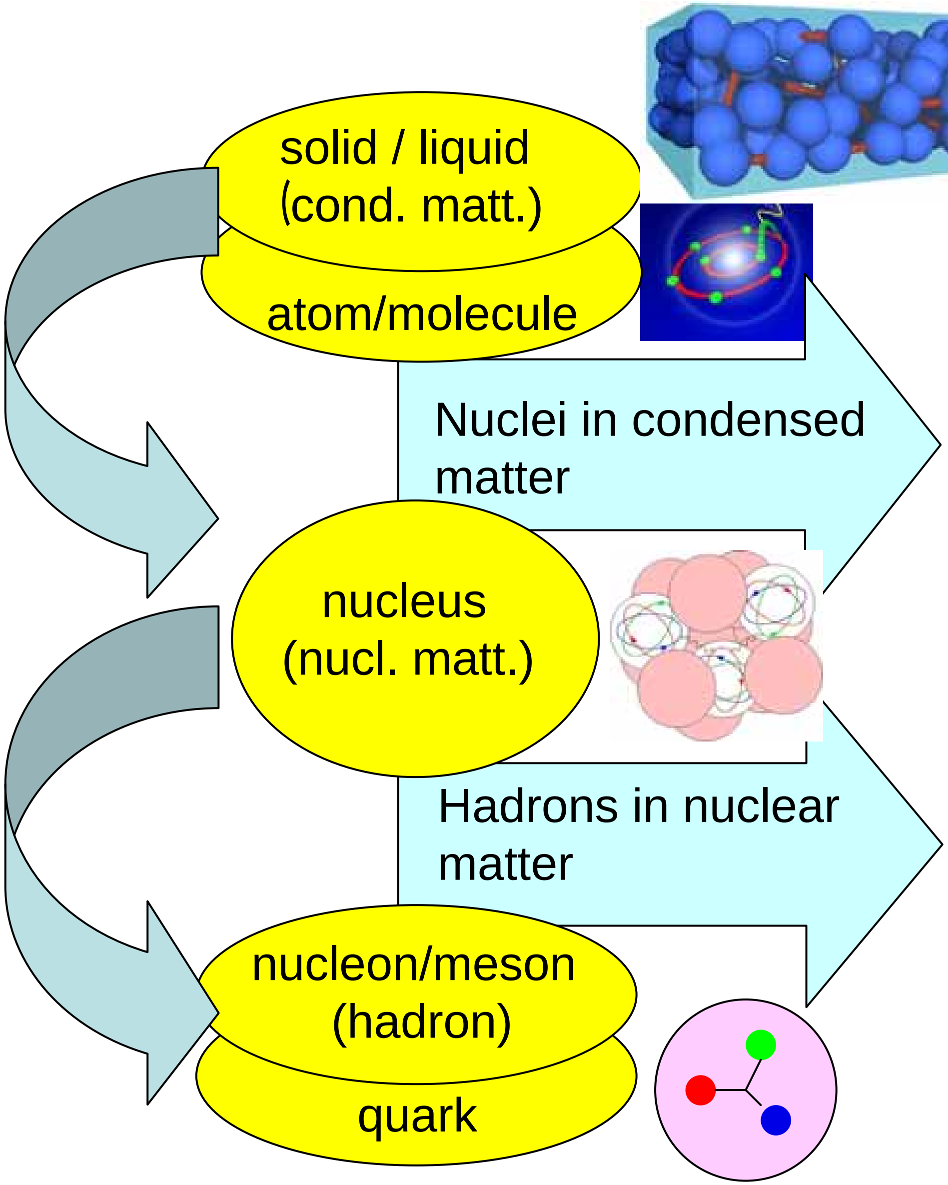
Medium Effects:
Hadrons in Nuclear Matter
and
Nuclei in Condensed Matter

核物質中のハドロン･凝縮系中の原子核に及ぼす媒質環境の効果

原子核理学研究施設　笠木　治郎太

How are basic corpuscles affected by surrounding media?
Are their properties modified very much?



solid / liquid
(cond. matt.)

atom/molecule

Nuclei in condensed matter

nucleus
(nucl. matt.)

Hadrons in nuclear matter

nucleon/meson
(hadron)

quark

Low-energy nuclear reactions
- D+D, Li+D reactions in metals
  (Kasagi, Takigawa, Kawakatsu)

Nuclear decay
- Electron-capture of ^{7}Be in C_{60}
  (Ohtsuki)

Nucleon resonances in nuclei
- (γ,η) reactions on C and Cu
  (Kasagi, Shimizu)

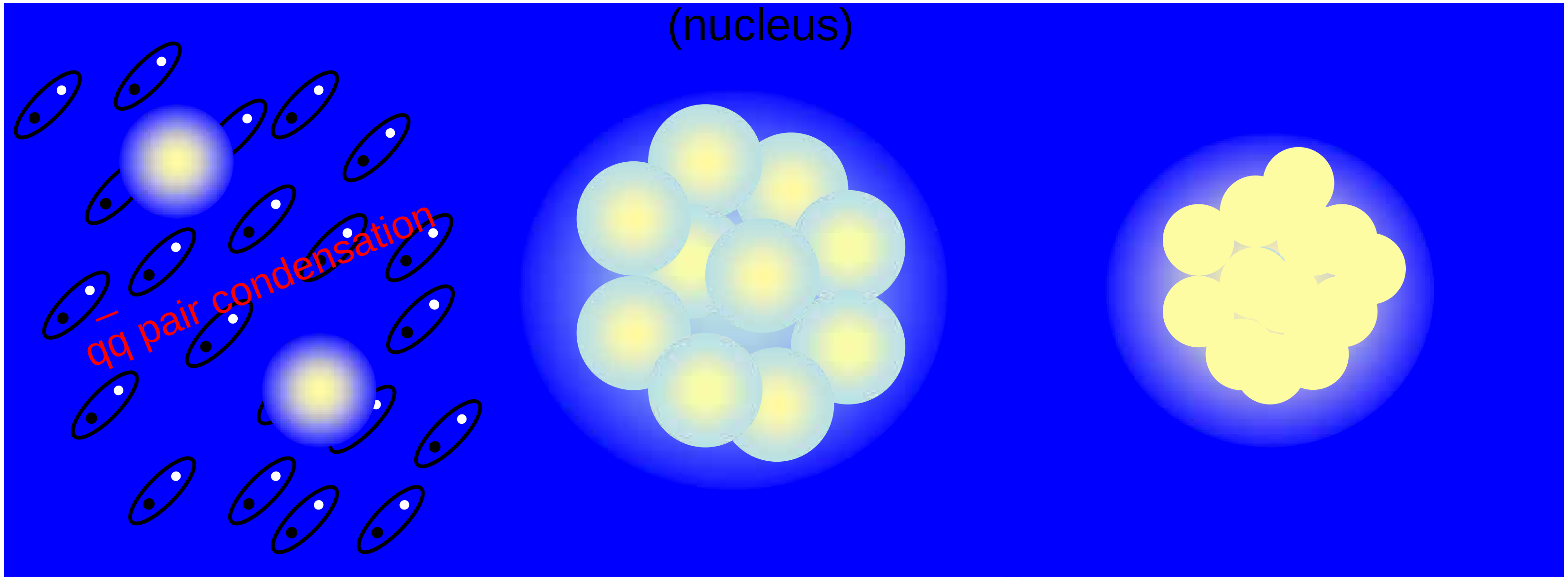
Mesons in nuclei
- (γ,$\pi^0\pi^0$) reactions on C and W
  (Shimizu)

Nucleons in various media

vacuum

cold nuclear matter (nucleus)

cold quark matter



$\rho_{\text{nucleon}} \sim 0$ $\rho_{\text{nucleon}} \sim 0.15\ \text{fm}^{-3}$ no nucleon identity

$R_{\text{nucleus}} \sim 1.2\ A^{1/3}\ \text{fm}$ $R << 0.8\ A^{1/3}\ \text{fm}$

$\rho_{\text{quark}} \sim 0\ \text{fm}^{-3} \longrightarrow \rho_{\text{quark}} \sim 0.45\ \text{fm}^{-3} \longrightarrow \rho_{\text{quark}} >> 1.4\ \text{fm}^{-3}$

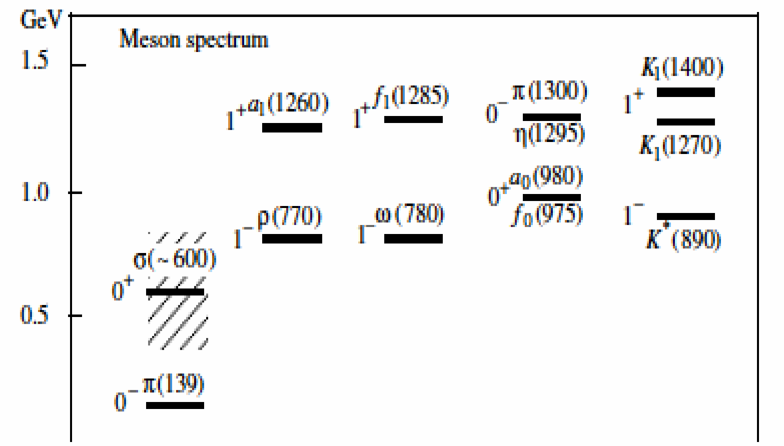
$|\langle \bar{q}q \rangle| \sim 2\ \text{fm}^{-3} \longrightarrow |\langle \bar{q}q \rangle| \sim 1.4\ \text{fm}^{-3} \longrightarrow |\langle \bar{q}q \rangle| \sim 0\ \text{fm}^{-3}$

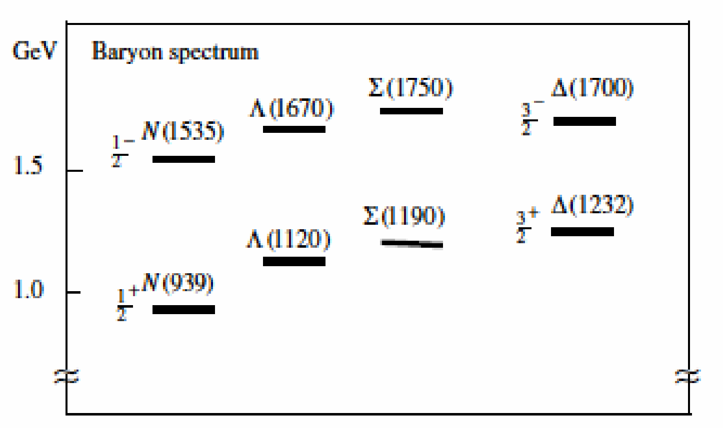
Chiral sym. no partially yes yes

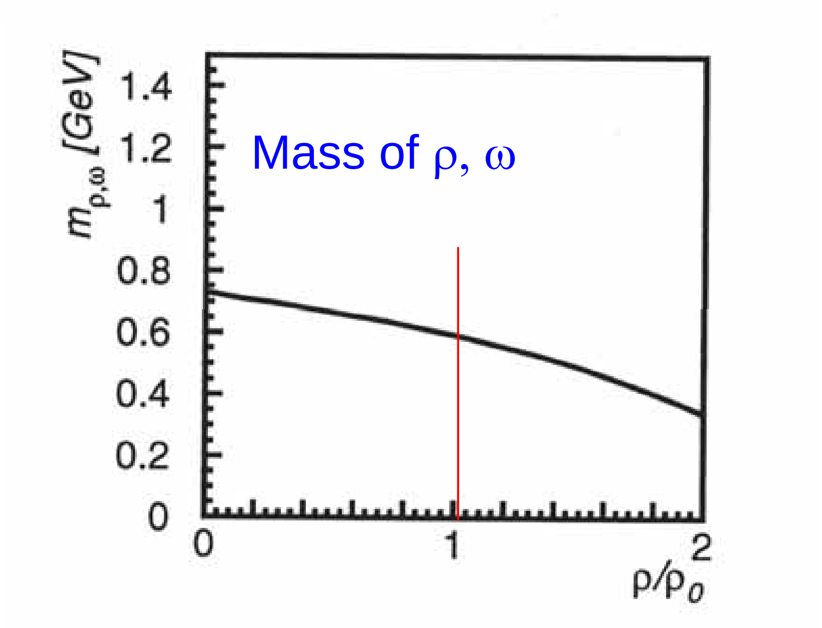
Quarks; confined confined (partially deconfined?) free

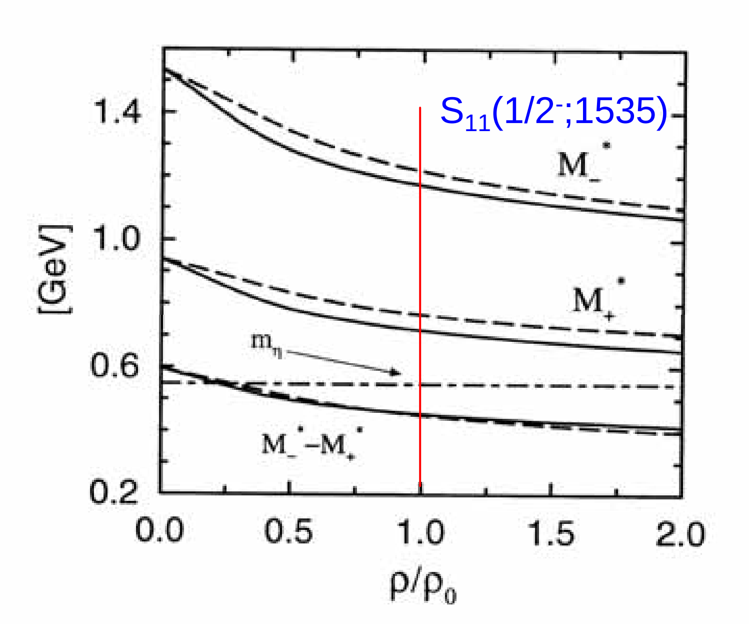
Parity doublet, Mass reduction in nuclei?

Chiral symmetry: axial vector transformation in isospin (flavor) space
Parity doublet in chiral symmetric phase

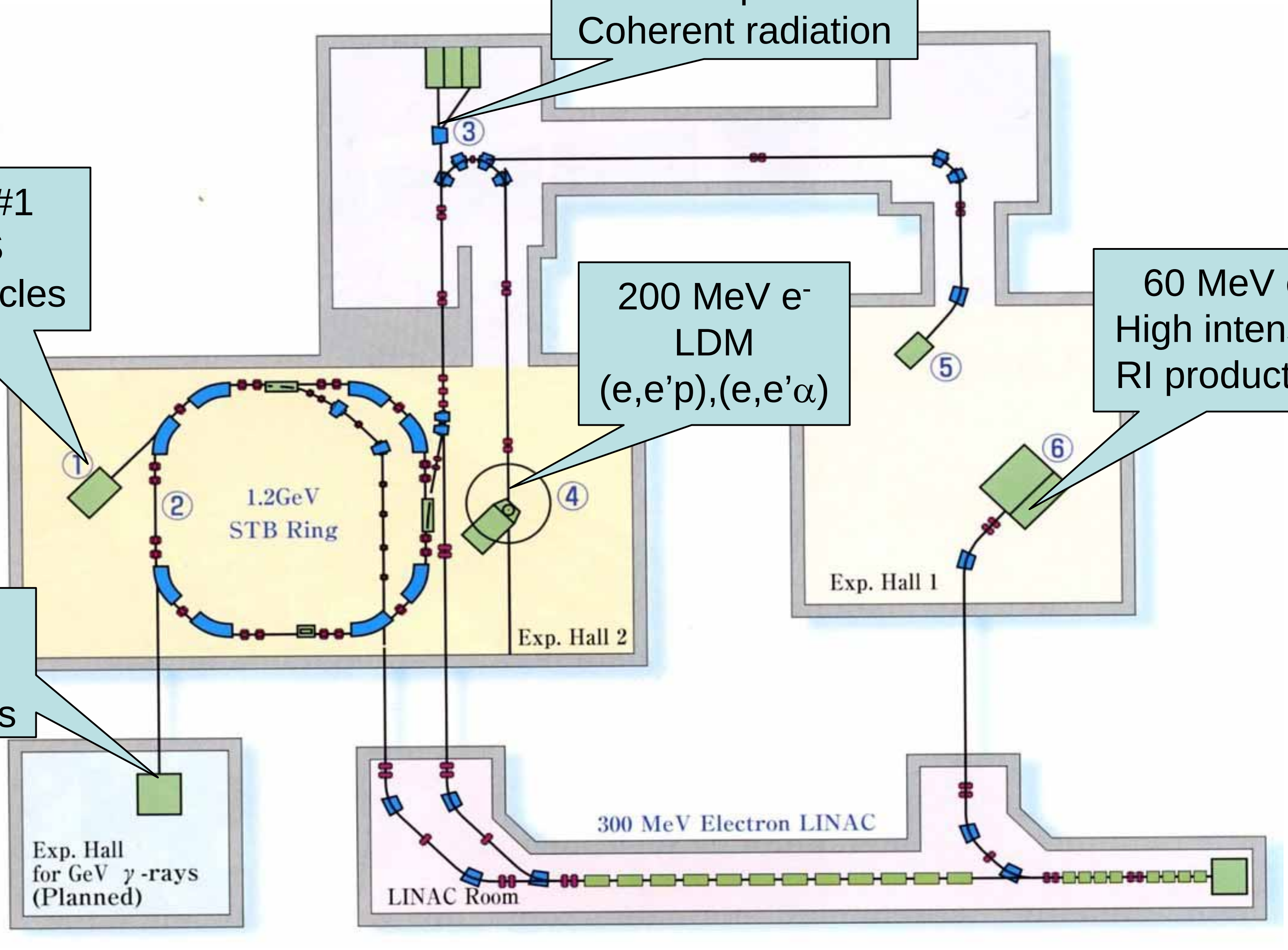





Mass of ρ, ω


$S_{11}(1/2^{-};1535)$

Nucleon resonances in nuclei; experiments at Laboratory of Nuclear Science (LNS)



200 MeV pulsed e$^-$
Coherent radiation

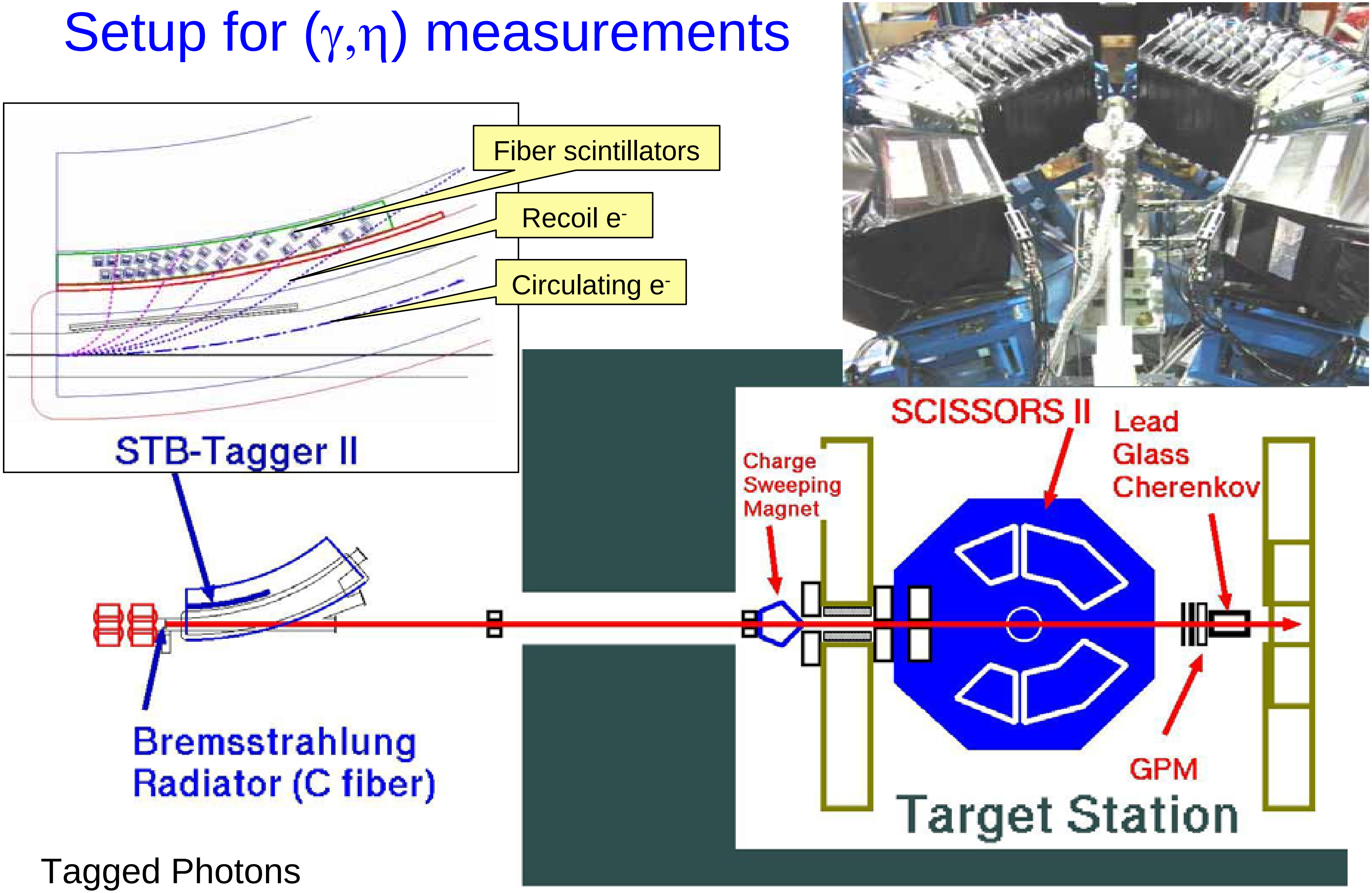
GeV γ line #1
New NKS
charged particles

200 MeV e$^-$
LDM
(e,e'p),(e,e'α)

60 MeV e$^-$
High intensity
RI production

GeV γ line #2
SCISSORS II
neutral mesons

Setup for (γ,η) measurements

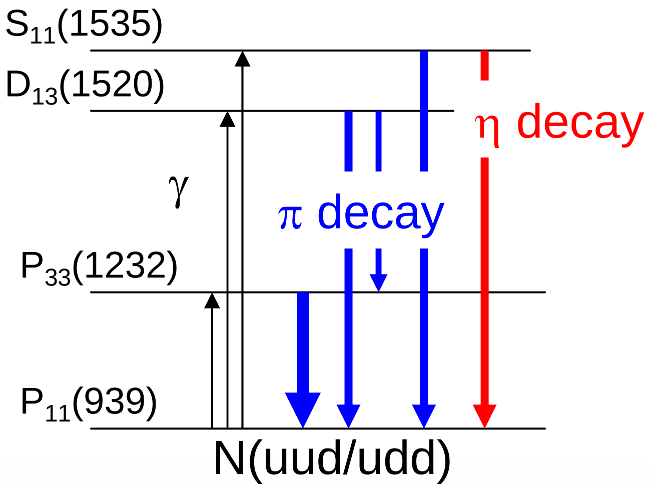


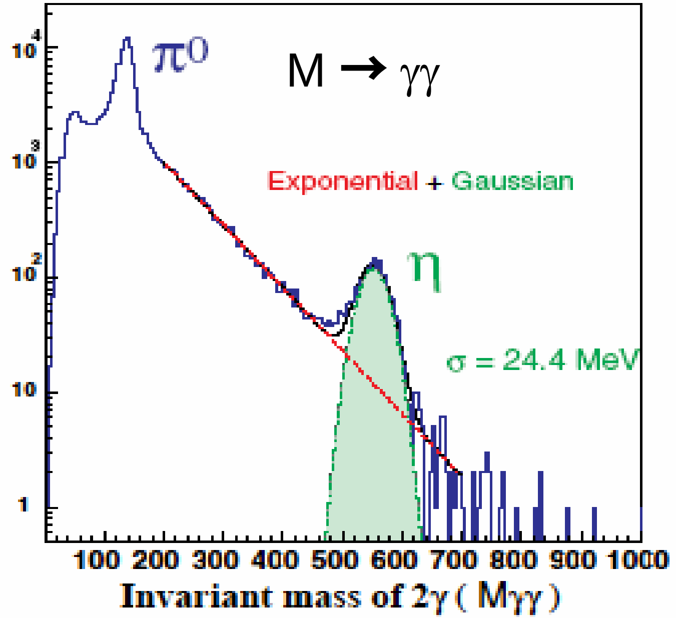
Tagged Photons

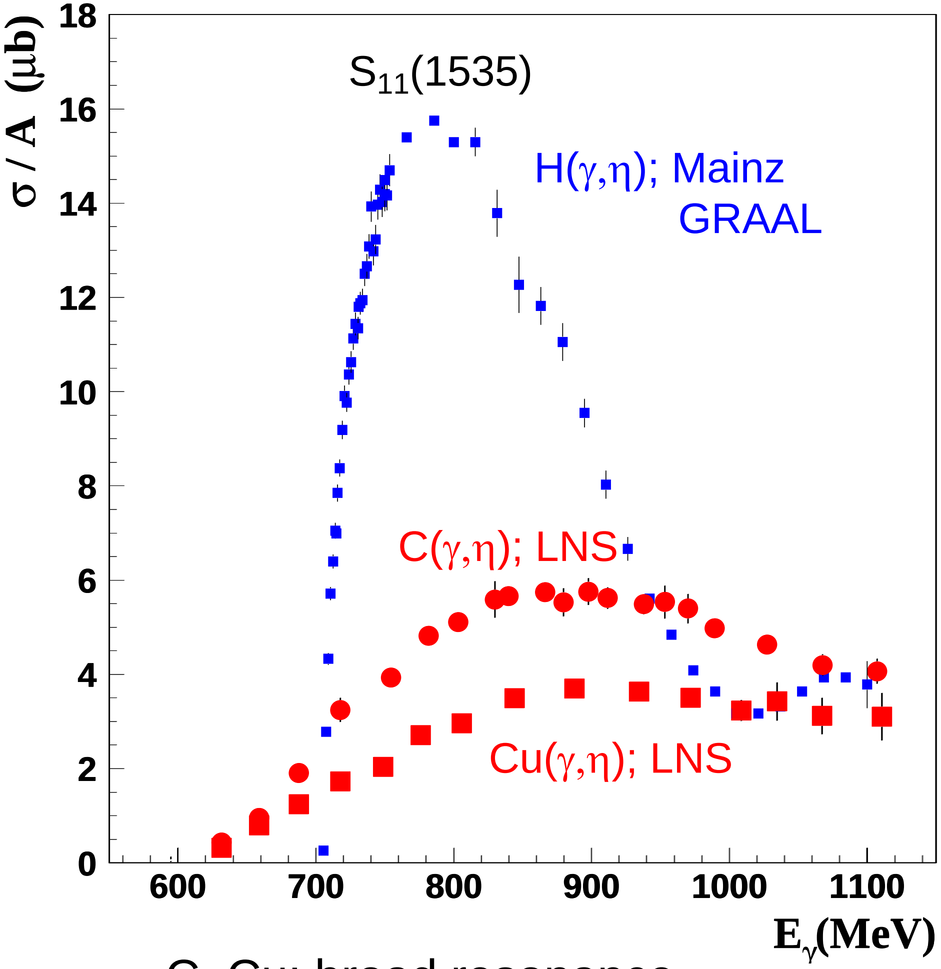
0.79〜1.15 GeV: E_e=1.2 GeV

0.59〜0.89 GeV: E_e=0.92 GeV

$S_{11}(1535)$ in C,Cu(γ,η) reactions

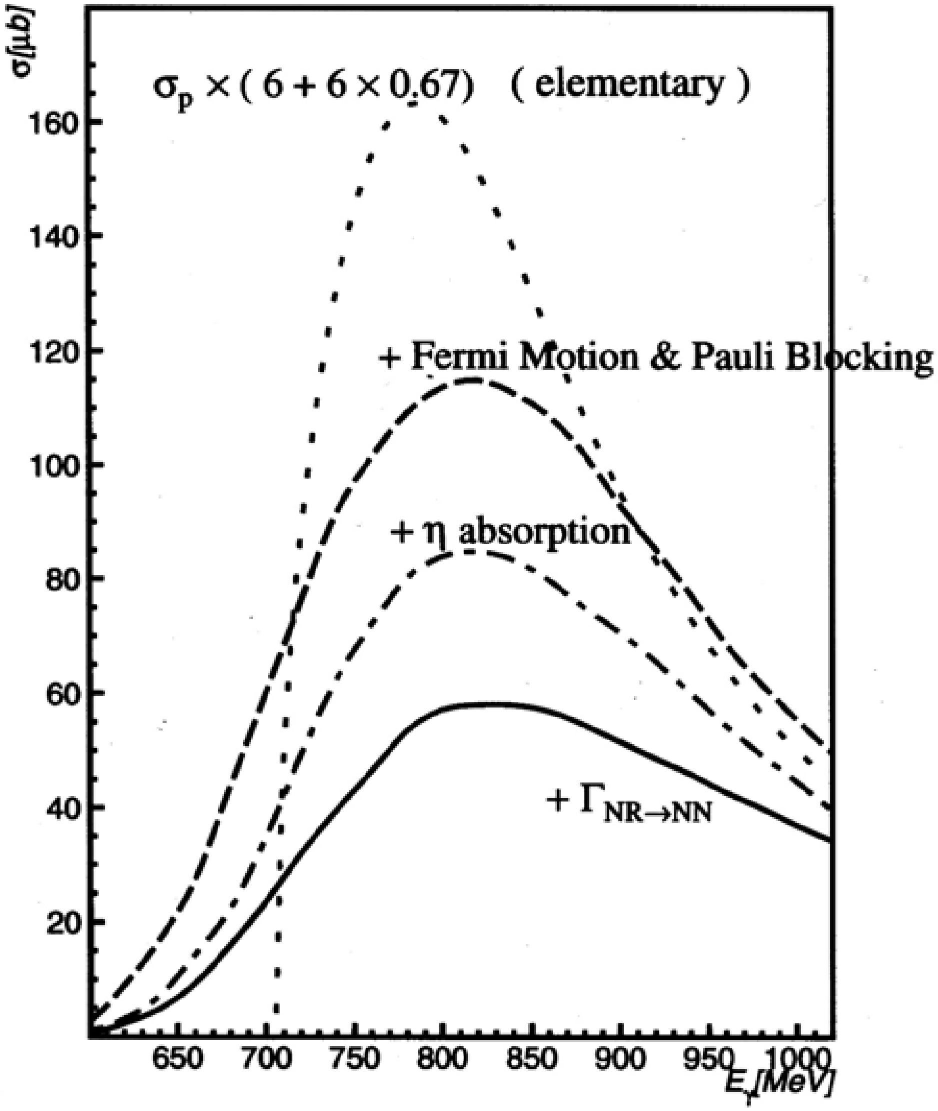


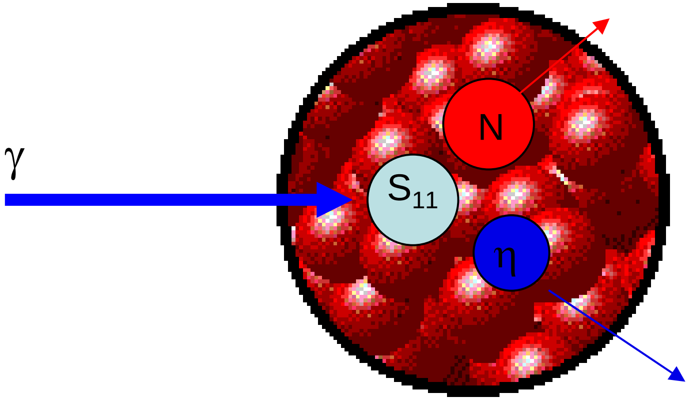




C, Cu; broad resonance
peak at higher energy
σ/nucleon; smaller and smaller

QMD calculation





Elementary process

$\gamma N \rightarrow S_{11} \rightarrow \eta N$

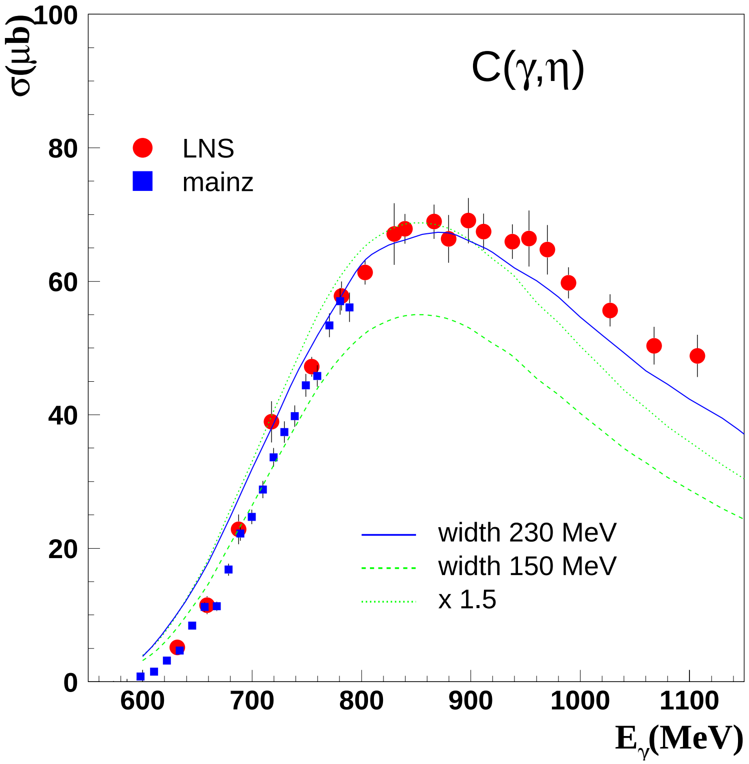
$$\sigma_{\gamma p\to\eta p} = A\left(\frac{k_0}{k}\right)^2 \frac{s\Gamma_\gamma\Gamma_\eta}{(s - M_{S_{11}}^2)^2 + s\Gamma_{tot}^2}$$

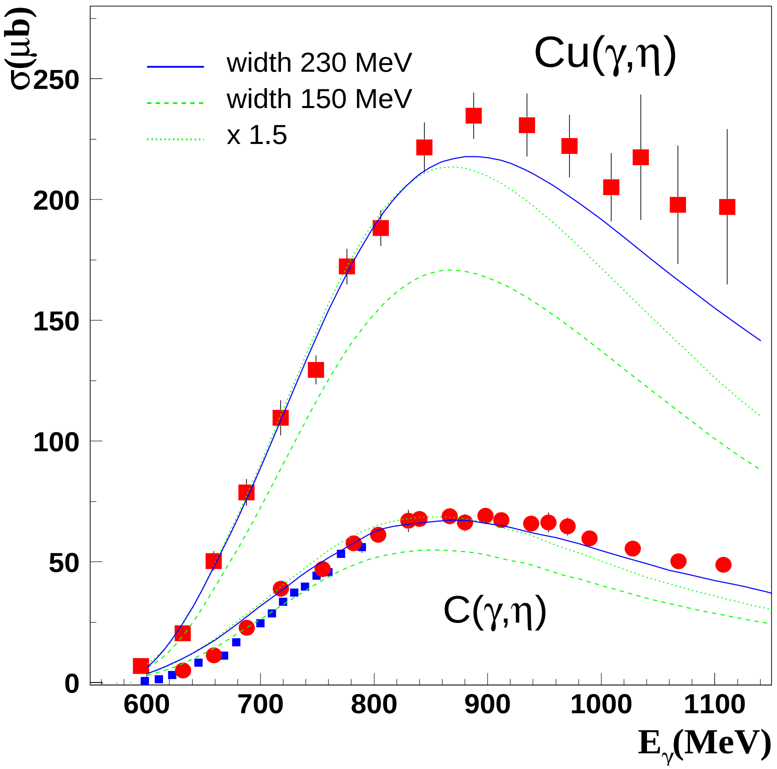
M_R = 1540 MeV, Γ_0 = 150 MeV

In a nucleus

- nucleon momentum distribution
  (Fermi motion)
- Pauli blocking
- S_{11}+N → N+N; collisions
- ηN → πN,…; η absorption

Comparisons with QMD





Conclusion:

Increase of Γ_0 is required to explain the data; 150 ➝230 MeV.

i.e., Γ_γ, Γ_π, Γ_η increase; related to swelling of nucleon in a nucleus.

No M_R shift is observed: no mass shift or the same amount for N and S_{11}.

More sensitive measurements ➝ future experiments with new setup

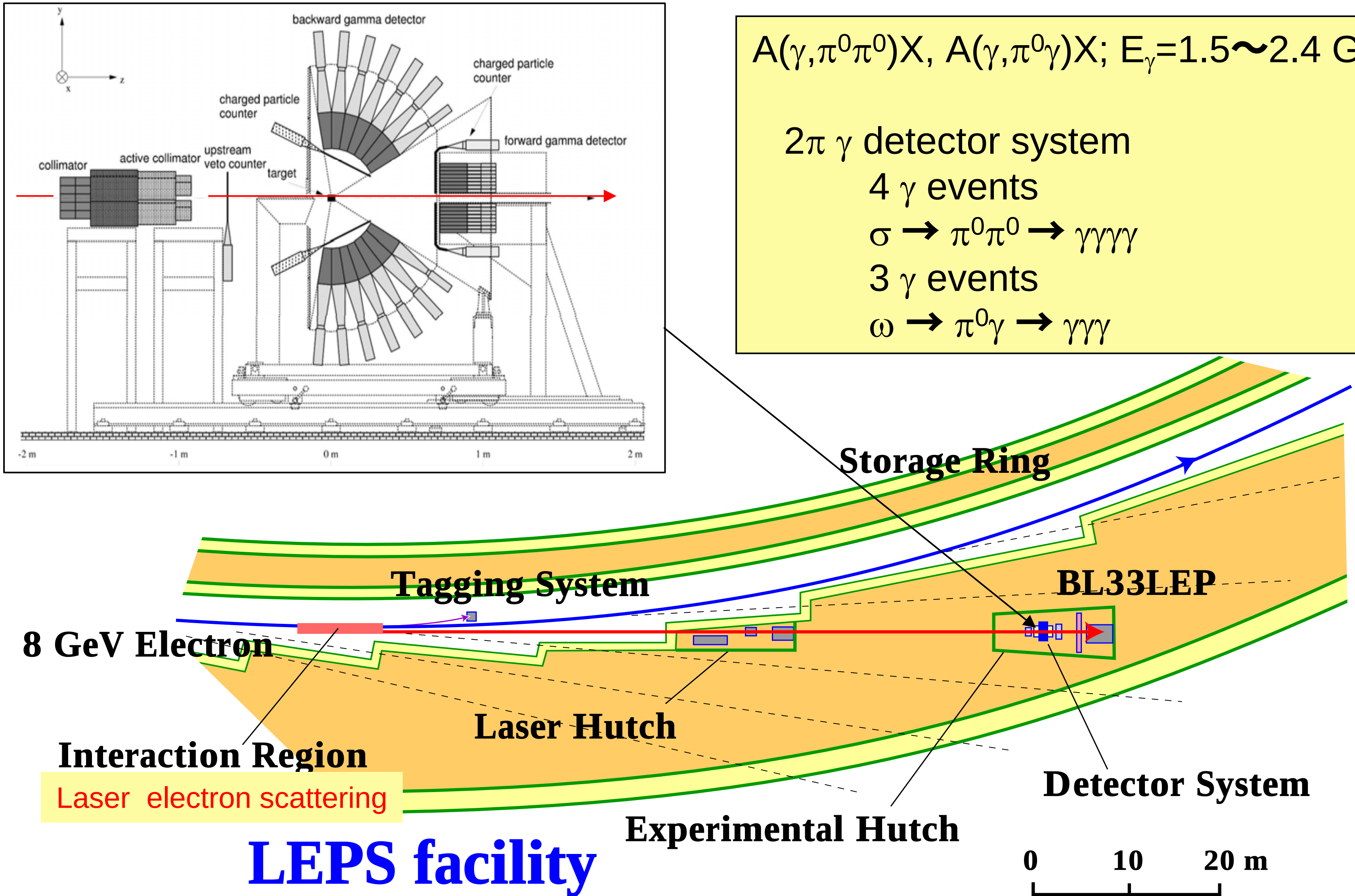
heavier nuclei, (γ,ηp) measurements, selection s-state nucleon

Mesons in nuclei experiments at SPring8 LEPS

$A(\gamma,\pi^0\pi^0)X$, $A(\gamma,\pi^0\gamma)X$; $E_\gamma=1.5\sim2.4$ GeV

2π γ detector system

- 4 γ events
  - $\sigma \rightarrow \pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma$
- 3 γ events
  - $\omega \rightarrow \pi^0\gamma \rightarrow \gamma\gamma\gamma$

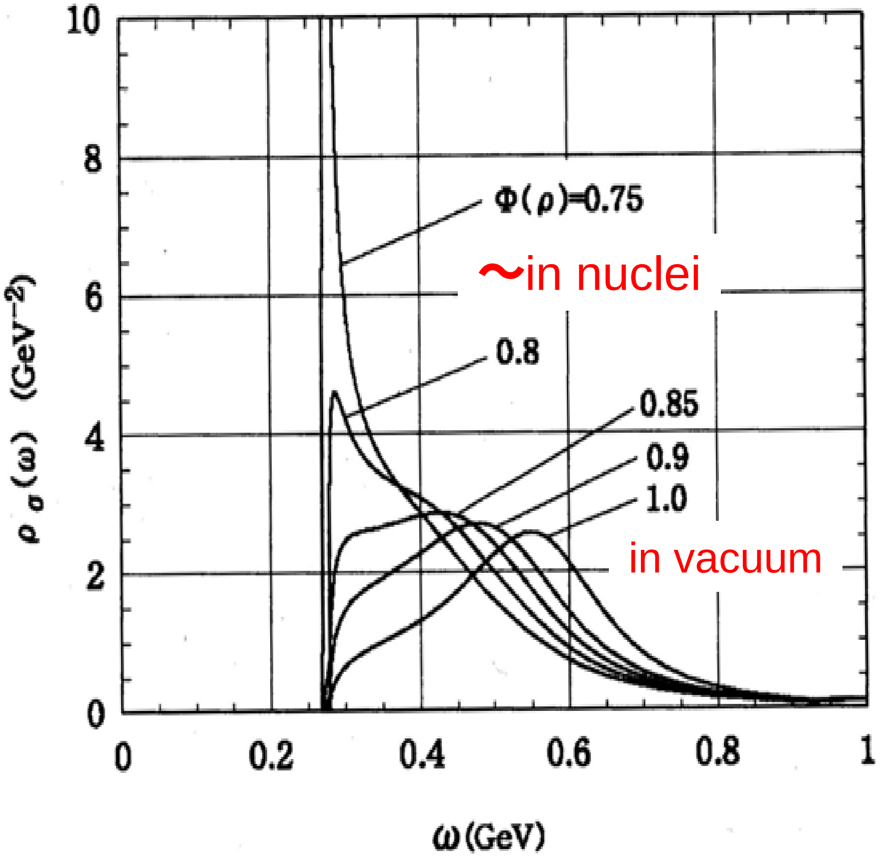


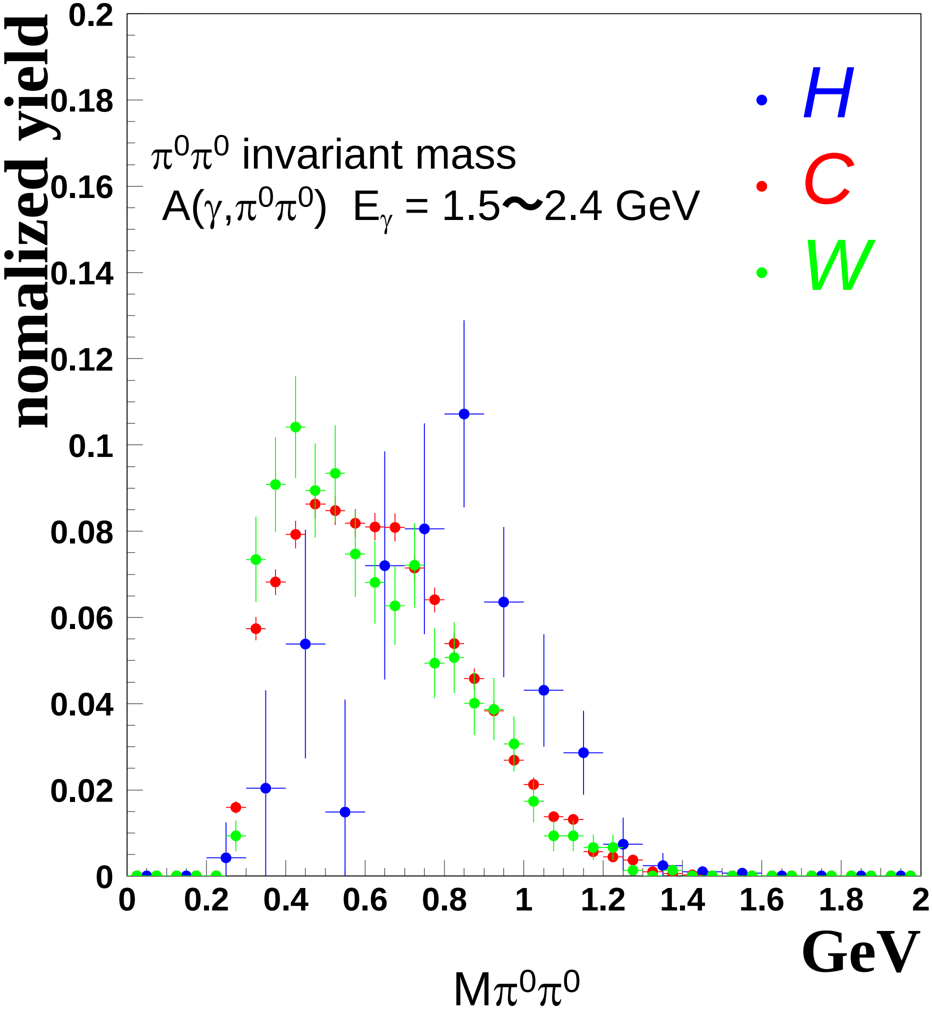
Laser electron scattering

LEPS facility

σ meson in nuclei?

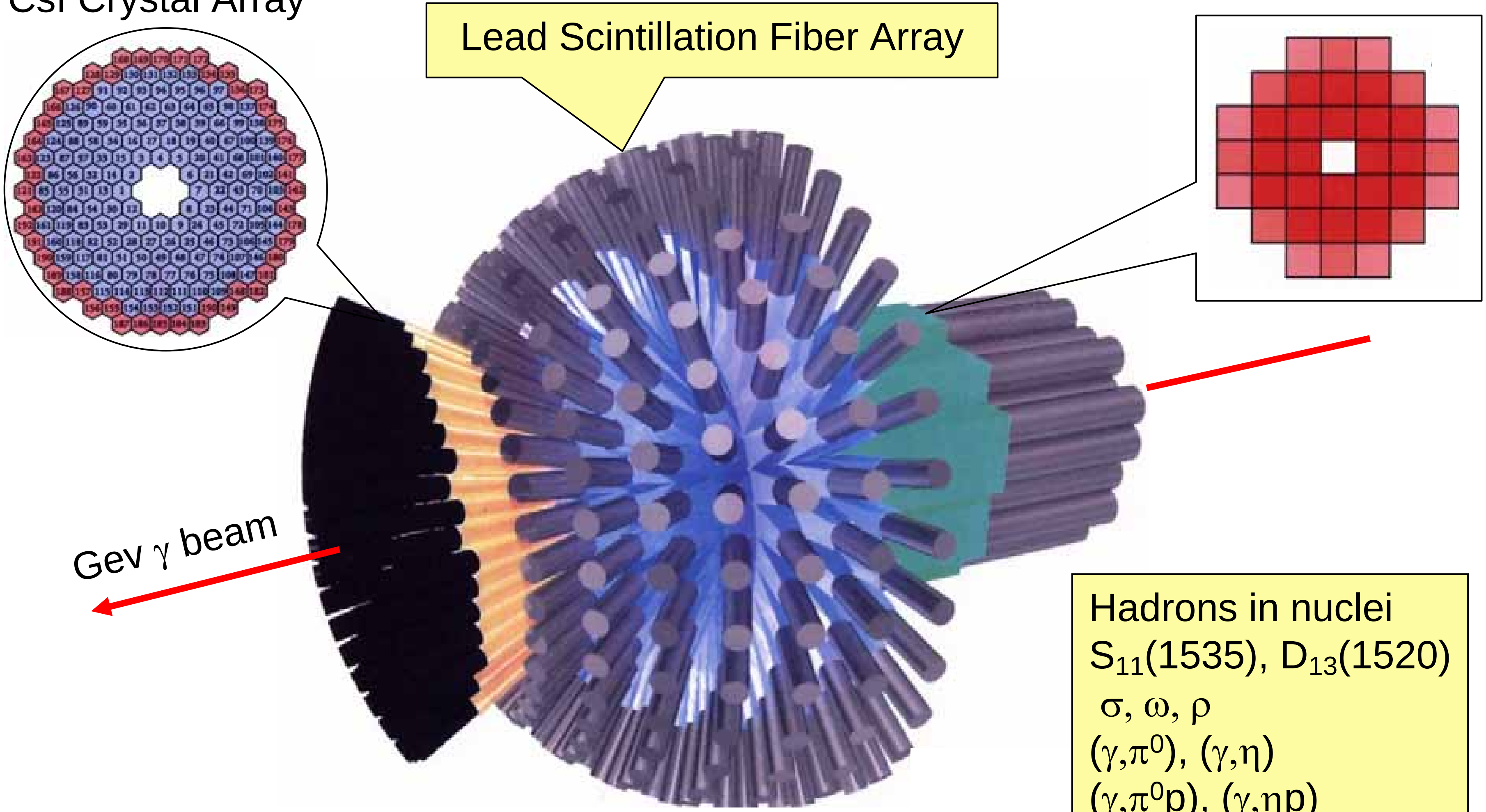
Predicted spectral function of σ
Hatsuda et al., PRL 82(1999)2840





Mass spectrum changes considerably; density dependence?
Quantitative analysis on $2\pi^0$ photo-production are needed including FSI.

multi-γ-ray detecting system for GeV γ line #2 (to be replaced with SCISSORS II)


CsI Crystal Array

Lead Scintillation Fiber Array

Lead Glass Array

Hadrons in nuclei

$S_{11}(1535)$, $D_{13}(1520)$

σ, ω, ρ

(γ,π^0), (γ,η)

$(\gamma,\pi^0 p)$, $(\gamma,\eta p)$

$(\gamma,\pi^0\pi^0)$, $(\gamma,\pi^0\gamma)$

$(\gamma,\pi^0\eta)$,..

How does condensed matter affect nuclear phenomena?

Nucleus: 10^{-14} m, Mev ⇔ Condensed matter: 10^{-10} m, eV

■ Gamma-ray absorption and emission

Mossbauer effect: Lattice absorbs the recoil momentum up to 〜100 keV/c.

QED Casimir effect: Lifetime can be modified by changing a QED vacuum?

■ Beta decay, Electron capture

Lifetime change: Electron wave function is modified in chemical compound, under ultra-high pressure, …

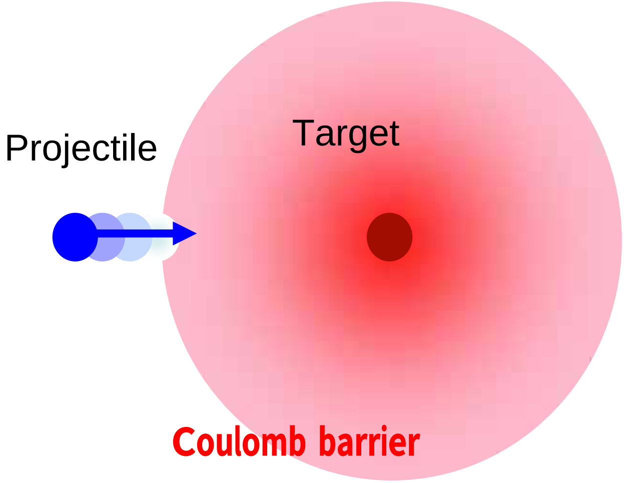
■ Charged particle induced reactions

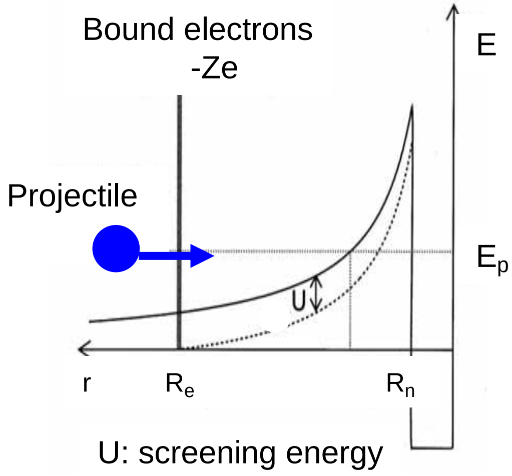
Fusion reaction rate: screening effects of bound electrons, in plasma, ….

Mu-on catalyzed fusion:

Low-energy nuclear reactions in condensed matter

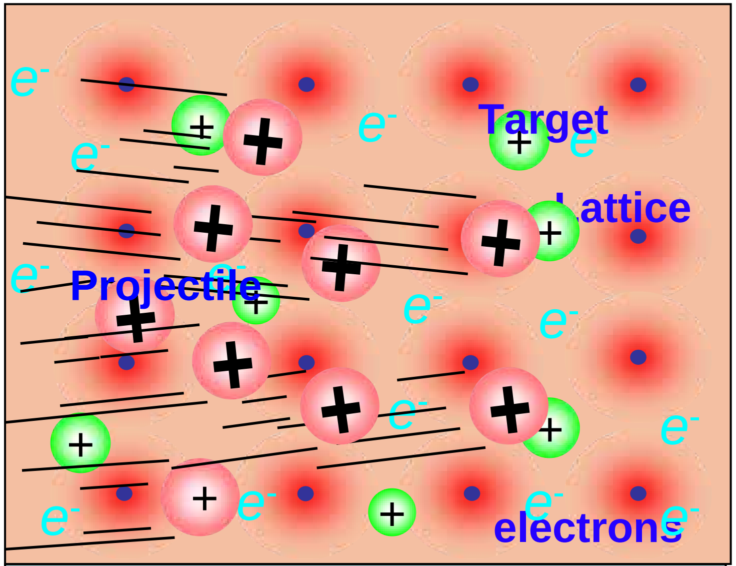
Low-energy Nuclear Reaction





How does environment affect nuclear reaction ?

Nuclear reactions in metal



Environment **?**

Nuclei ⇔ Lattice and Electron

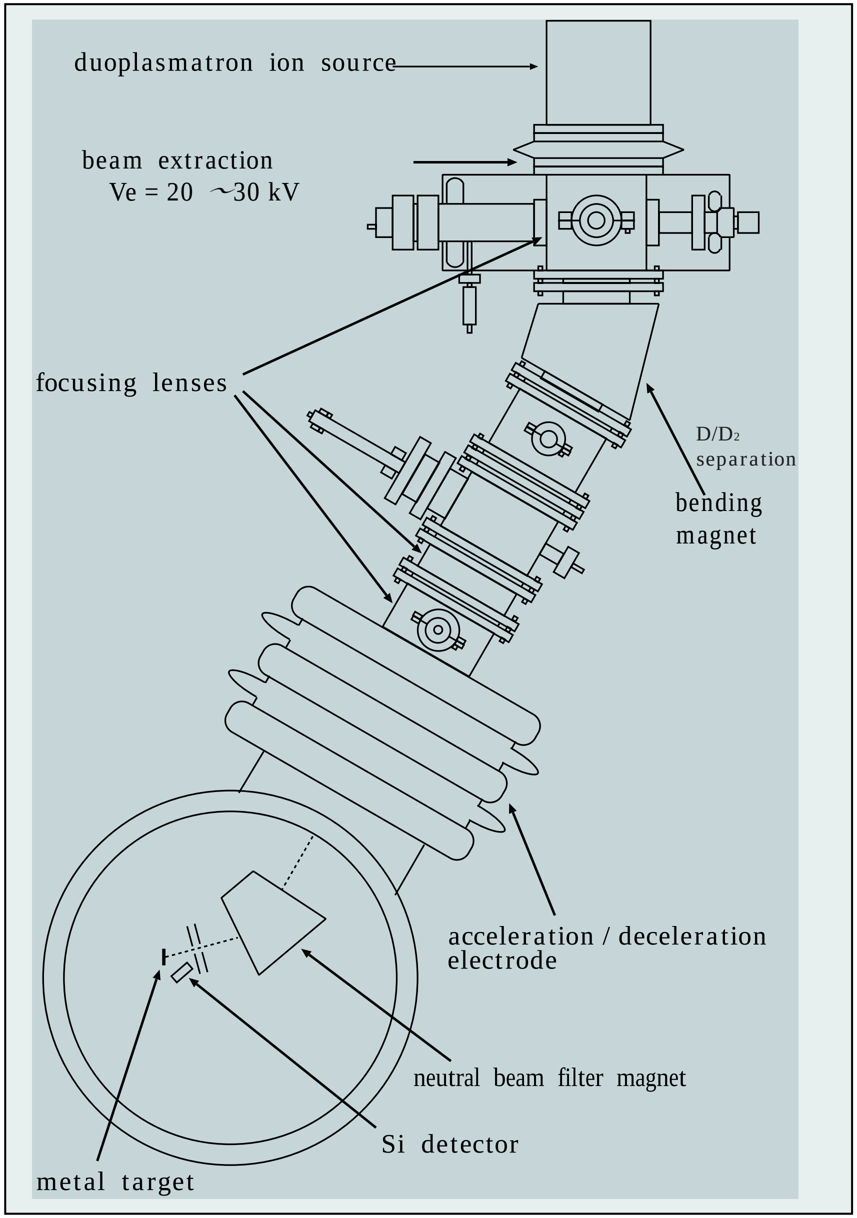
Many-body co-operation

Reduction of Coulomb energy

Zero-point vibration

Enhancement of reaction rate **?**

Low-energy deuteron generator at LNS

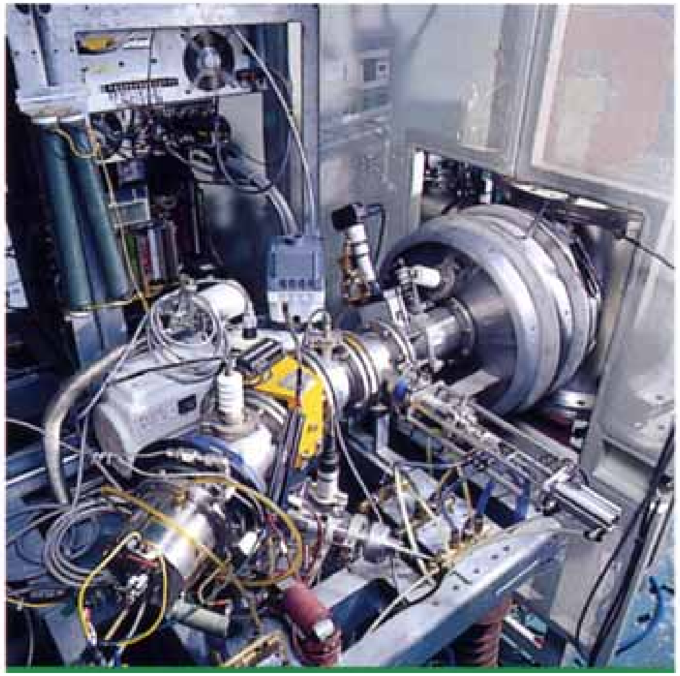


- $E_d = 2 \sim 100$ keV

  25 ~ 100 keV; acceleration mode

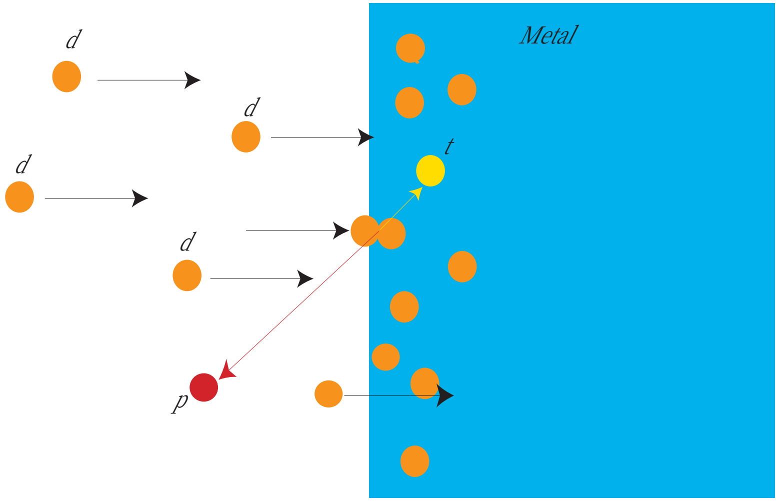
  2 ~ 25 keV; deceleration mode

- I_d up to 500 μA

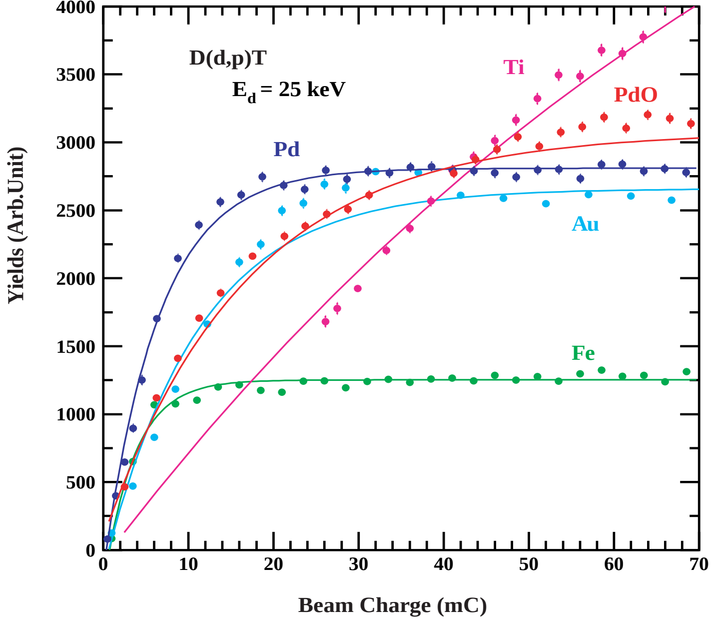


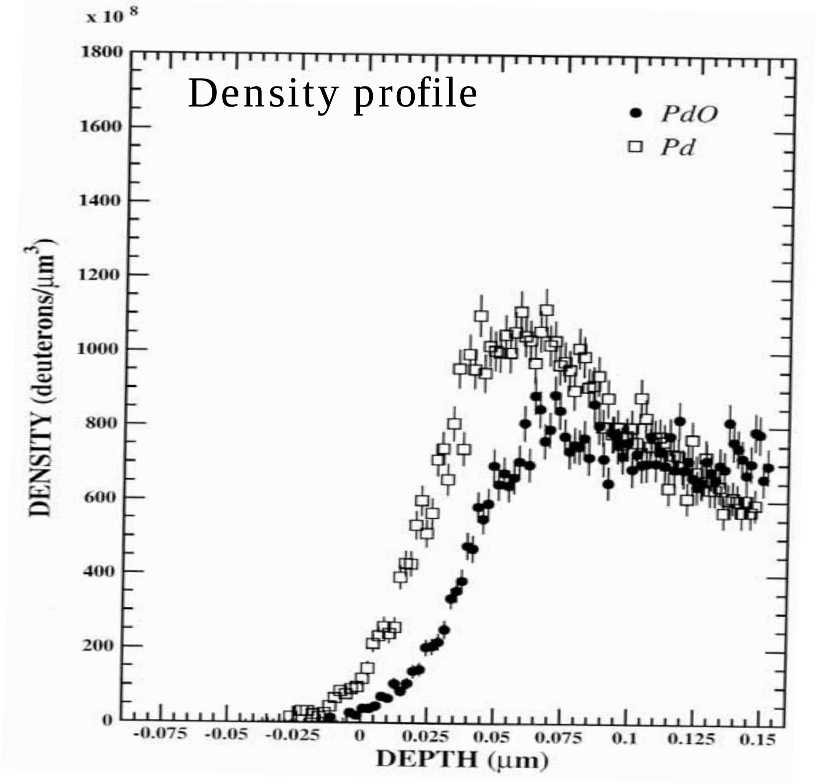
Deuterons in metals

Deuteron bombardment



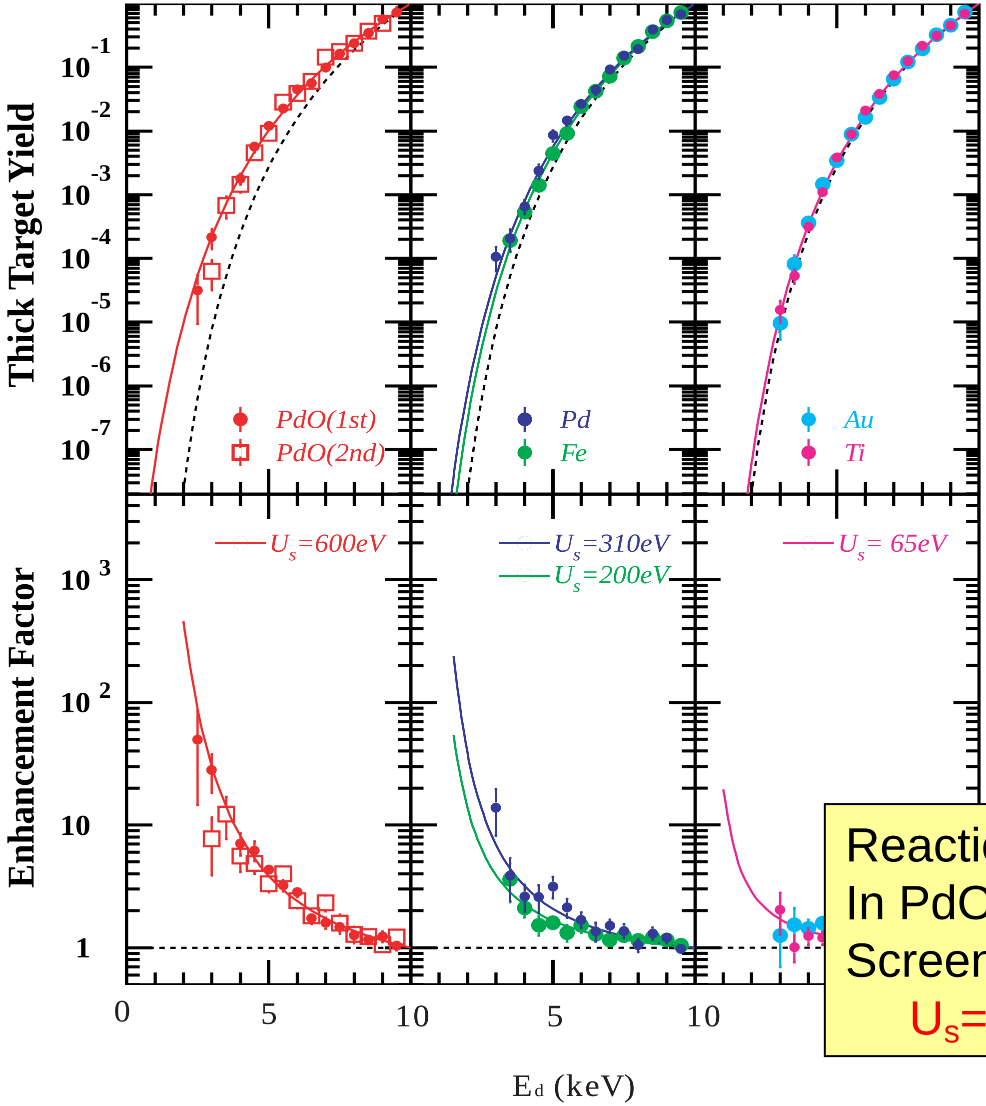
Accumulation of target D




Density profile

Deuteron density becomes constant
Density saturation
Large diffusion during D bombarding

DD fusion in metal;
Strongly enhanced reaction rate



●Thick target yield normalized at 10 keV

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

σ(E): dd reaction cross section

$\sigma_{bare}(E) = S(E)/E \exp(-2\pi\eta)$

S(E); Bosch and Hale

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

U_s; screening energy

Expected screening energy

$U_s = 25\pm5$ eV (gas target exp.)

$U_s \sim$ 14 eV for atomic D

$U_s \sim$ 27 eV for molecular D_2

Reaction rates depend strongly on host metal.

In PdO, more than 100 times at 2 keV.

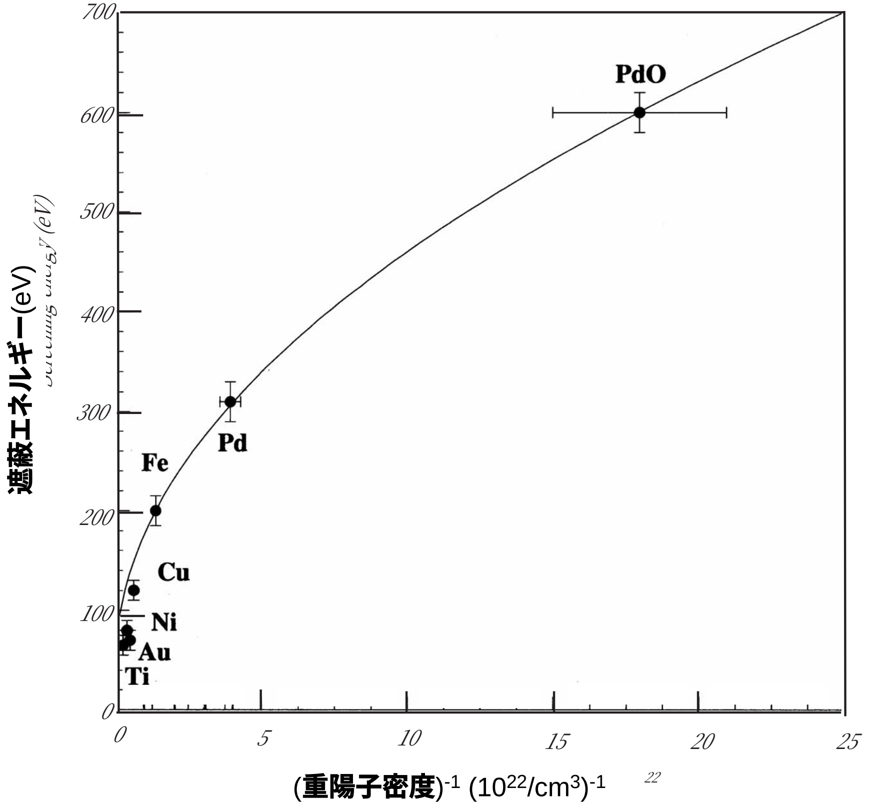
Screening energy: ∼additional kinetic energy

U_s=600 eV→1.2 keV addition in E_{Lab}

Screening energy for various metals

Metal – Screening energy (U_s)

	U_s(eV)		U_s(eV)
PdO	600±30	Yb	80±10
Pd	310±30	Ni	80±10
Fe	200±20	Au	70±10
Re	160±40	Ti	65±20
Cu	120±20	Be	40±20



U_s ⇔ host metal

⇔ deuteron density in metal

Fluidity of deuteron in metal?

Temperature, etc.?

Max. Us: 600 eV, so far observed

Us → DD reaction rates at E ～ eV

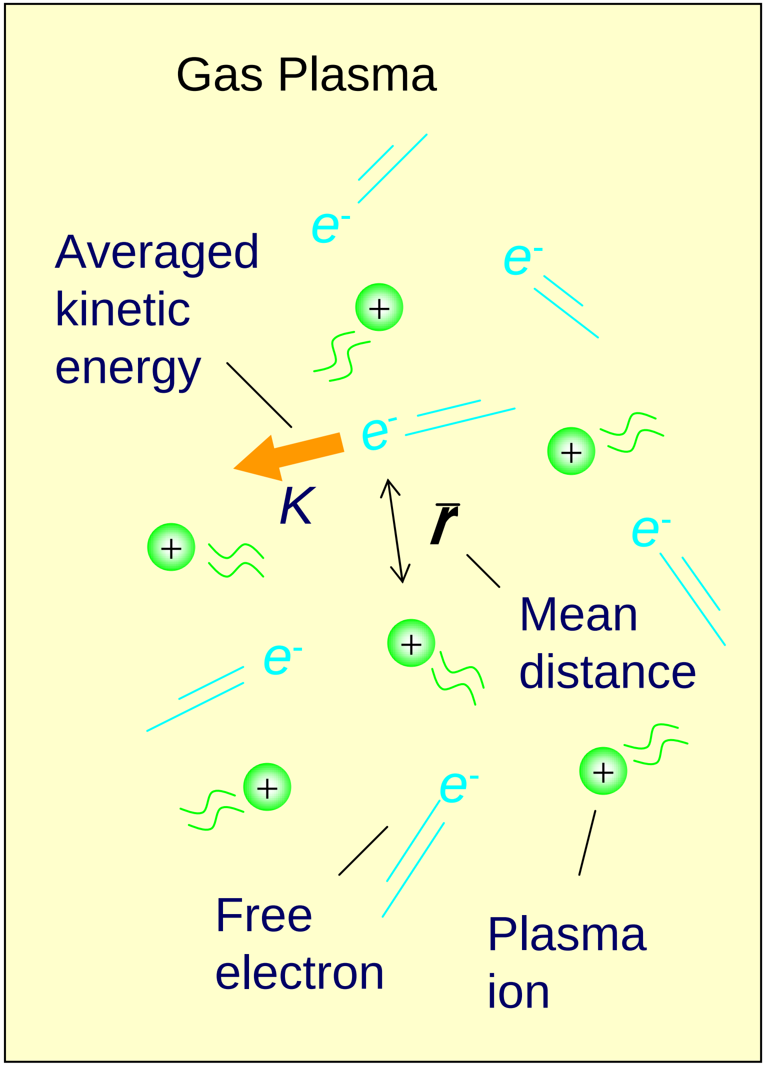
U_s(eV)	rate(/cc/sec)	σ(b)
300	$4 \times 10^{-4 \sim -2}$	10^{-27}
600	$4 \times 10^{7 \sim 9}$	10^{-16}
1000	$4 \times 10^{11 \sim 13}$	10^{-12}

D^+ and e^- plasma in metal lattice?

Ion-electron system: $M^{q+} + XD^+ + (q+X)e^-$
$n_M \sim 10^{22}/cm^3$, $n_D \sim 10^{21}/cm^3$ $n_e \sim 10^{22}/cm^3$

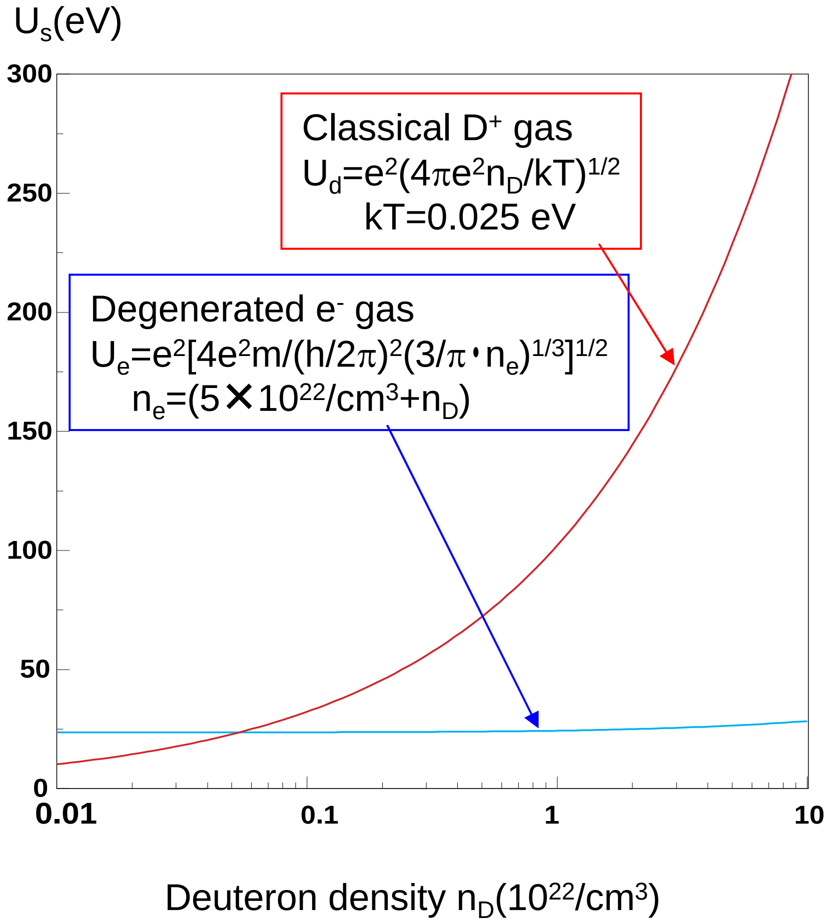
Plasma Parameters:
Wigner-Seitz radius (mean distance)
$a=(3/4\pi n)^{1/3}$; $a_D \sim 0.62$ nm, $a_e \sim 0.28$ nm
Coulomb coupling parameter
$\Gamma=(e^2/a_D)/kT \sim 100$ for classical deuterons
$r_s=a_e/a_B \sim 5$ for quantum electrons
strong coupling condition; $\Gamma \gg 1$, $r_s \gg 1$
Quantum (degeneracy) parameter
$\Lambda=h/(2\pi MkT)^{1/2}/a$; <<1 classical, >>1 quantum
$\Lambda \sim 0.1$ (for D^+); classical
$\Lambda \sim 15$ (for e^-); quantum

D^+; ～classical gas, strongly coupled
e^-; quantum gas, ～strongly coupled



Screened potential: $\phi(r)=e/r\cdot\exp(-ar)$
Debye screening, Thomas-Fermi screening

Naïve assumption; classical D^+ and quantum e gas



Classical D^+ gas

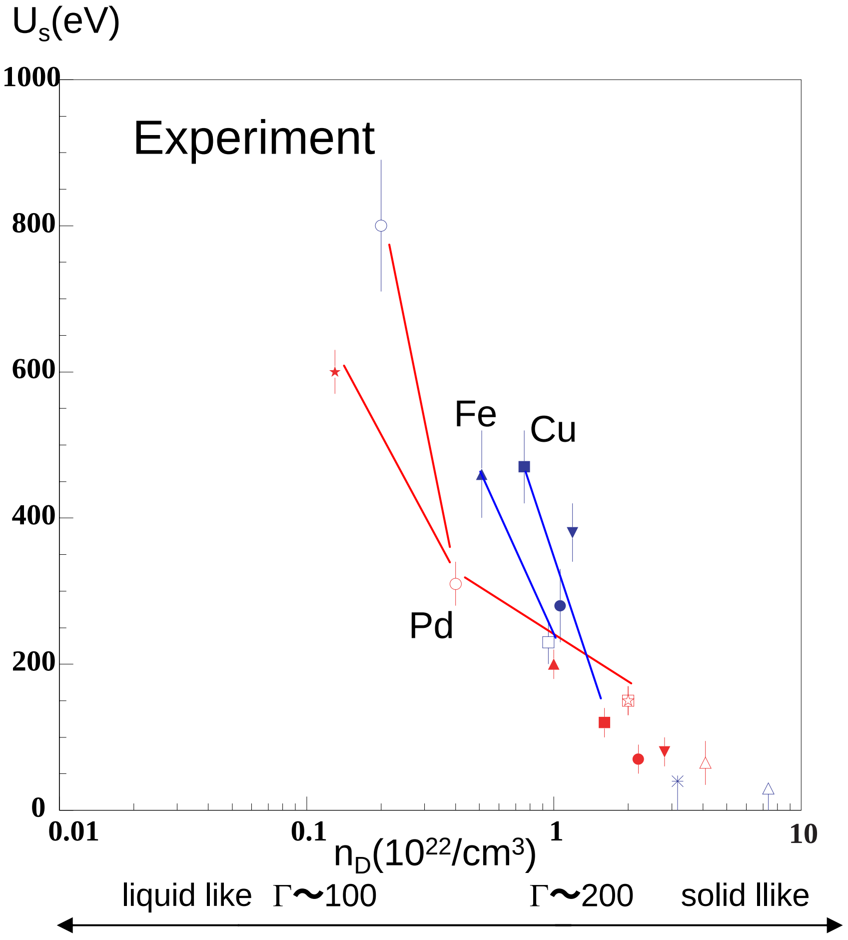
$U_d=e^2(4\pi e^2 n_D/kT)^{1/2}$

kT=0.025 eV

Degenerated e^- gas

$U_e=e^2[4e^2m/(h/2\pi)^2(3/\pi\cdot n_e)^{1/3}]^{1/2}$

$n_e=(5\times10^{22}/cm^3+n_D)$



Simple picture does not work.

small $n_D \propto$ fluidity of D^+ ?

Simple Debye and Thomas-Fermi picture are failed!

1. Non-ideal plasma?

   $\Gamma \sim 100$ for deuterons in metal

   $r_s \sim 5$ for electrons in metal

   i.e., strong coupling

   → simple prediction cannot be applied

2. Effect of host metal structure ?

   Strong dependence of Us on host metals

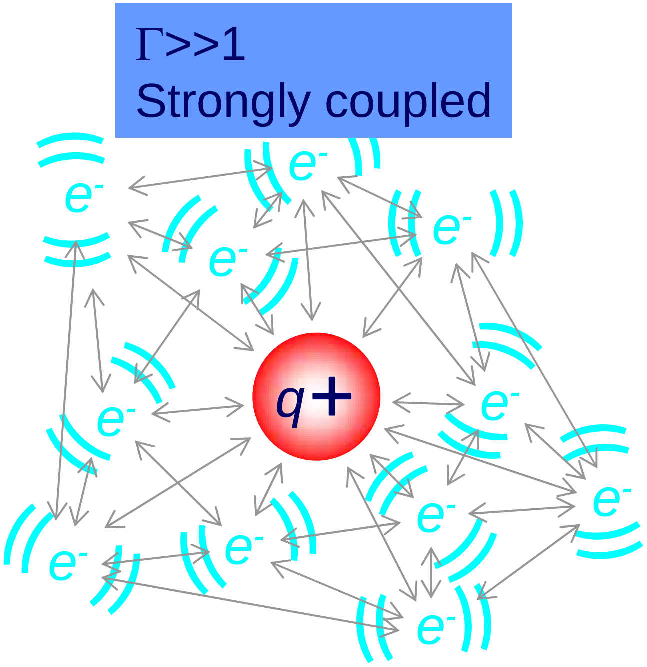
3. Effect of irradiation?

   Defects of lattice during bombardment

   Vacancy trapping multi deuterons

4. Reaction rates at room temperature?

U_s(eV)	reactions/cc/sec
300	$4\times10^{-4\sim-2}$
600	$4\times10^{7\sim9}$



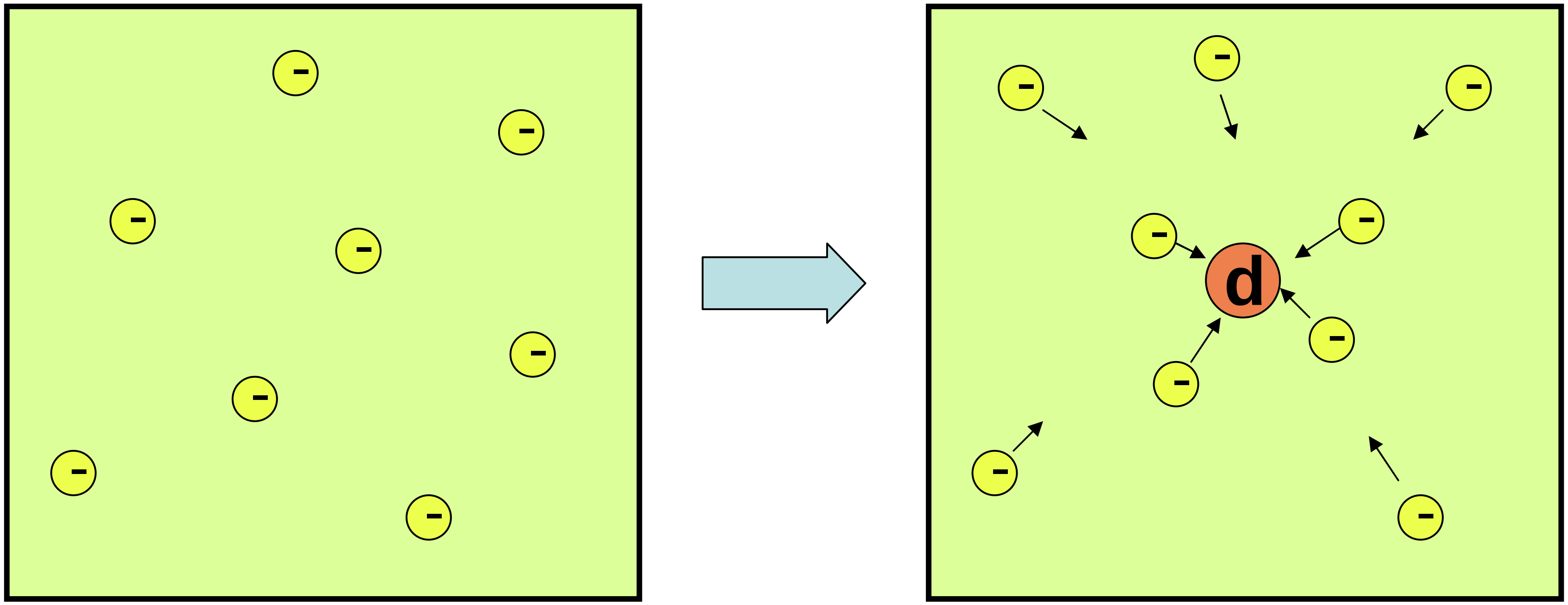
Γ>>1

Strongly coupled

Theoretical study by Kato and Takigawa

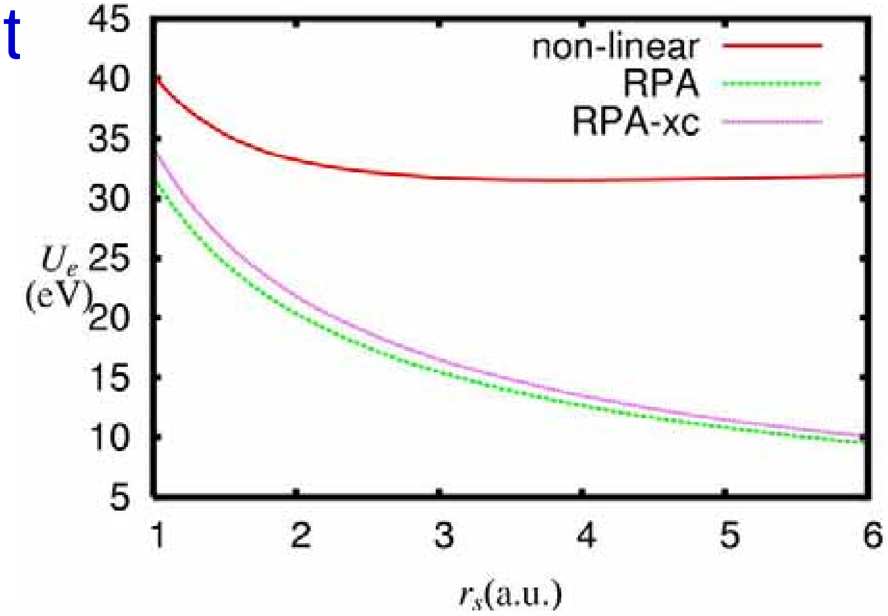
Jellium model

Metal is replaced by a uniform electron gas with a compensating positive background having the same mean electronic density.



Theoretical study by Kato and Takigawa

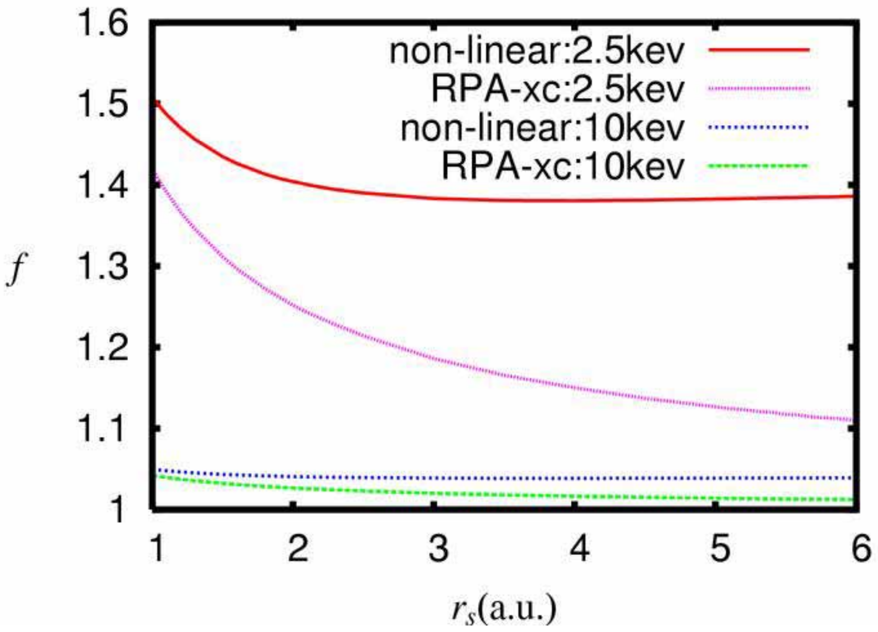
Screening energy against



Experimental result

600 eV : PdO
310 eV : Pd
200 eV : Fe
70 eV : Au, Ti

Enhancement factor *f*



$$f(E) = \frac{P(E+U_e)}{P(E)} \approx \exp\left(\pi\eta\frac{U_e}{E}\right)$$

$$P(E) \propto \exp\left(-2\pi\frac{Z_1Z_2e^2}{\hbar\upsilon}\right)$$

Theoretical study by Kato and Takigawa

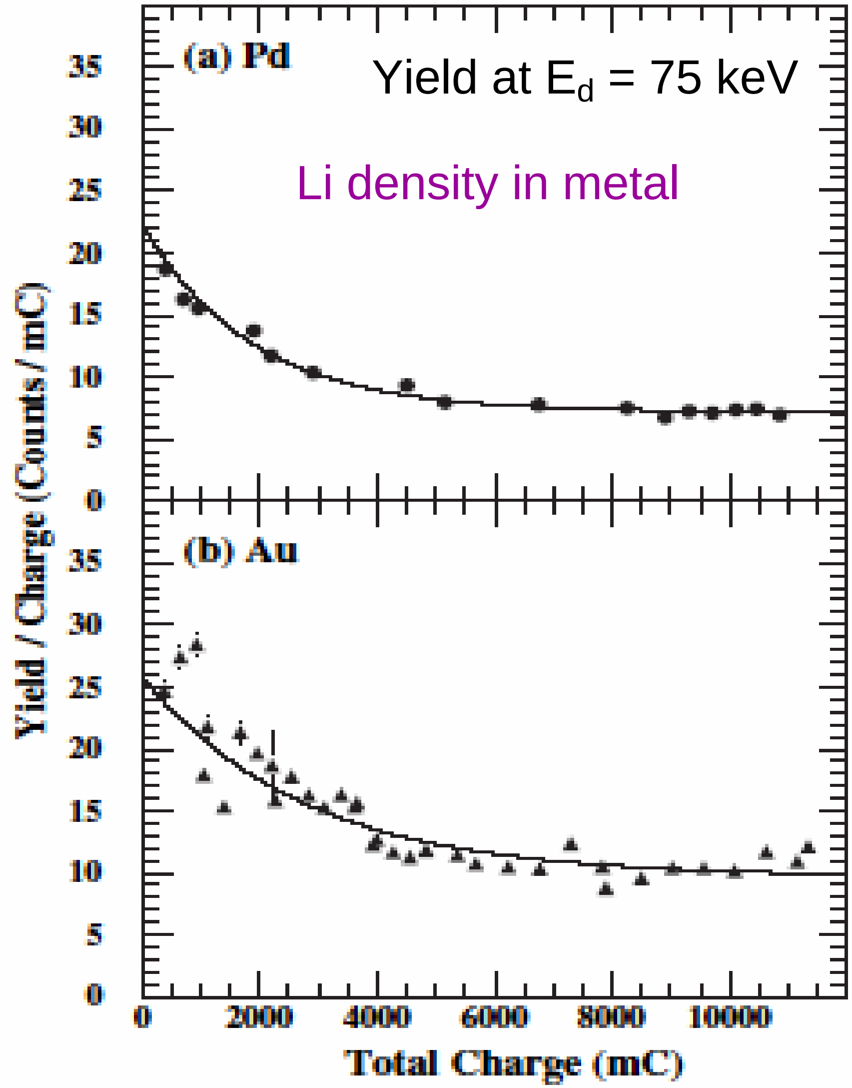
Summary

- Non linear screening energy is a few times larger than linear one.
- In non linear case, screening energy is almost constant in the range here studied.
- Only the screening effect by the valance electron is too small to understand the experimental result.

Future

- Pile up to incident deuteron
- The dynamics of the implanted deuteron
- Structure of metal

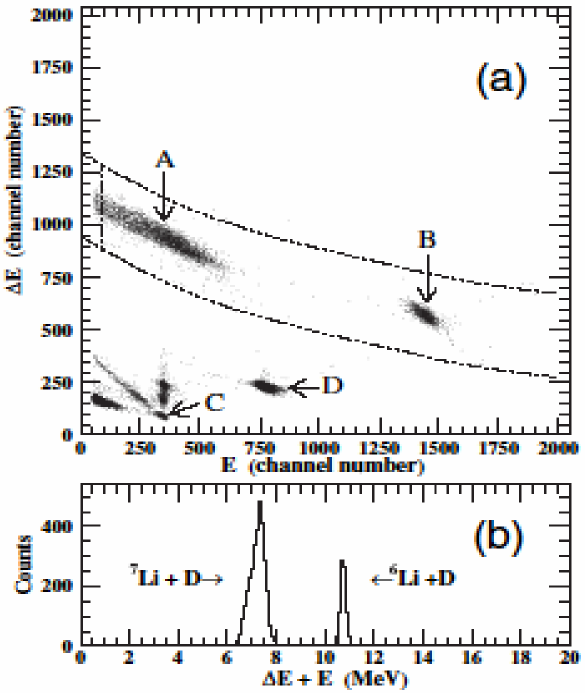
Li+D reactions in Pd and Au



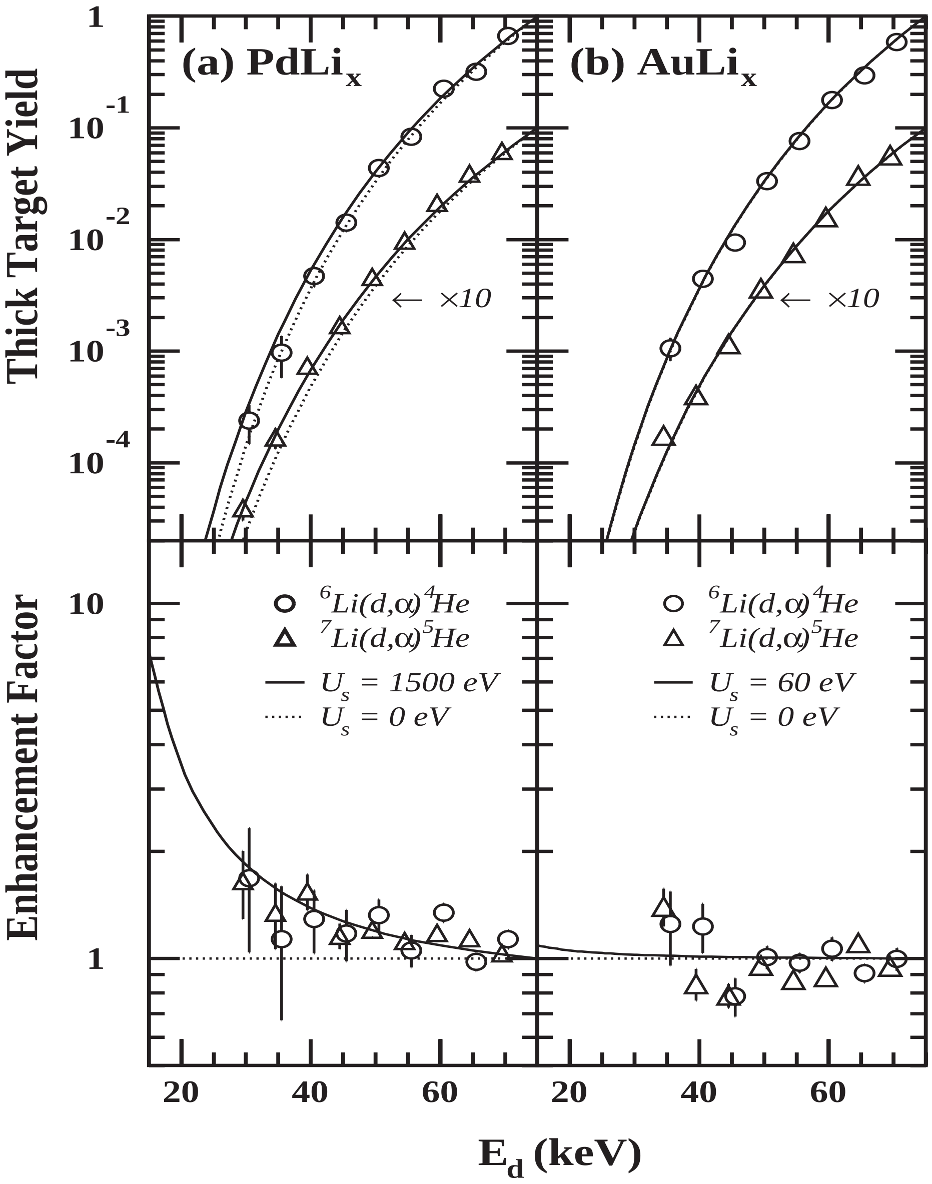
Yield at E_d = 75 keV

Li density in metal

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

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

Again, large enhancement in Pd!
Us = 1500 eV
Us∼ 300 eV (LiF)

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 ?

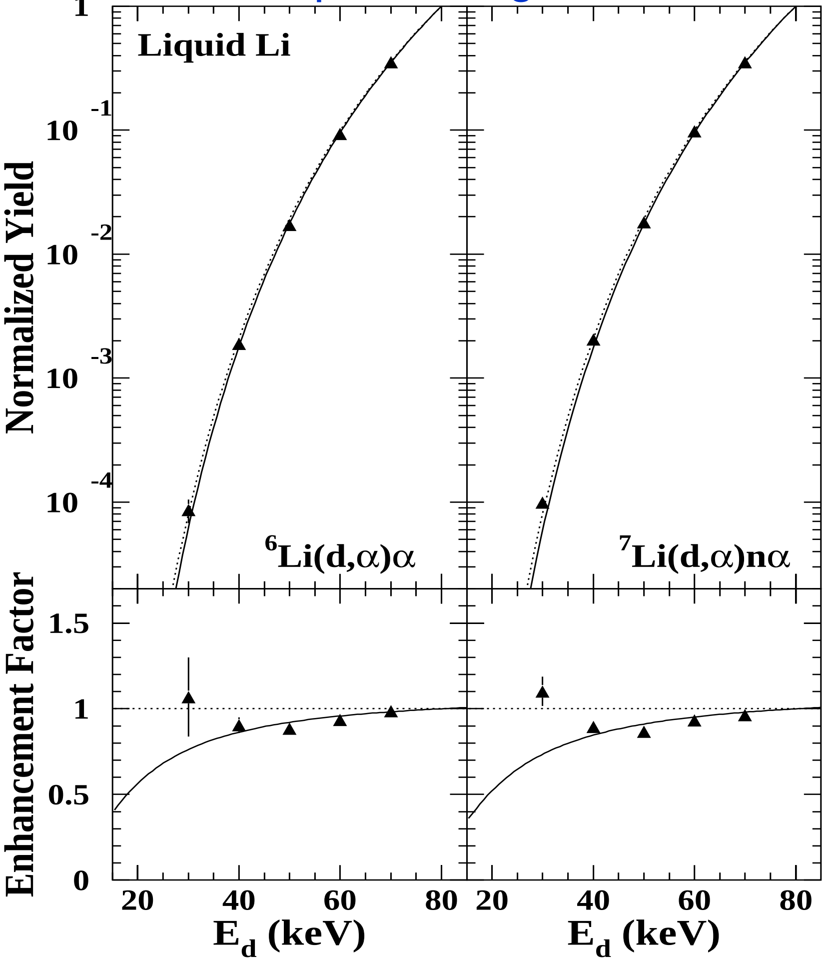
$\phi_s = Z_1 e/r \exp(-\kappa r) \sim Z_1 e/r\,(1-\kappa r)$

$U_s = Z_1 Z_2 e^2 \kappa$

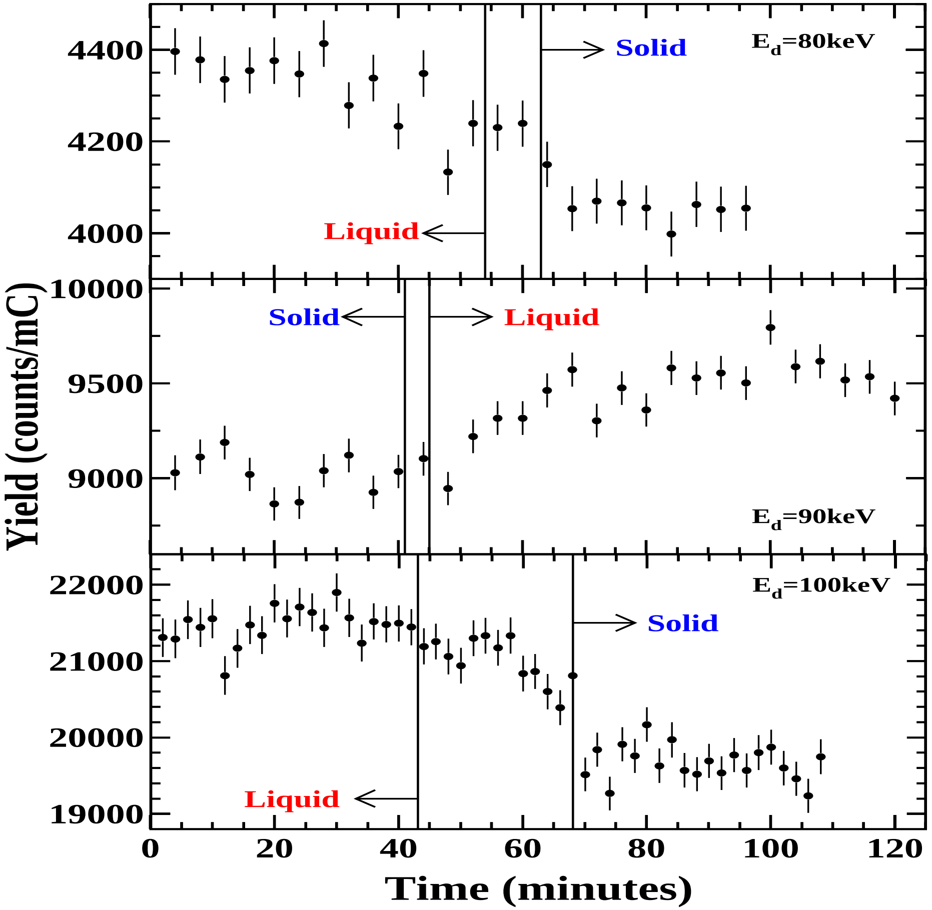
$\rightarrow U_s(\text{Li+d}) = 3U_s(\text{D+D})$

Li+D reactions in solid and liquid phases

Liquid Li target, Li+d



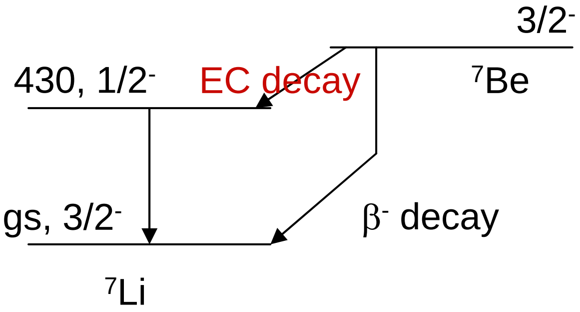
Liquid – Solid change



No simple parameterization of Us

Y(liquid) > Y(solid)
Reaction rate depends on the phase

Lifetime of ^{7}Be



$3/2^-$

430, $1/2^-$ EC decay

^{7}Be

gs, $3/2^-$

β^- decay

^{7}Li

Electron capture
Changing electron wave function
→ lifetime of nucleus change ?

^{7}Be lifetime in various chemical compounds
H.W. Johlige et al. Phys. Rev. C2 (1970) 1616

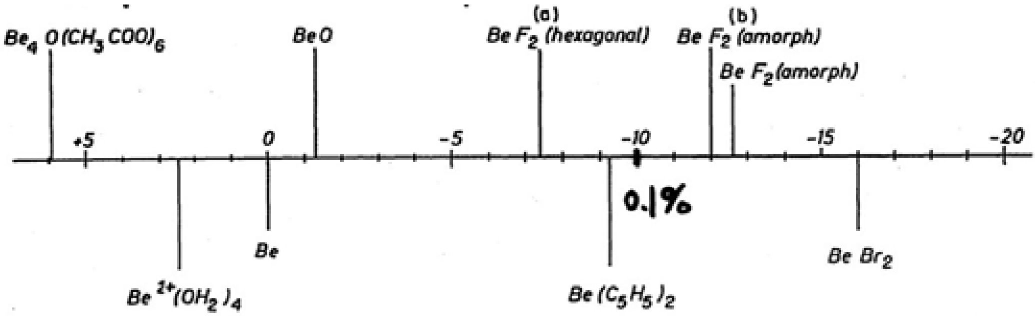


FIG. 7. Differences of electron densities at the Be nucleus in various compounds (BeX) of Be: $|\psi_s|^2_{Be} - |\psi_s|^2_{BeX}$ in units of $10^{-4}|\psi_s|^2_{Be}$. (a) Measurement of Ref. 3; (b) measurement of Ref. 4.

Maximum change ~ 0.2% !

^{7}Be lifetime under high pressure
W.K. Hensley et al. Science 181 (1973) 1164

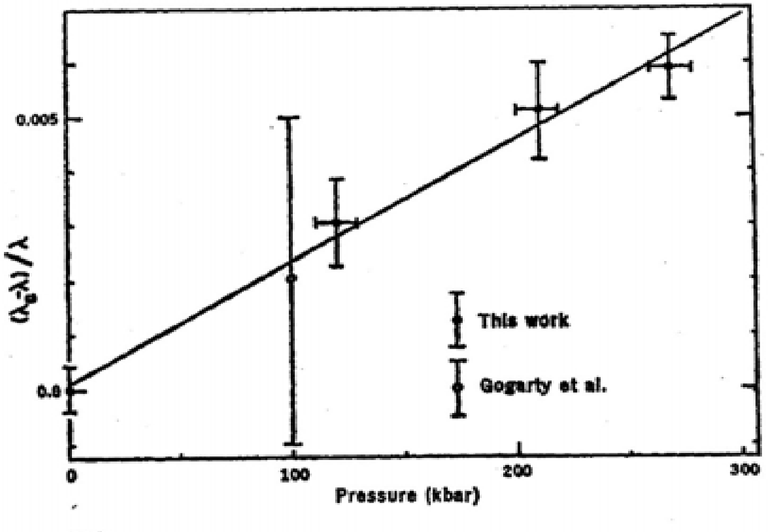
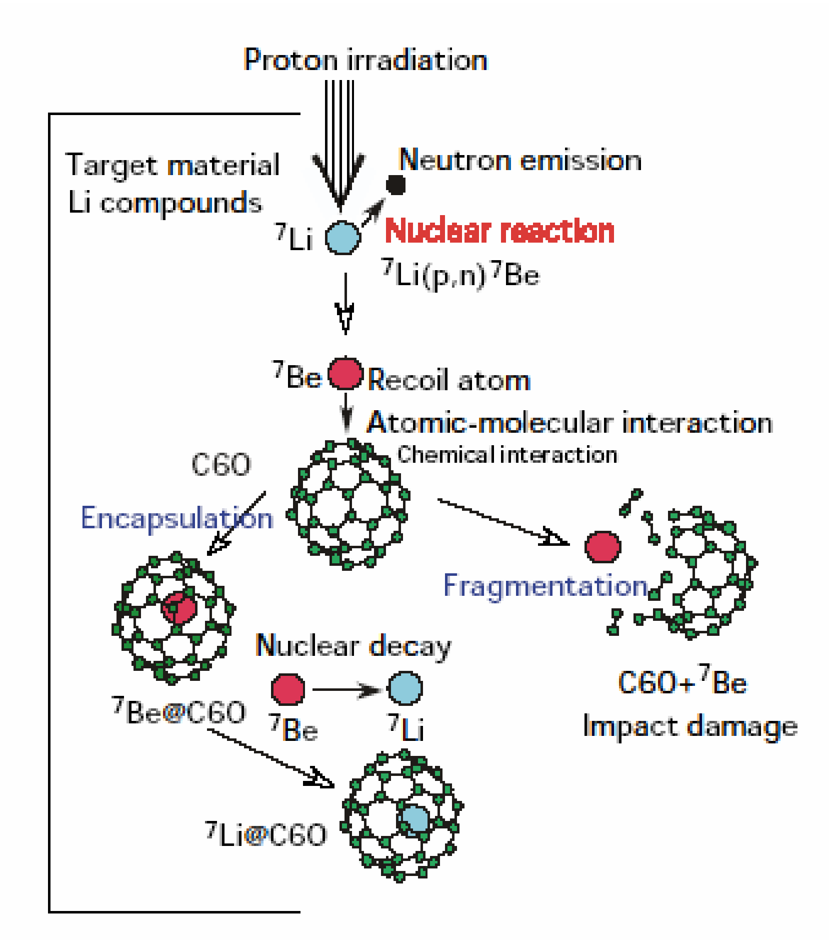


Fig. 1. Fractional increase in the total decay constant of ^{7}Be in ^{7}BeO as a function of pressure; the line is a least-squares fit of our data (see text). Error bars represent one standard deviation. The data point of Gogarty *et al.* (5) is calculated from a least-squares fit of 20 measurements near 100 kbar.

~ 0.6% change

^{7}Be encapsulated in C_{60}



HPLC: High Pressure Liquid Chromography

Nuclear reactions: ^{7}Li(p,n), ^{12}C(γ,αn)

10 mg C_{60} + Li_2CO_3 powder

Irradiated
Sample

Dissolved
In CS2

Milipore filter
size: 045 mm

evaporate CS2
into Toluene-hexan

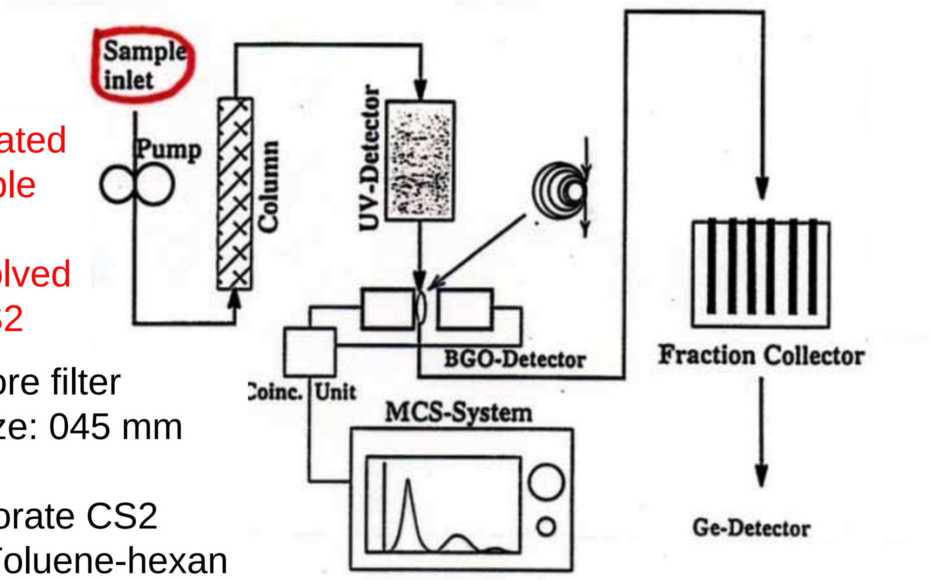
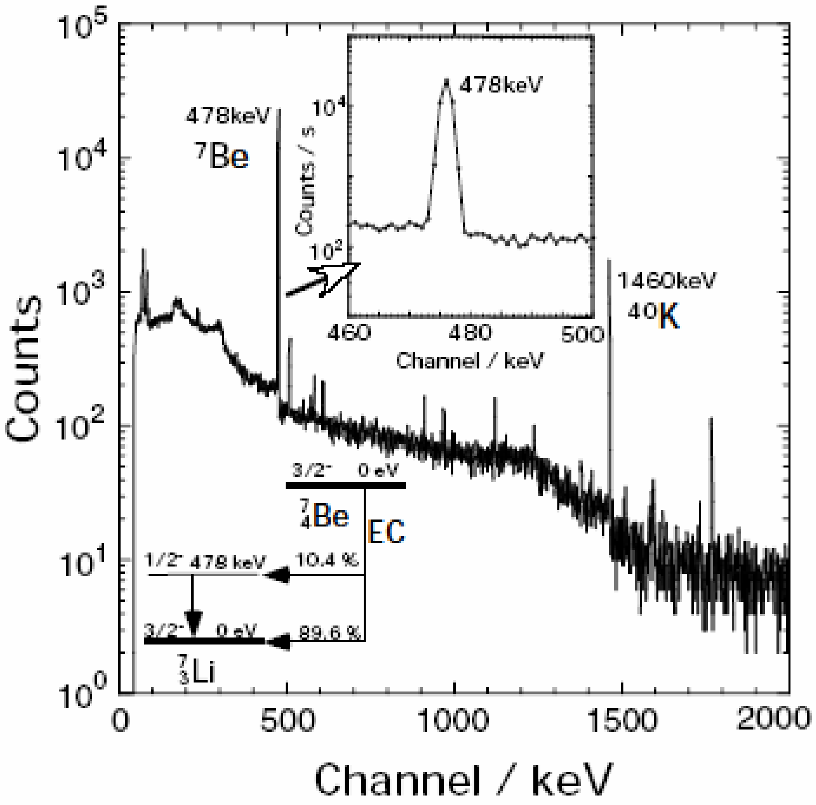


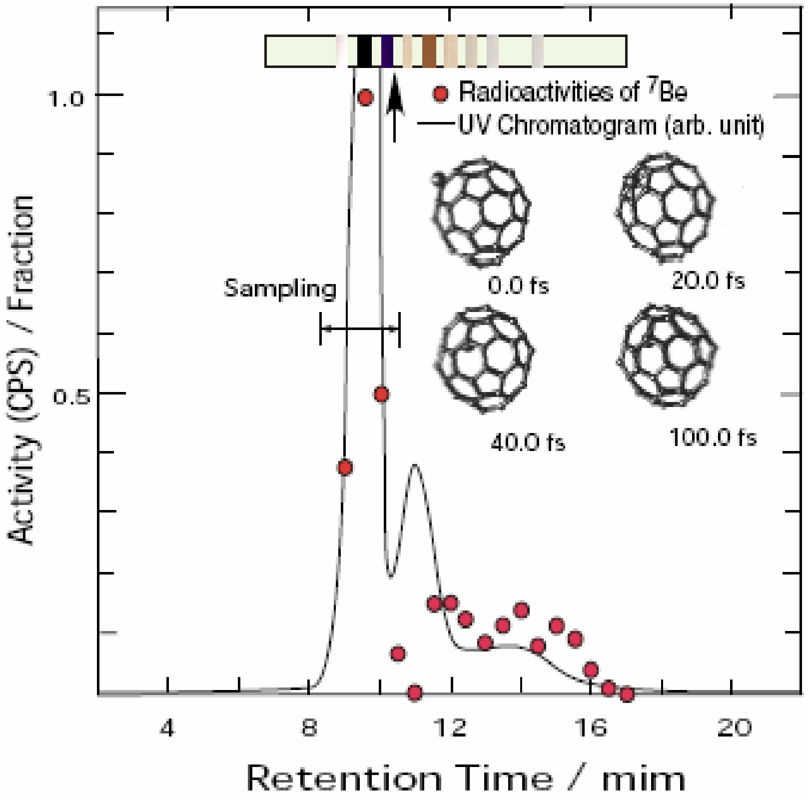
Fig. 1. Schematic view of the radiochromatograph system. To measure the 511 keV annihilation γ-rays from ^{13}N with a high statistics, a capillary loop was set between the two BGO-detectors. A geometrical efficiency for counting the γ-rays in coincidence was estimated to be about 30%.

Spectra on ^{7}Be in C_{60}

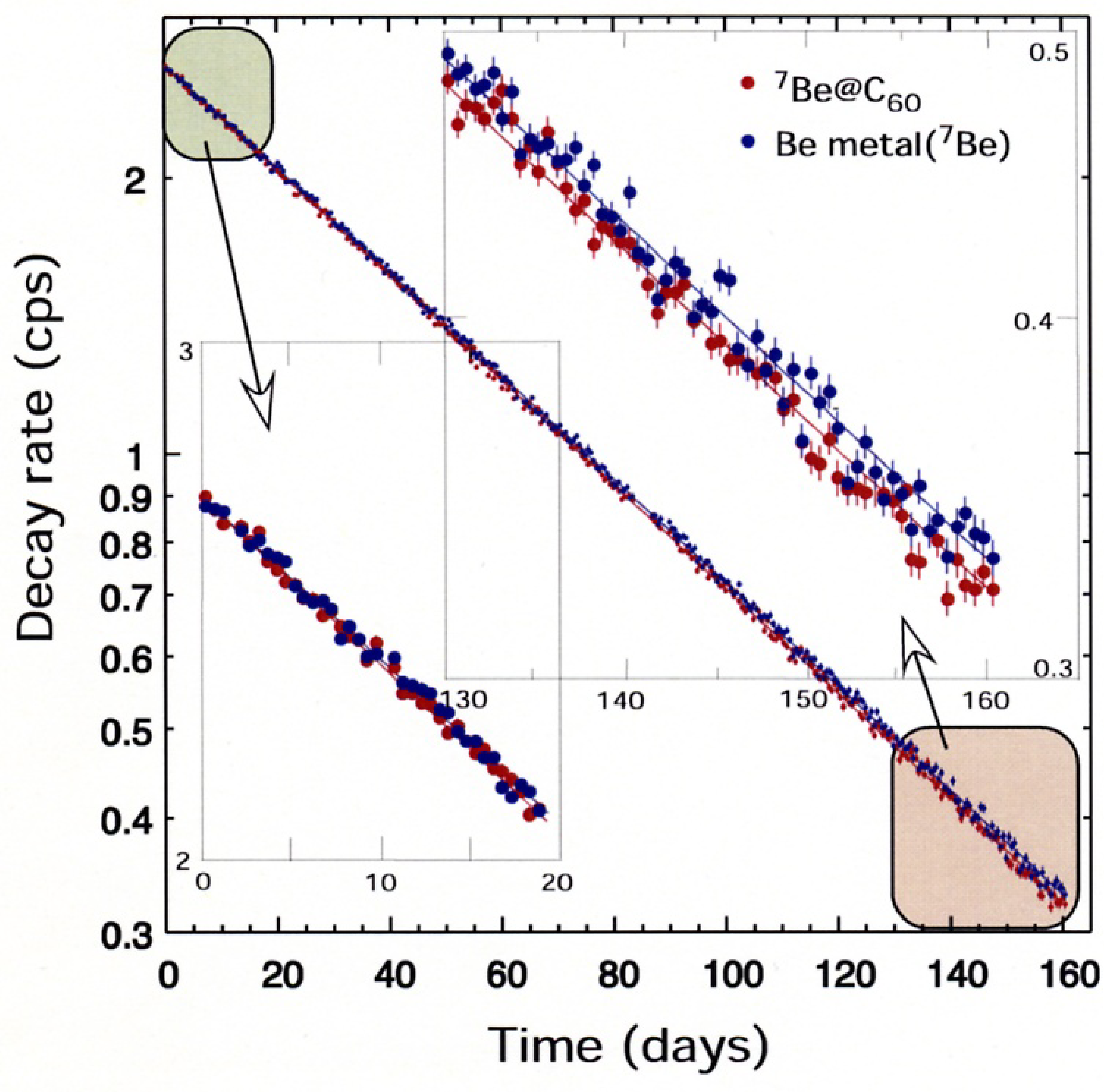
γ-ray spectrum



HPLC spectrum



Decay curve of ^{7}Be in C_{60}



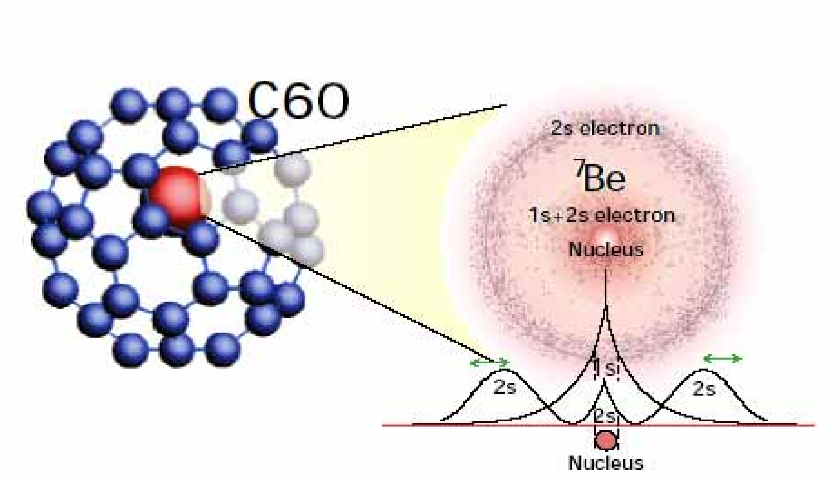
$T_{1/2}$(days) of ^{7}Be

52.68±0.05 in C_{60}
53.12±0.05 in Be metal

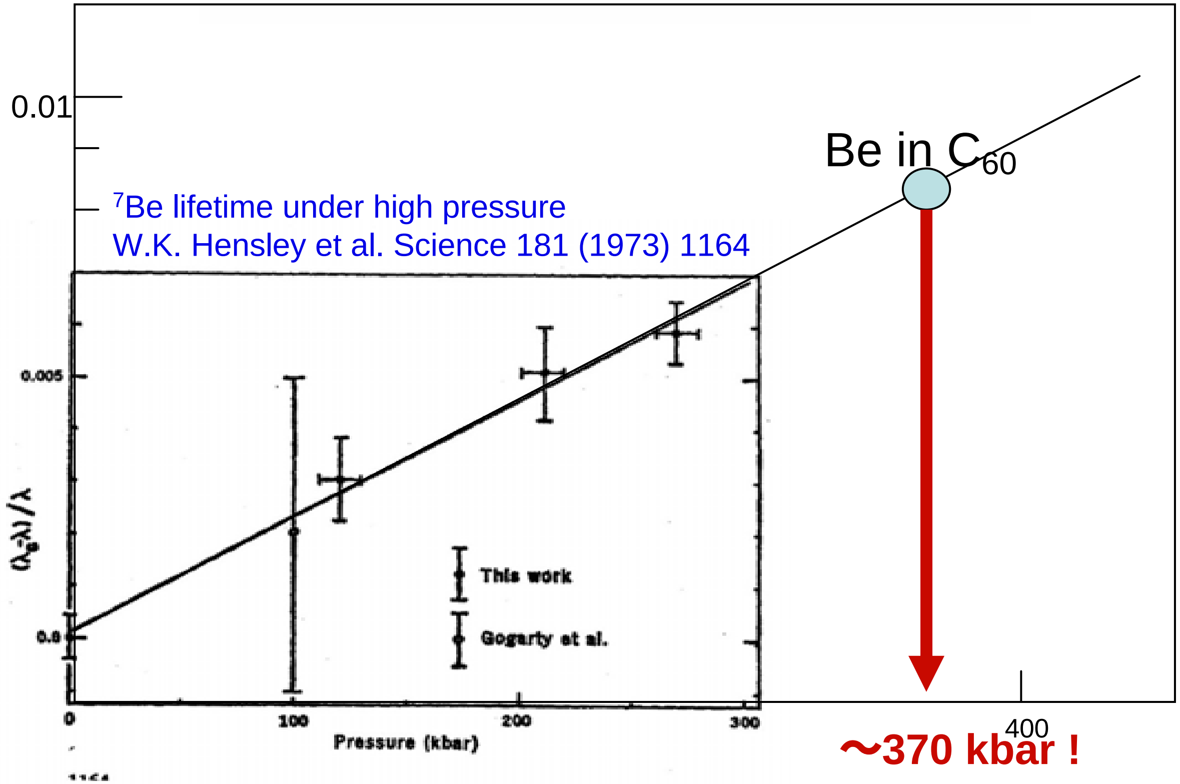
~0.8 % change!

The largest change
so far observed

Chemical or Physical effect?



Electron density at nucleus
chemical bonding
effective pressure



^{7}Be lifetime under high pressure
W.K. Hensley et al. Science 181 (1973) 1164

Be in C_{60}

∼370 kbar !

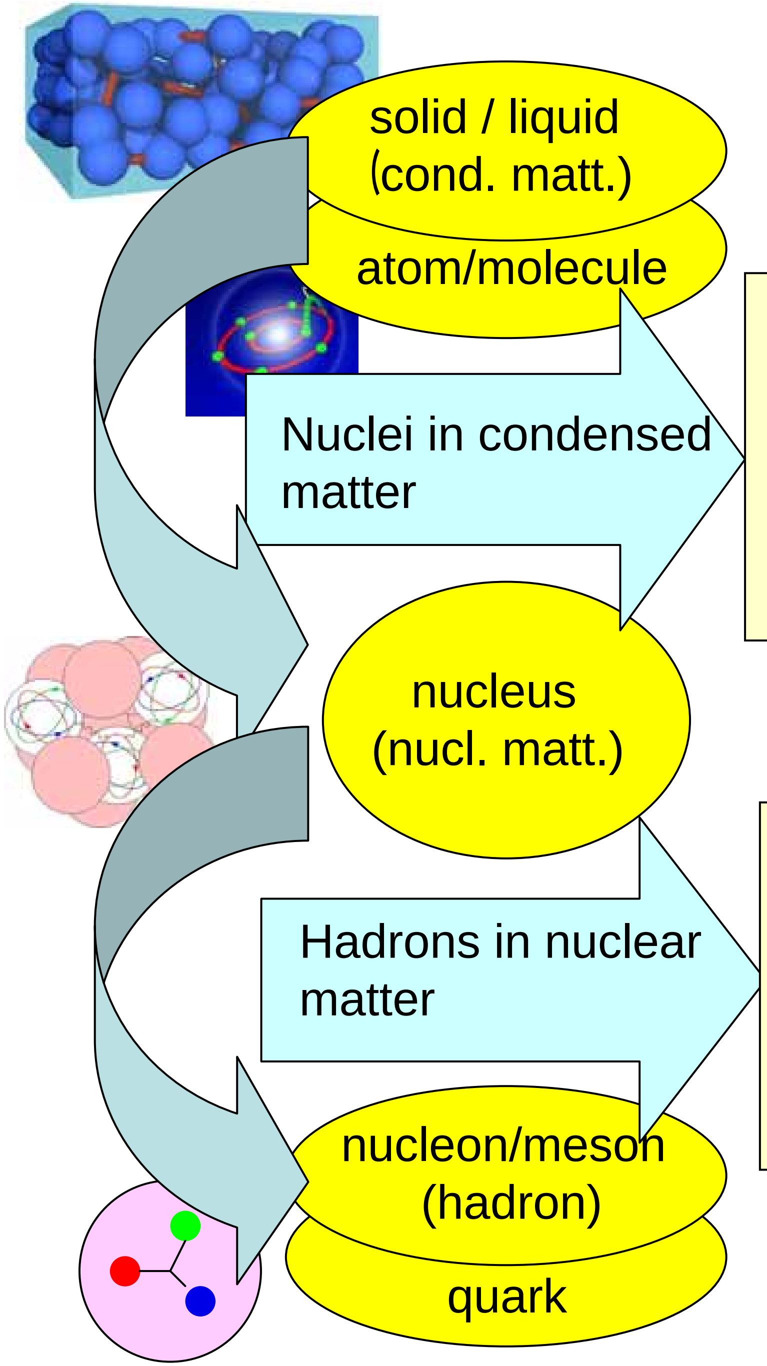
a particle in a small sphere being bounced back by the sphere wall

$P = 1/3\, m\langle v^2\rangle/V = 1/V\, kT$;
$\langle v\rangle$ average velocity, **V** volume
$r = 10^{-8}$ cm, $T = 300$ K

$P \sim 10^6$ bar = 1000 kbar
∼3 times of the deduced value

Temperature dependence

Summary



Low-energy DD, LiD reactions

strongly enhanced in metals

mechanism? reaction at eV?

Nuclear decay

$T_{1/2}(^{7}Be@C_{60})\sim 1\ \%$ shortened

chemical or physical? T dep.?

Contribute to applications

Find new concepts

Nucleon resonances in nuclei

S_{11}: large Γ_R increase

M_R shift? →$(\gamma,\eta p)$ measurement

Mesons in nuclei

$\pi^0\pi^0$ spectrum change

quantitative analysis

Answer to fundamental problems