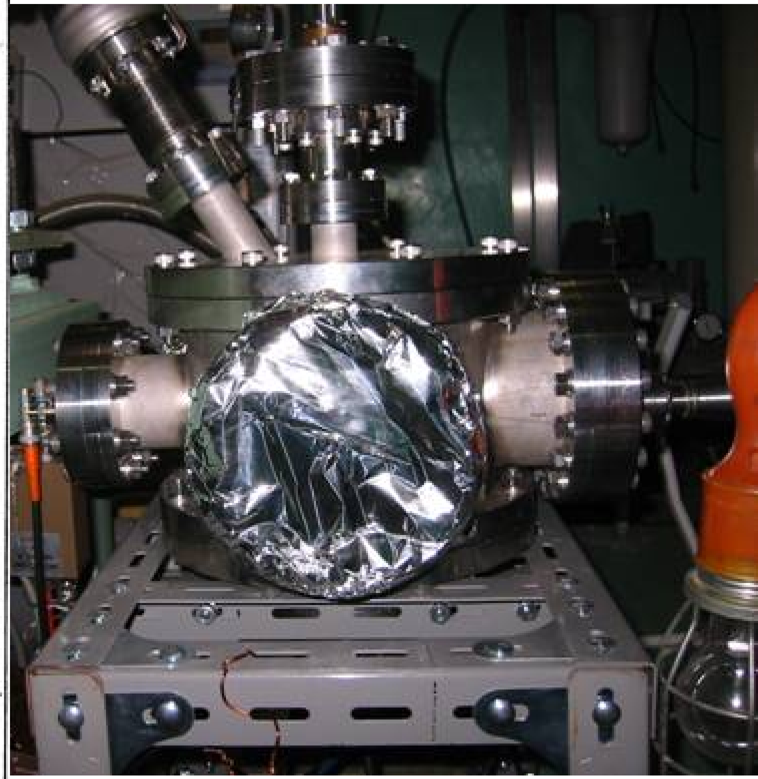
Low-energy ion beam generator



Bending magnet (60 degree)
Small chamber for liquid target

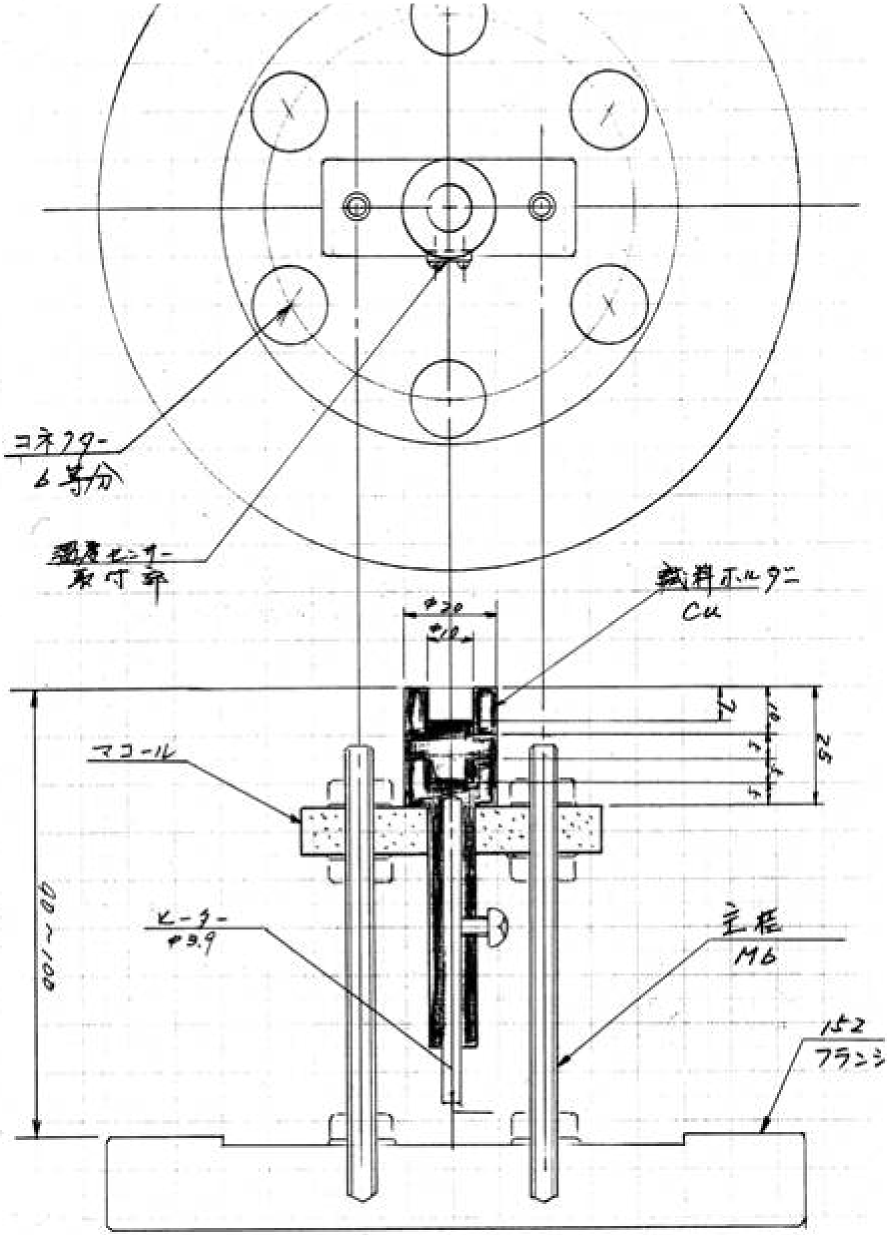
# Target chamber for liquid Li



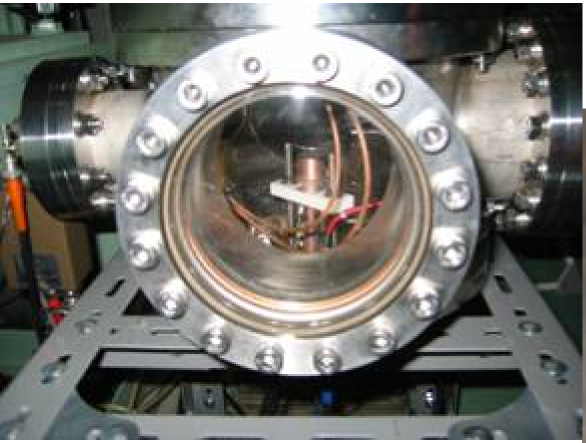



Vacuum: $10^{-8}$ Torr
Beam size: 5 mmϕ on target (aperture at the entrance)

# Target holder



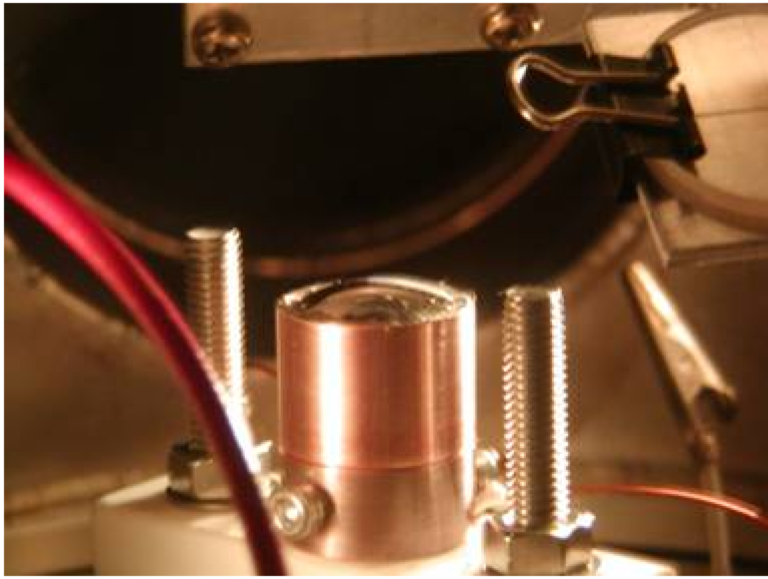

# Liquid Li target prepared in scattering chamber



Li target is transferred to a vacuum chamber with a plastic bag filled with Ar gas.

Target is melted and its surface is shaved to clean up.

Li liquid metal target.



# Charged particle measurements

Counter telescope: cooled at ~10 $^{o}$C

5μm Al + 17 μm Si (ΔE) + 300 μm Si(E)

$\theta_d$ = 150$^{o}$, $R_d$ ～ 5 cm

Beam intensity: 100 nA ～ 100 μA

(target current)

Temperature measurement:

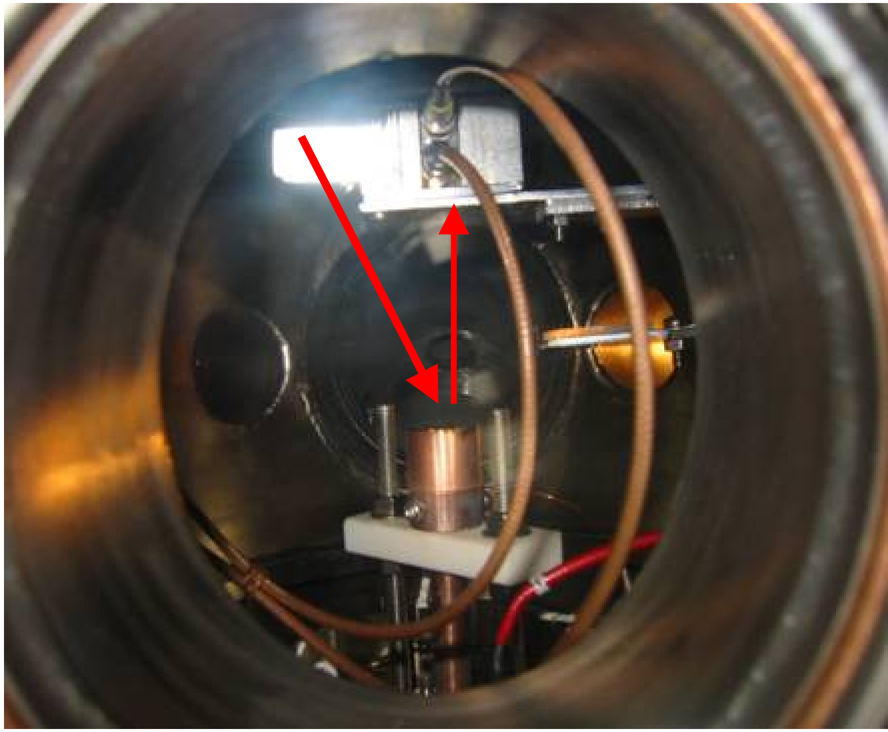
Target temperature; 40 ～ 250$^{o}$C

(target holder)

melting point; 180 $^{o}$C

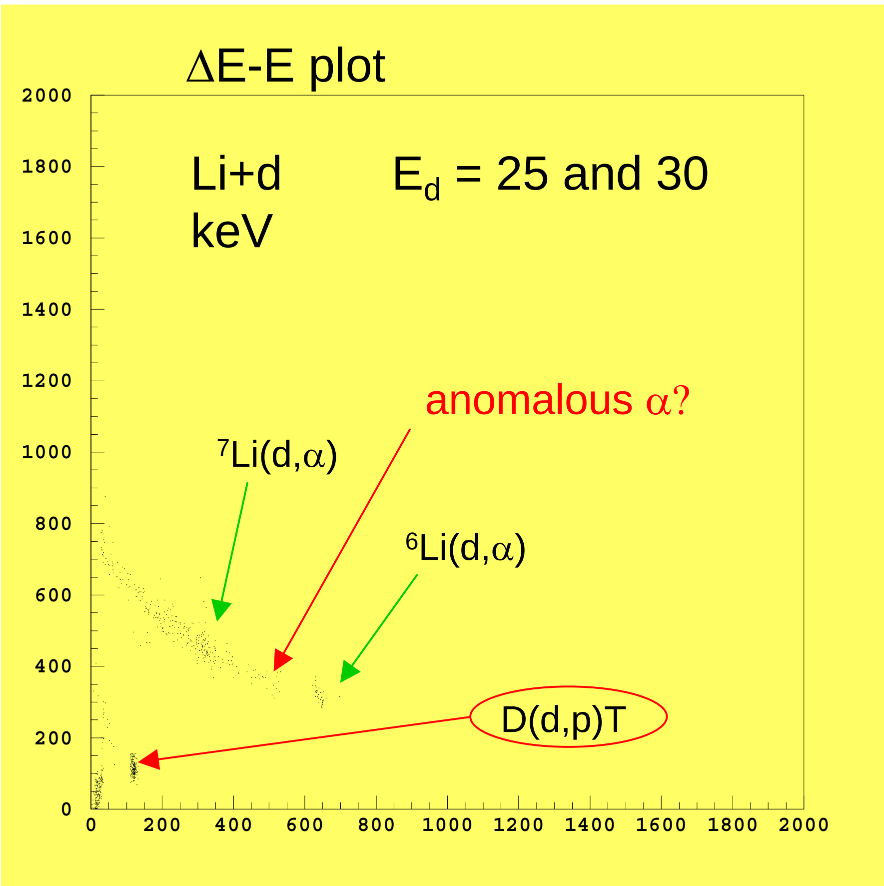
Temperature at the beam spot

directly measured by infrared thermometer

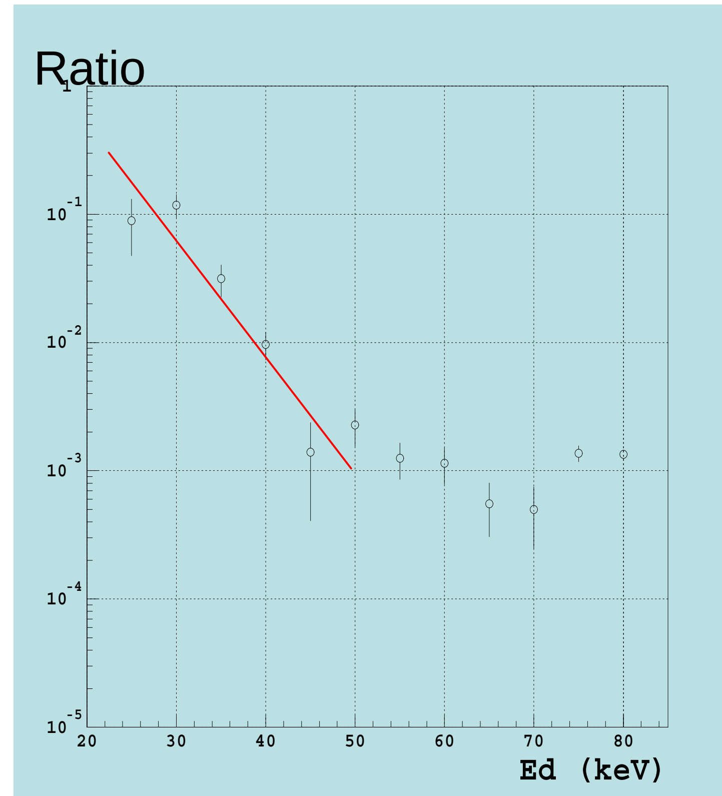


# Charged particle spectrum

2 dimensions spectrum (solid Li)



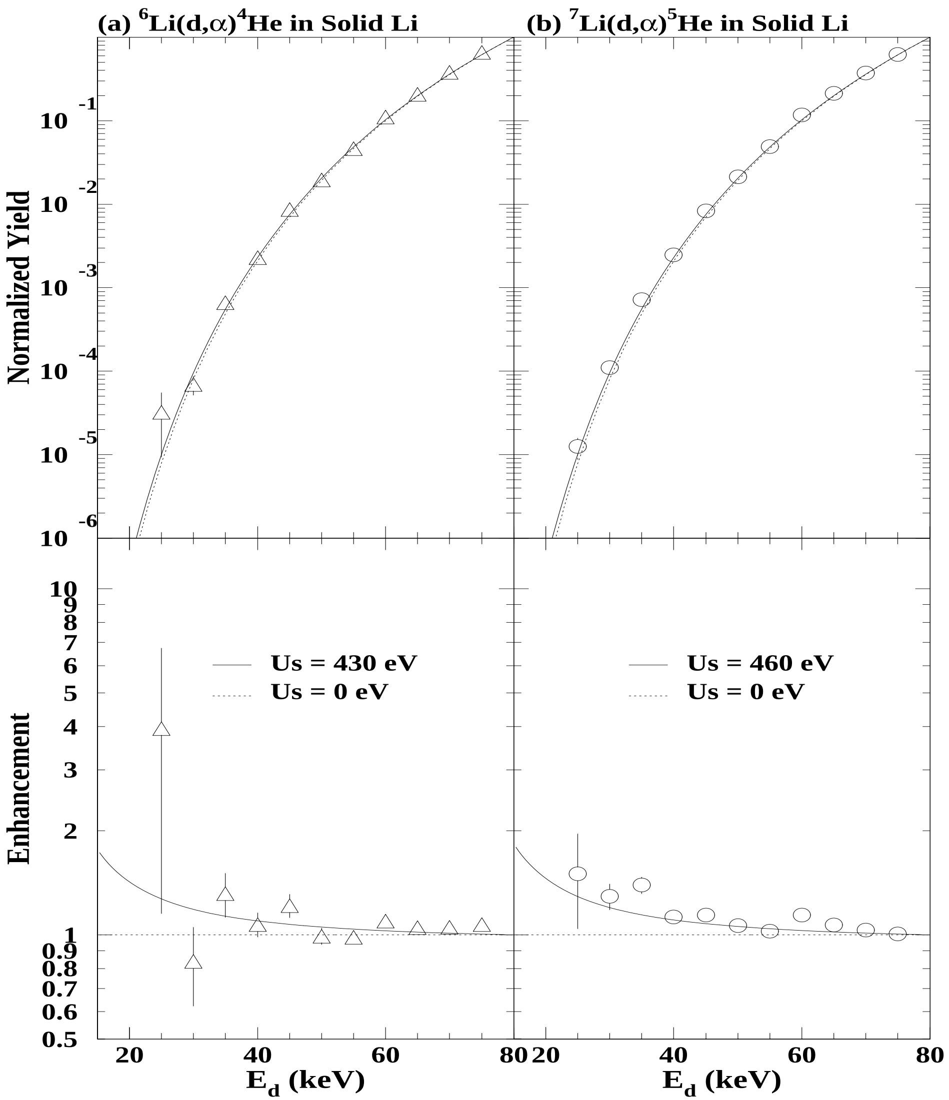

Yields(anomalous α)/Li(d,α)




2-step Sequential reaction?

D(d,p)T → $^7$Li(p,α)$^4$He

# Screening energy of Li+D reaction in solid Li




- Thick target yield normalized at 80 keV

$Y(E_d) \propto \int^{E_d} N_{Li}(x)\sigma(E)(dE/dx)^{-1}dE$

$N_{Li}(x)$: Number of target Li
cancelled (uniform distribution)

dE/dx: stopping power of d
Anderson-Ziegler

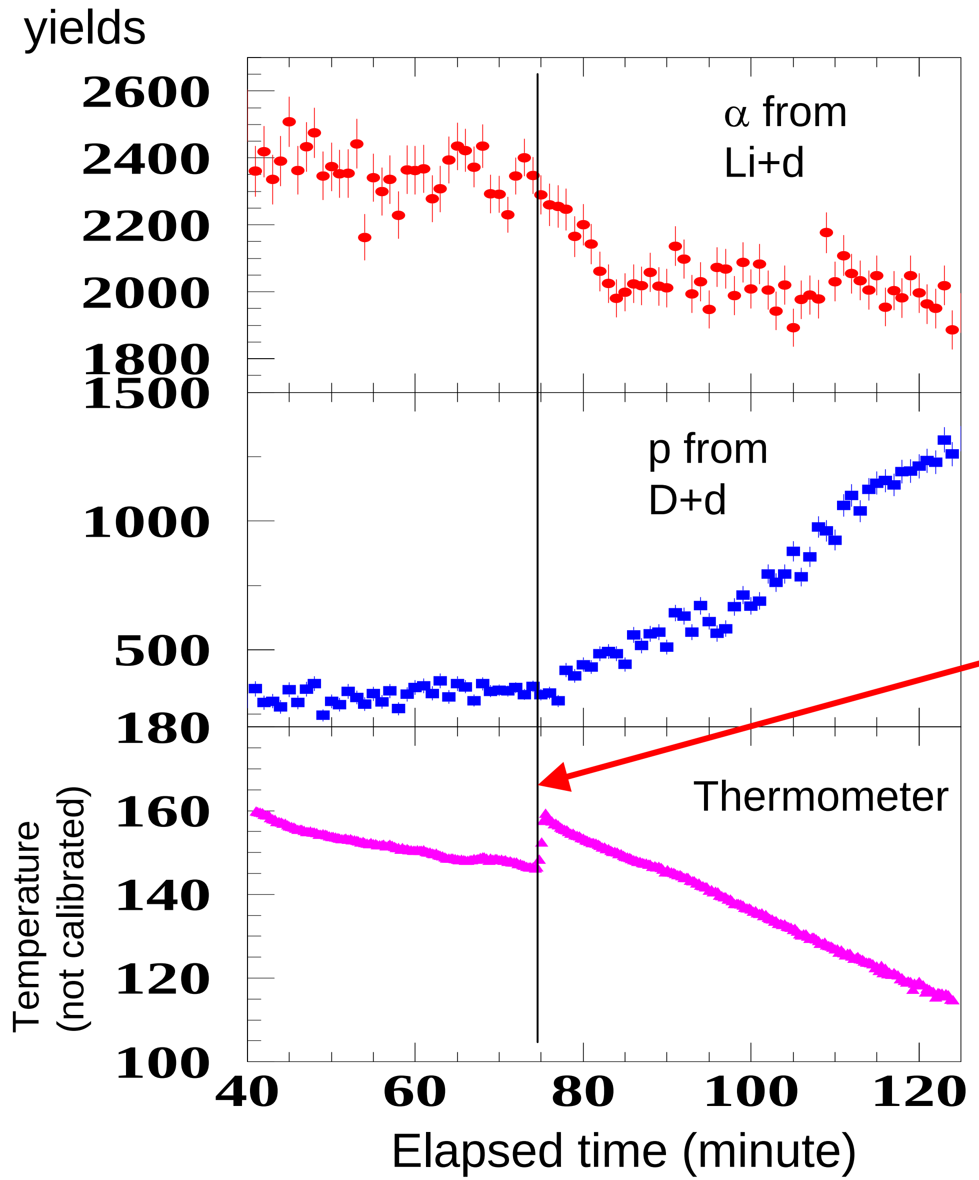
σ(E): LiD reaction cross section
$\sigma_{bare}(E) = S(E)/E \exp(-2\pi\eta)$
S(E); $^{6}$Li+d; Engstler et al.
$\sigma_{enhance} = \sigma_{bare}(E+U_s)$
$U_s$; screening energy

------------- $U_s = 0$

———— $U_s$ = 430 eV for $^{6}$Li+d
$U_s$ = 460 eV for $^{7}$Li+d

Atomic model prediction
$U_s \sim 240$ eV

# Temperature dependence ($E_d$ = 80 keV)

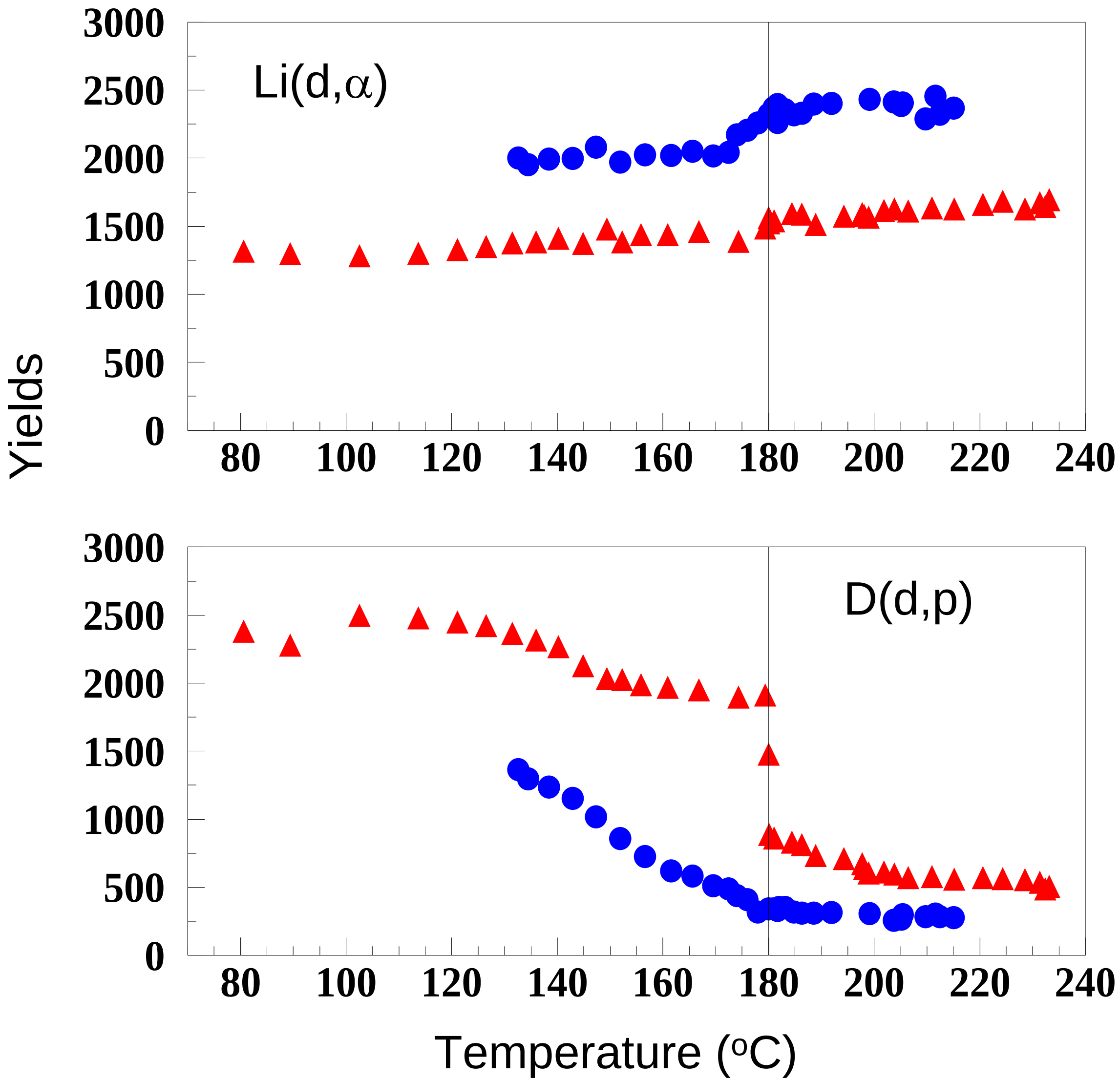



Temperature at the beam spot
infrared thermometer (IMPAC)

Liquid-solid
phase change

Radiation efficiency is changed
normalized to be the melting point

# Solid-Liquid phase change



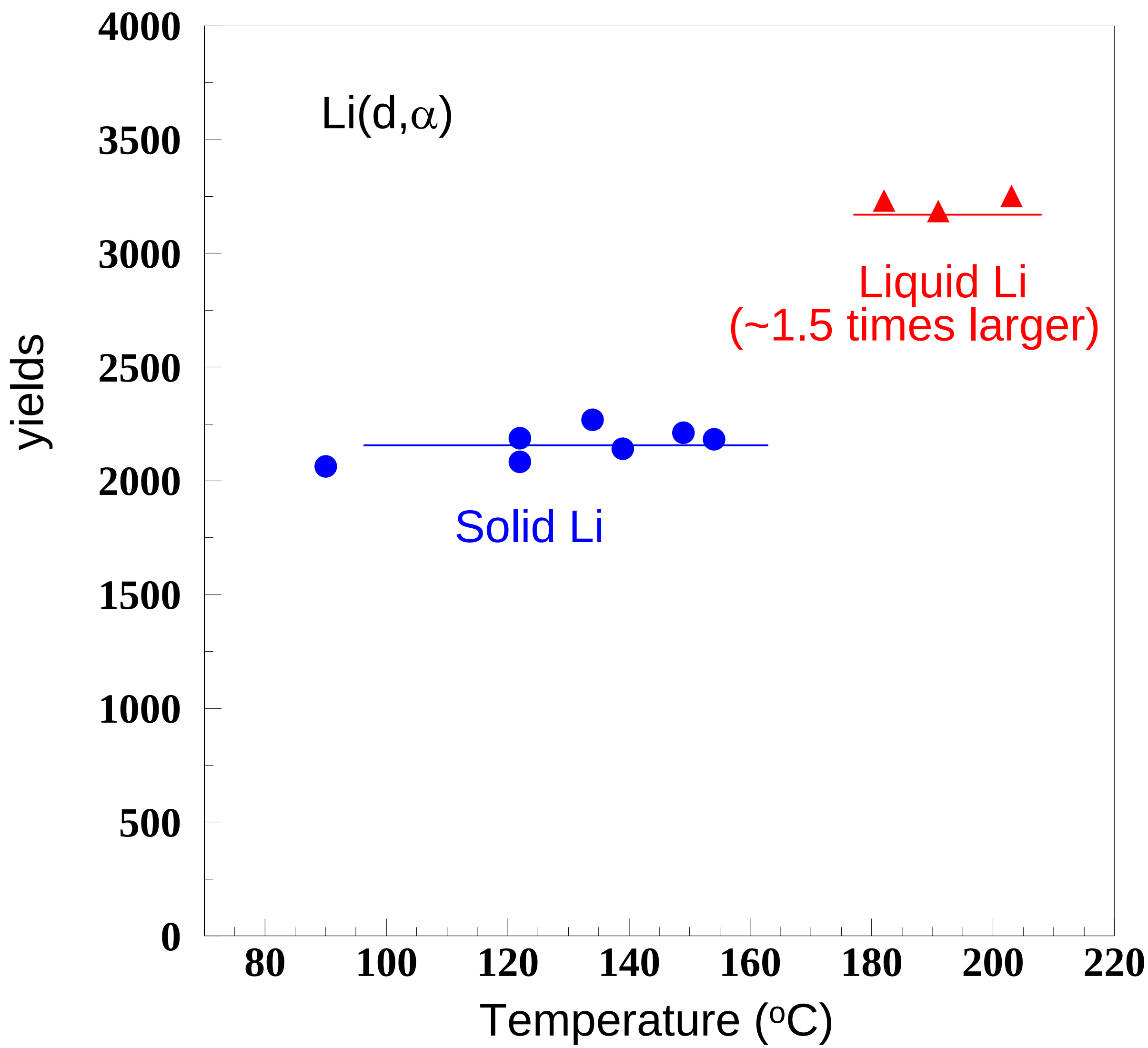

Continuous measurement
during temperature change
$E_d$ = 80 keV

▲ increase temperature
● decrease temperature

Depend on surface condition

D(d,p) Data
deuteron density ⇔ fluidity
high fluidity → low densjity

# Reaction yields at $E_d$ = 80 keV



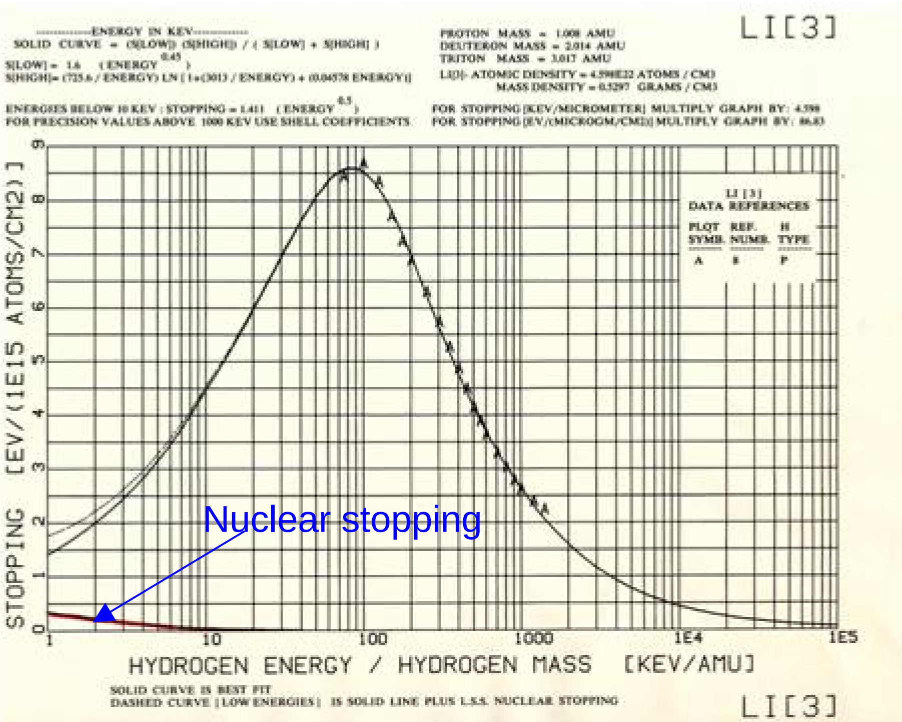

Temperature fixed for each run
Surface cleaned up for each run

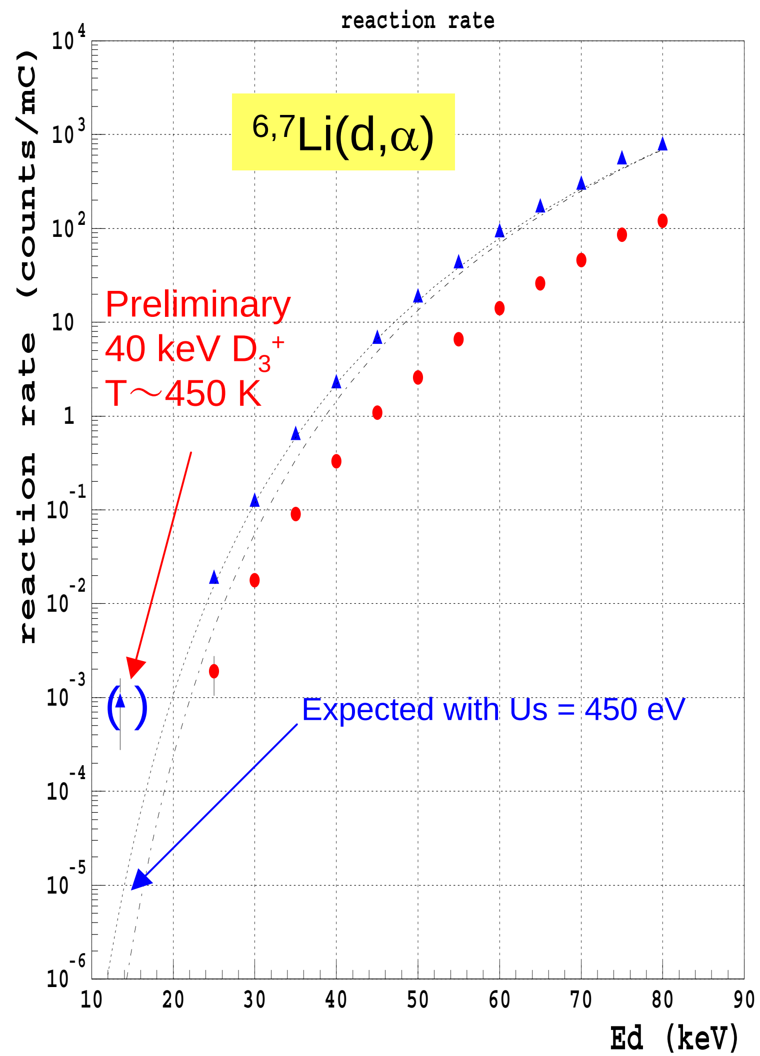
Confirm a sudden jump associated with the phase transition of Li

Change of
reaction cross section?
energy loss of deuteron?

# Equilibrium condition?

Bombarding beam:
 thermal equilibrium condition?
 low energy is better?



# Summary

## Li+D reactions in Pd and Au

In Pd, enhanced strongly as D+D reaction

Scaling of the screening energy; only qualitatively

## Li+D reactions in solid and liquid Li

Temperature at the beam spot during bombarding

Clear observation of solid-liquid phase change

DD in Li → correlation between yield and fluidity

LiD in Li → sudden jump of reaction yield

enhanced reaction rate?

at $E_d$~13 keV?