Experimental Challenges of Fusion Reactions in Nuclear Astrophysics

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- *Stellar condition from astrophysical interests*
- *Screening potential for low energy nuclear reactions*
- *^{3}He + ^{3}He – 2p + alpha at Gamow energy (Ecm~23 keV)*
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Motivation : what has happened inside the stars ?

- ***Screening problems(cross section enhancement by electrons) in stars (super novae, neutron stars, stars like the Sun) p-p chain reactions are strongly correlated to phenomena observed in atomic physics, plasma physics and nuclear physics***
- ***Laboratory experiments to realize stellar condition <u>are incomplete</u>***

<u>To satisfy all condition is impossible</u>

- ***<u>for understanding of nature</u> ideas, data of atomic physics, nuclear physics as well as other fields are crucial.***

Physics Reports 311(1999) G.Shaviv and N.J.Shaviv

- ***The idea that nuclear reactions in stars may be affected by the surrounding plasma was first discussed by Schatzman(1948) and Salpeter(1954).The weak and the strong screening limits were treated by Salpeter.***
- ***The limit depends on the ratio of the Coulomb energy to the mean kinetic energy of the particles***
- ***Typical plasma particles with mean energy kT and ignored the kinetic energy of the interacting particles*** (by Salpeter's first approach)

After about half century

We would study

1) Surrounding effects to discover several (more) hidden phenomena,

2) Surrounding effects to study

neutrino production and its related problem,

3) Surrounding effects for fusion plasma in various stellar states.

In elementary particle physics

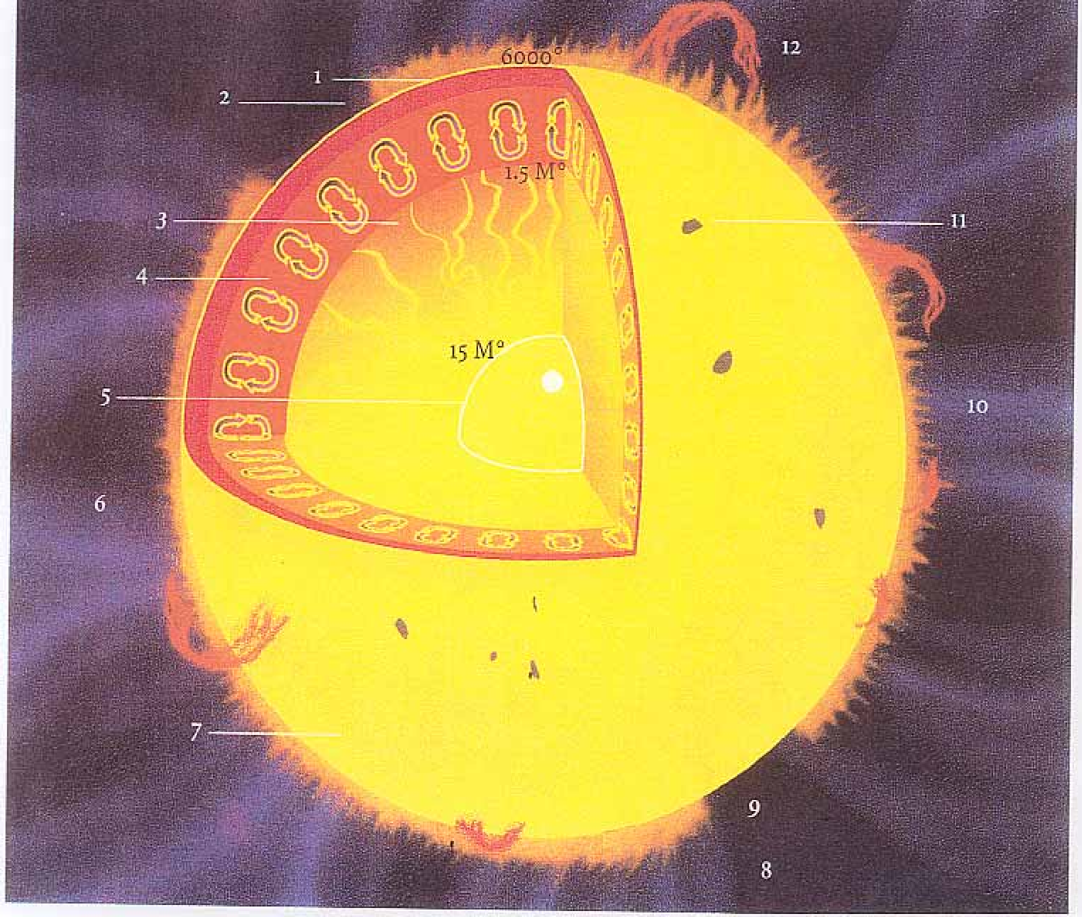
- ***Recent strong motivation to study the effect due to the surrounding of interacting particles; electron screening***

  might solve the so called neutrino deficient problem. –so many works for this issue.

however

Motivation : What has happened inside the stars or in the Sun ?

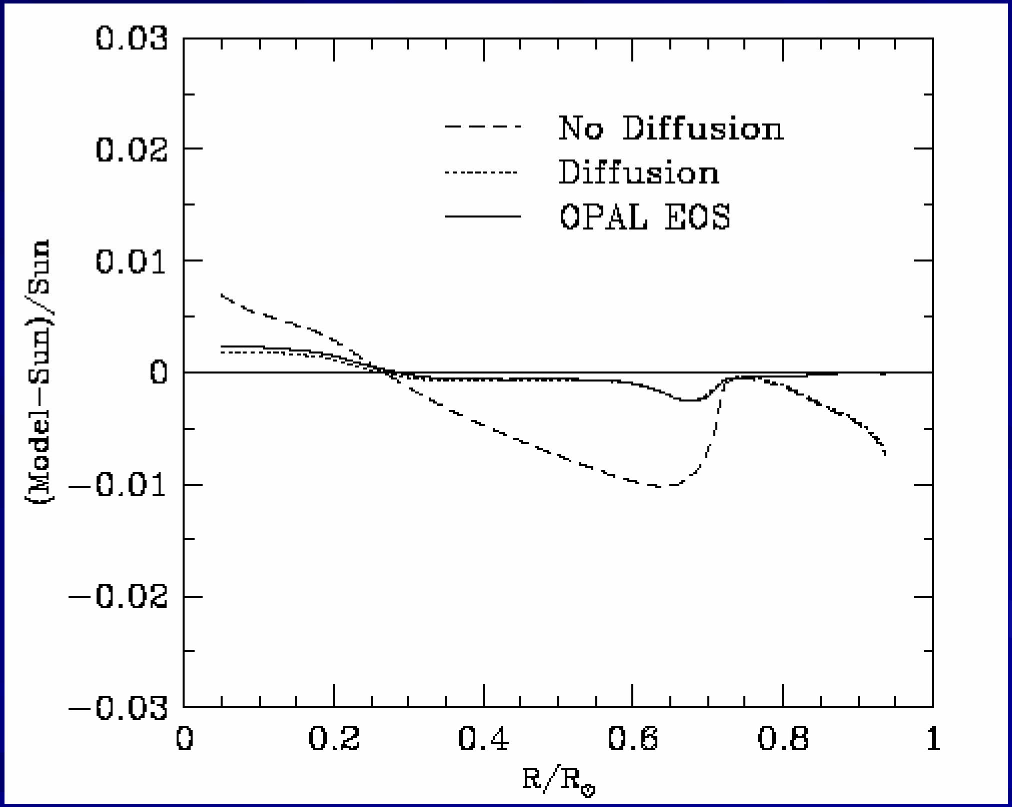
- ***Screening problems (cross section enhancement by electrons) in stars (super novae, neutron stars, stars like the Sun) p-p chain reactions are strongly correlated to atomic physics***
- ***Laboratory experiments to realize stellar condition are incomplete, that is, to satisfy all condition is impossible***
- ***for understanding of nature ideas and experimental data are crucial***



from Sun, Earth and Sky by Prof. K.R. Lang

Interior View of the Sun

Comparison of sound speeds predicted by different standard solar models with the sound speed measured by helioseismology.



Solar model and solar interior

The Sun has radius $R_s = 6.96x10^{10}$ cm and mass M_s=1.99x 10^{33} g; its mass density 1.41 g/cm^3 on average

- Interiors of main sequence stars such as the Sun are dense plasma constituted mostly of hydrogen.
- The total luminosity is Ls ~ 3.85 x 10^{26} W , Ls/Ms ~ 1.93 x 10^{-7}
- The central part of the Sun has a mass density of approximately 1.56 x 10^2 g/cm^3 a temperature of approximately 1.5 x 10 K
- A pressure of approximately 3.4 x 10^5 Mbar
- The mass fraction of hydrogen are 0.36 near the center and 0.73 near the surface.

- *Brown dwarfs*

  Central temperature and mass density of a brown dwarf may range **(2-3)x10^6(6E) K**

  And **10^2 ~ 10^3 g/cm^3**

- *Jupiter*

  The mass density, temperature, and pressure of its interior (outside the central rock) **2~5 g/cm^3, 5000~ 20000 K and 30 bar,** ***respectively.***

- *White dwarfs*

  A final stage of stellar evolution

  1 ***solar mass compressed to a characteristic radius of*** **5000 km** ***and an average density of*** **10^6 g/cm^3**

  type-I supernova, a white dwarf with an interior consisting a carbon-oxygen mixture; a kind of binary-ionic mixture with a central mass density of **10^7 ~10^{10} g/cm^3** ***and a temperature of*** **10^7~ 10^9 K**

- *Neutron star*

  radius **~10 km** ***density in the range of*** **10^4~ 10^7 g/cm**

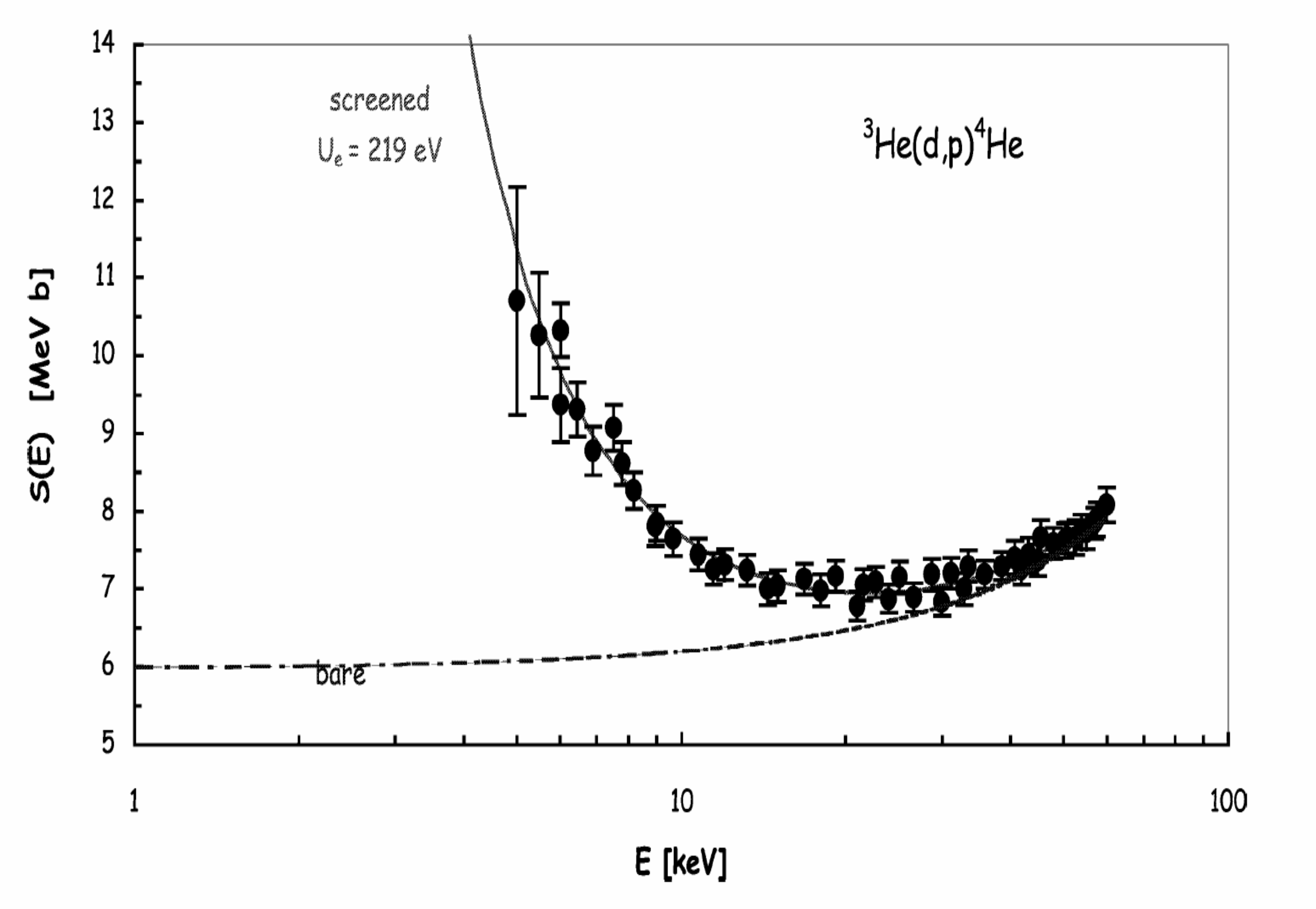
From Nuclear fusion in dense plasma, Rev. of Modern Physics (1993)

- ***Surrounding of interacting particles***

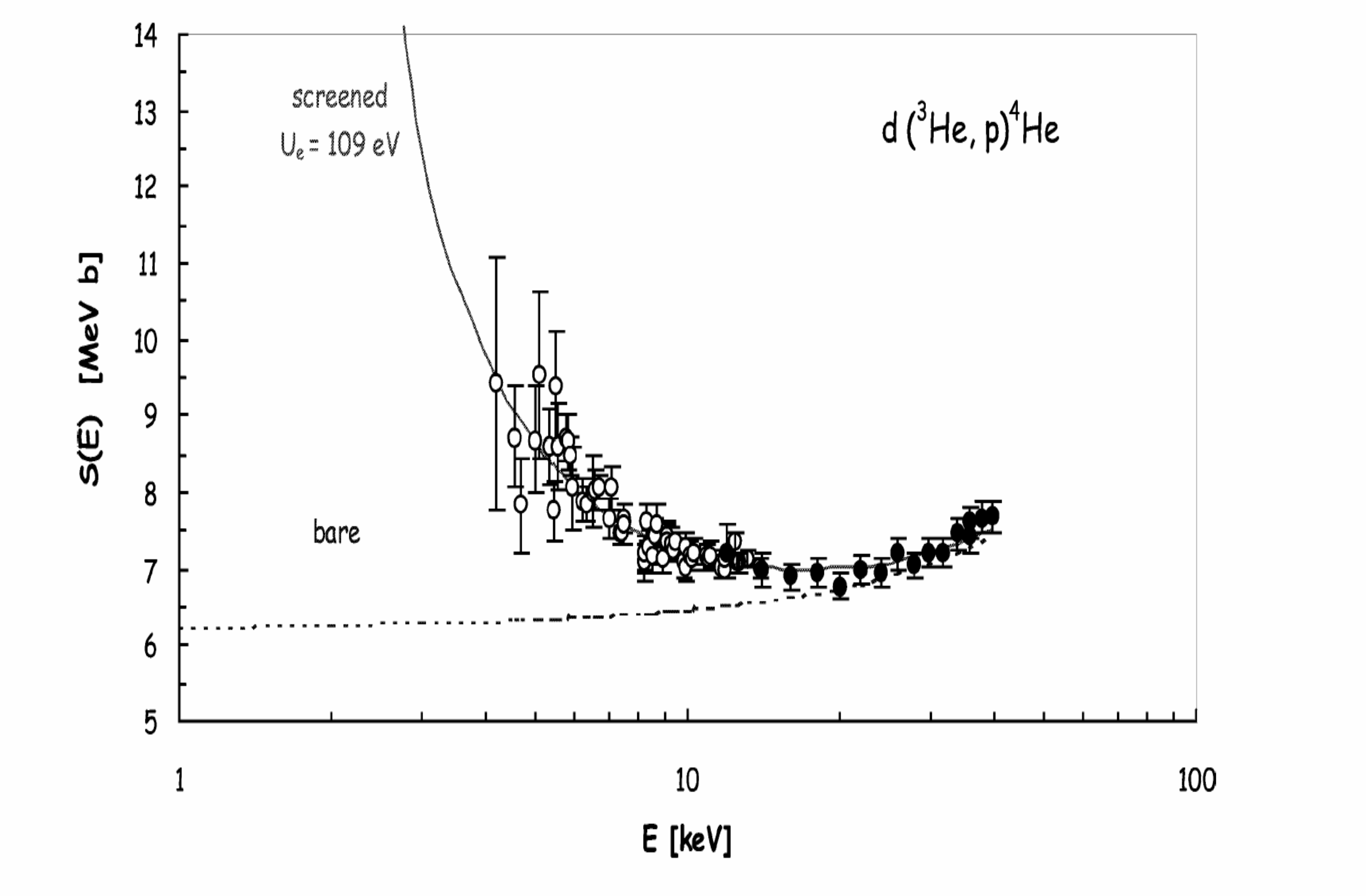
?

in stellar condition

in laboratory condition



screened
U_e = 219 eV
$^3He(d,p)^4He$
bare
S(E) [MeV b]
E [keV]
14
13
12
11
10
9
8
7
6
5
1
10
100



screened
U_e = 109 eV
d (^{3}He, p)^{4}He
bare
S(E) [MeV b]
E [keV]
14
13
12
11
10
9
8
7
6
5
1
10
100

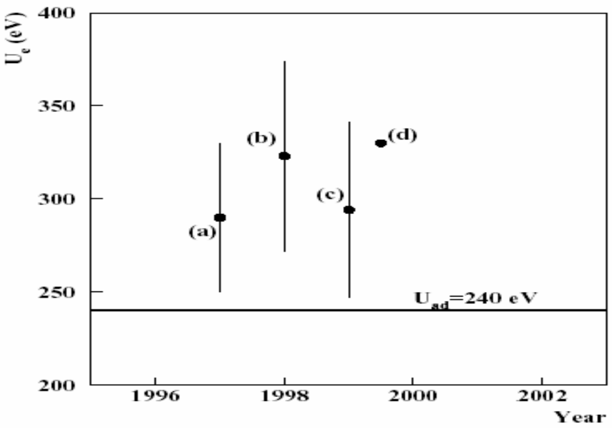


Fig. 1. Screening potential for ^{3}He(^{3}He,2p)^{4}He interation otained by (a),[36] (b),[38] (c),[37] and (d).[38]

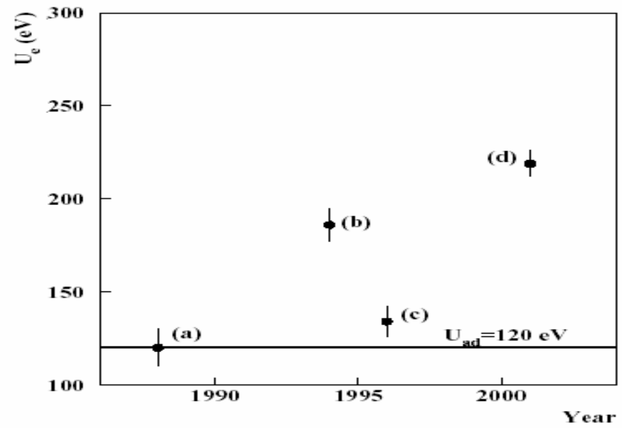


Fig. 2. Screening potential for ^{3}He(d,p)^{4}He interation otained by (a),[15] (b),[4] (c),[5] and (d).[21]

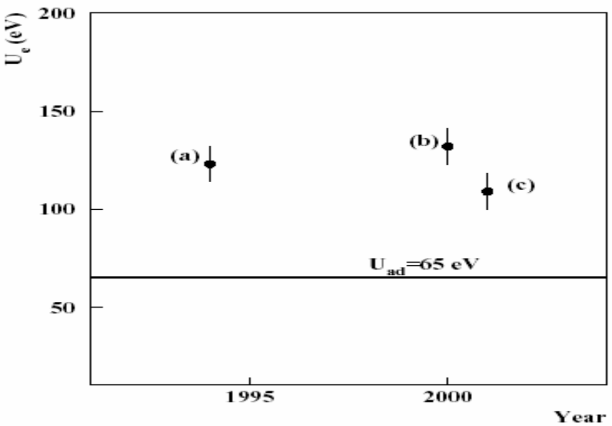


Fig. 3. Screening potential for d(^{3}He,p)^{4}He interation otained by (a),[4] (b),[7] and (c).[21]

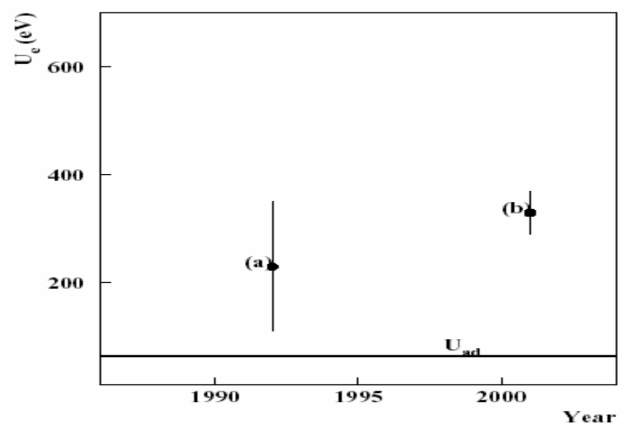


Fig. 4. Screening potential for ^{6}Li(d,d)^{4}He and ^{7}Li(p,α)^{4}He interation otained by (a) and (b).[39]

Cross section enhancement due to

Screening potential
Energy loss of charged particles in matter
Coulomb explosion
Non-linear effect
Beam-plasma interaction
Strong magnetic and electric effect
Vacuum polarization effect
Unclear experimental condition

Quests in nuclear astrophysics and experimental approaches is never-ending and intriguing subject.

Nowadays, in order to discover new and stimulating things in nuclear astrophysics precise measurements are needed.

Experimental approach, related expts.

Anomalous stopping power

recent discovery of quantum effect by which the atoms become nearly transparent for the ions at very low energy by C. Rolfs et.al.

Eur. Phys. J. A 8, 443–446 (2000)

THE EUROPEAN PHYSICAL JOURNAL A

Short note

Energy loss of deuterons in ^{3}He gas: a threshold effect

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Abstract. The energy loss of deuterons in ^{3}He gas was measured at E_d = 15 to 100 keV using the ^{3}He pressure dependence of the ^{3}He(d,p)^{4}He cross-section at a given incident energy. At the highest energies, the observed energy loss is in good agreement with a standard compilation. However, with decreasing energy the experimental values drop steadily below the theoretical values and near E_d = 18 keV they drop sharply (within 1 keV) reaching the domain of nuclear stopping power. This threshold behavior is due to the minimum 1s → 2s electron excitation of the He target atoms, *i.e.* it is a quantum effect. Some consequences are discussed.

PACS. 26.20.+f Hydrostatic stellar nucleosynthesis – 34.50.Bw Energy loss and stopping power

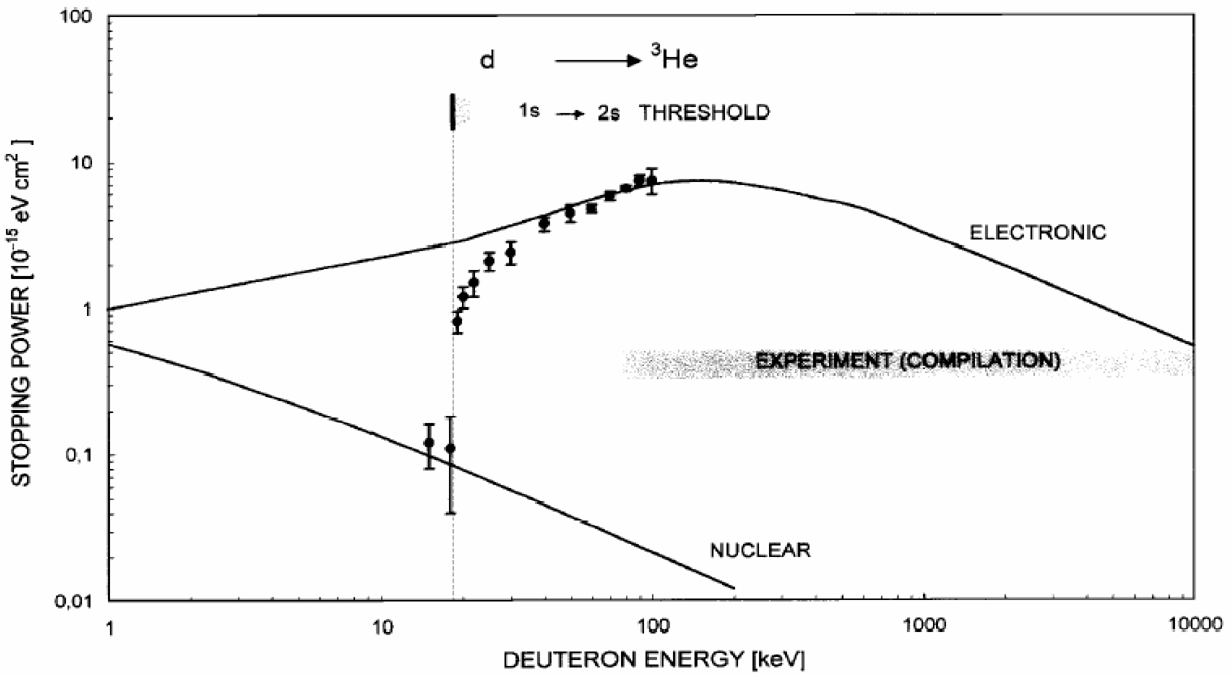

Fig. 2. Energy loss of deuterons in ^{3}He gas as function of deuteron energy. The "electronic" curve represents the electronic stopping power from the compilation [3] based on data above 80 keV (shadowed box) and the "nuclear" curve is the expected nuclear stopping power [3]. The present data show a threshold effect in the electronic stopping power at $E_d = 18$ keV.

***Theoretical approaches** (many works have been done for standard solar model to solve the so-called neutrino puzzle,other works are perspectives for nuclear fusion in dense plasma)*

*i) **electrons and ions in stellar plasma(Shaviv)***

*ii) **bound electrons(Beryaev)***

*iii) **very dense plasma (Ichimaru)***

*iv) **electrons in solid materials** (Not only for astrophysics but also for low temp. fusion study)*

Electron screening in molecular fusion reactions

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Received 9 January 1996; revised 3 May 1996

Abstract

Recent laboratory experiments have measured fusion cross sections at center-of-mass energies low enough for the effects of atomic and molecular electrons to be important. To extract the cross section for bare nuclei from these data (as required for astrophysical applications), it is necessary to understand these screening effects. We study electron screening effects in the low-energy collisions of $Z = 1$ nuclei with hydrogen molecules. Our model is based on a dynamical evolution of the electron wave functions within the TDHF scheme, while the motion of the nuclei is treated classically. We find that at the currently accessible energies the screening effects depend strongly on the molecular orientation. The screening is found to be larger for molecular targets than for atomic targets, due to the reflection symmetry in the latter. The results agree fairly well with data measured for deuteron collisions on molecular deuterium and tritium targets.

392 T.D. Shoppa et al. / Nuclear Physics A 605 (1996) 387–402

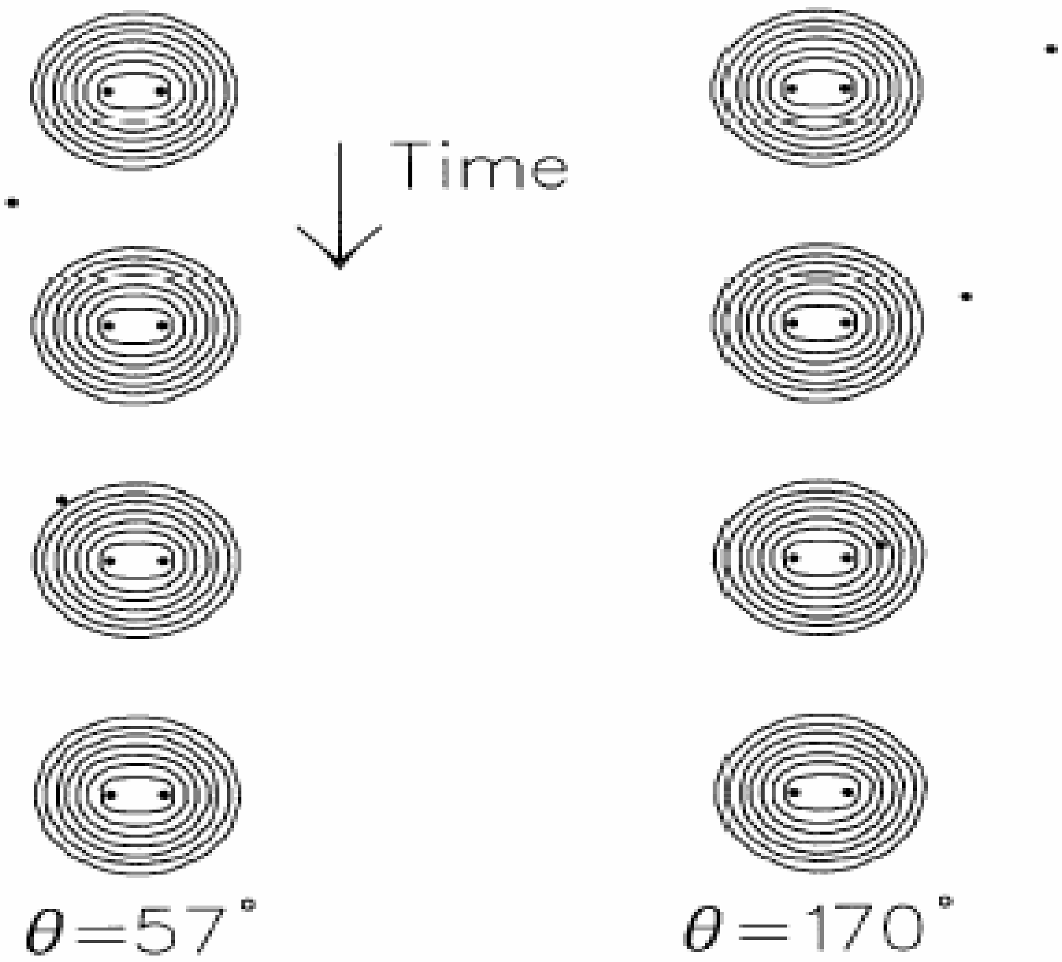
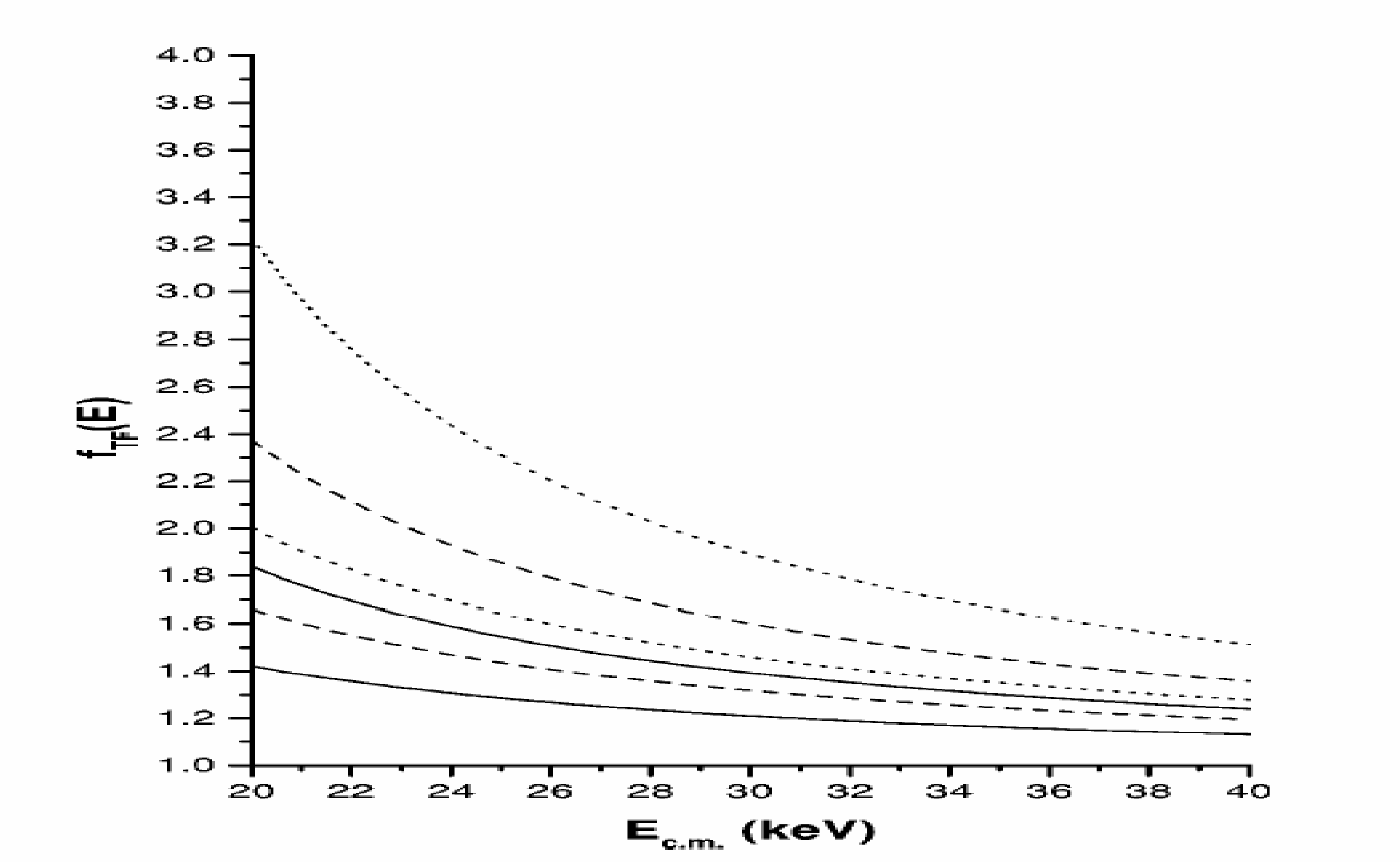


Fig. 2. Time evolution of the electron density for the collision with a hydrogen nucleus on a hydrogenic molecule at a collision energy of $E = 2.5$ MeV and at $\theta = 57°$ (left side) and $\theta = 170°$ (right side). The electron density is plotted as equally spaced contours. The positions of the nuclei are marked by dots.

The screening enhancement factor for the most important astrophysical nuclear reactions of the CNO bi-cycle, $^{13}C(p,gamma)^{14}N, E_{gp}=24.5$ keV, $^{14}N(p,gamma)^{15}O, E_{gp}=27.2$ keV $^{16}O(p,gamma)^{17}F$, Egp=29.8 keV, solid, dashed and dotted
sudden(lower) and adiabatic(upper)
Phys.Rev. C 63 (2001) T.E.Liolios



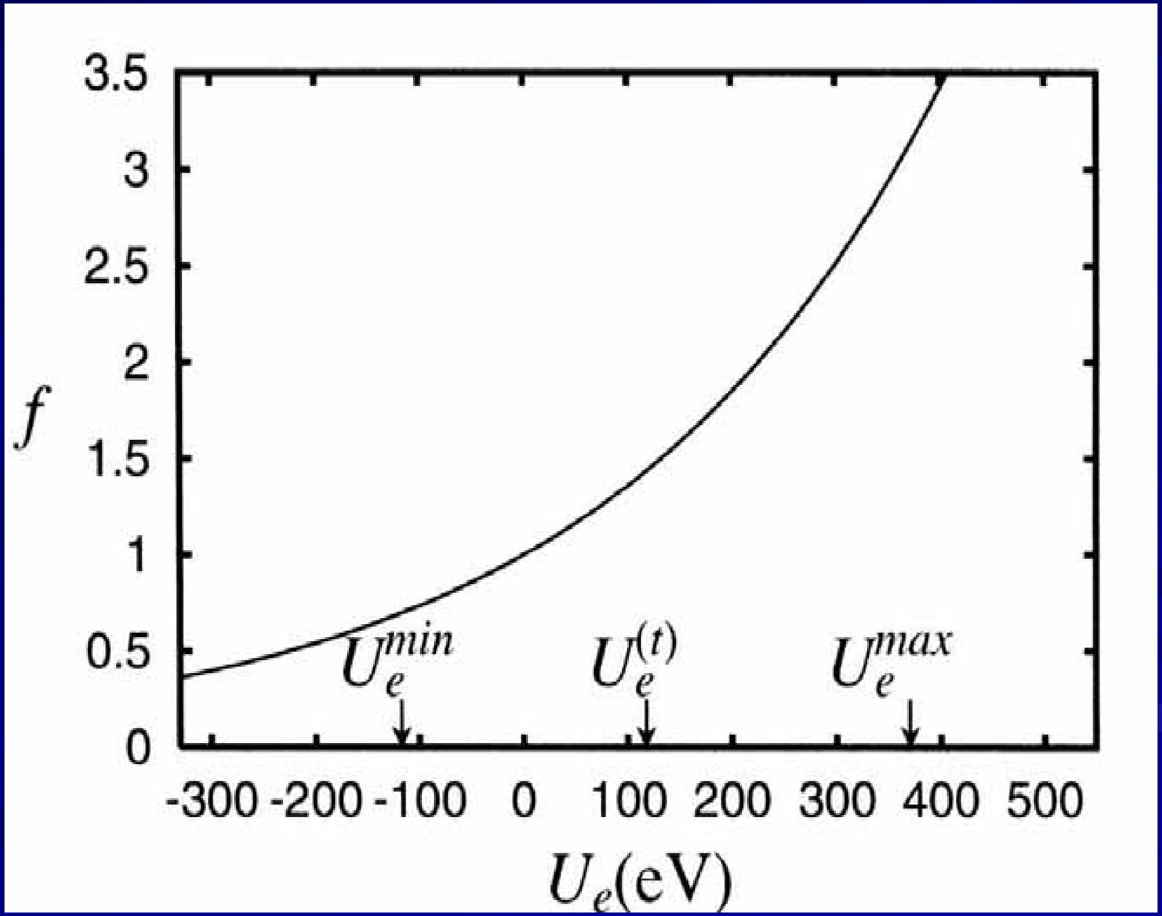
Influence of electron capture and Coulomb explosion on electron screening in low nuclear reactions in laboratories[*recent theoretical studies by N, Takigawa and Y. Kato*]

TABLE II: The apparent screening energy caused by the Coulomb explosion $U_e^{(a)}$ at each molecular beam energy.

D_2^+		D_3^+	
E(keV)	$U_e^{(a)}$(eV)	E(keV)	$U_e^{(a)}$(eV)
6.02	155.2	5.01	213.0
6.45	154.1	5.50	209.8
6.90	153.0	6.01	206.7
7.51	151.8		
8.18	150.5		
9.02	149.2		

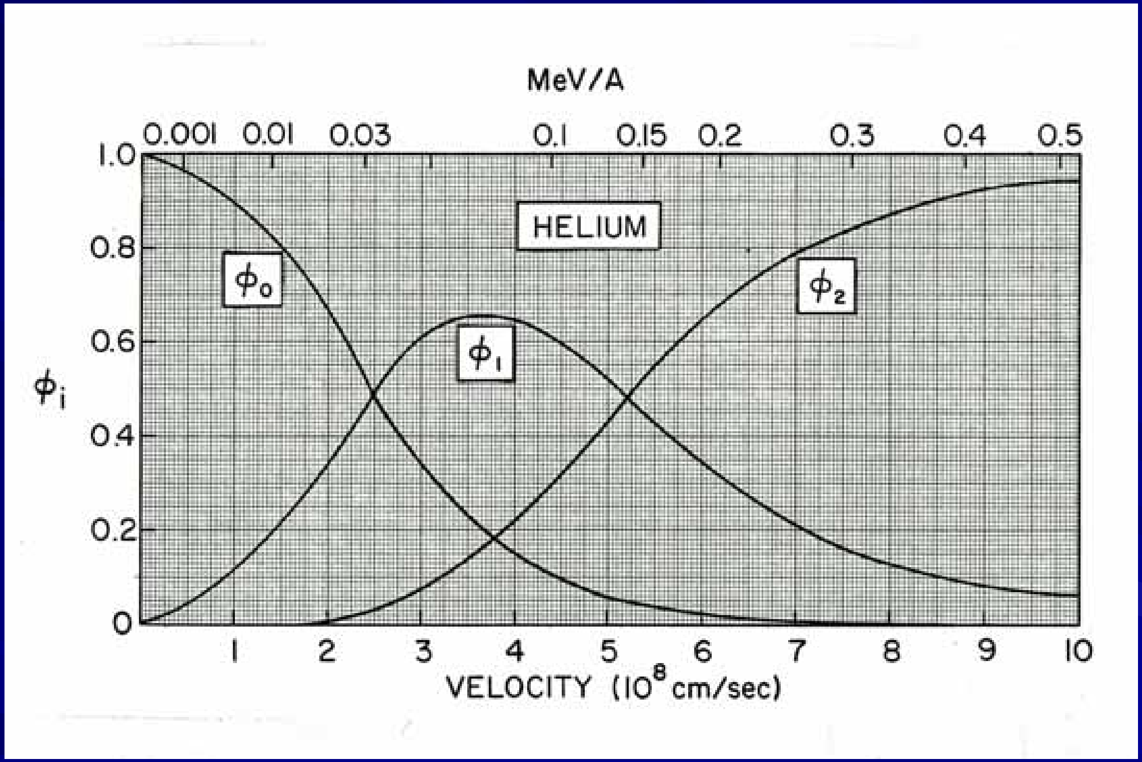
TABLE I: Comparison of the screening energy estimated by taking electron capture by the projectile into account $U_e^{(c)}$, that estimated by ignoring it U_e and the experimental value U_e^{exp}.

Reaction	E_{min} (keV)	U_e (eV)	$U_e^{(c)}$ (eV)	U_e^{exp} (eV)
D(d,p)T	1.62	22.0	35.7	25 ± 5 [17]
^{3}He(d,p)^{4}He	5.01	119.1	117.5	219 ± 7 [18]
D(^{3}He,p)^{4}He	4.22	70.6	105.3	109 ± 9 [18]



3.5
3
2.5
2
1.5
1
0.5
0
f
U_e^{min}
$U_e^{(t)}$
U_e^{max}
-300 -200 -100 0 100 200 300 400 500
U_e(eV)

The fraction of the total beam of ions with charge i plotted as functions of the ion velocities from Nuclear Reaction Analysis by Marion/Young



$^{3}He^{++}$ ion beam

Precise measurement of cross section of $^{3}He(^{3}He,2p)^{4}He$ by using He-3 doubly charged beam

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Abstract

The fusion cross section of $^{3}He(^{3}He,2p)^{4}He$ at a center of mass energy of 30 to 50 keV has been measured by using a helium-3 doubly ionized beam at a low-energy high current accelerator facility, OCEAN. Free from molecular interference in the beam, the measurement determines the astrophysical S-factor with better statistical and systematic errors than previous data. By using singly and doubly charged helium-3 ions, the facility envisages to provide the data from high energy to Gamow energy regions.

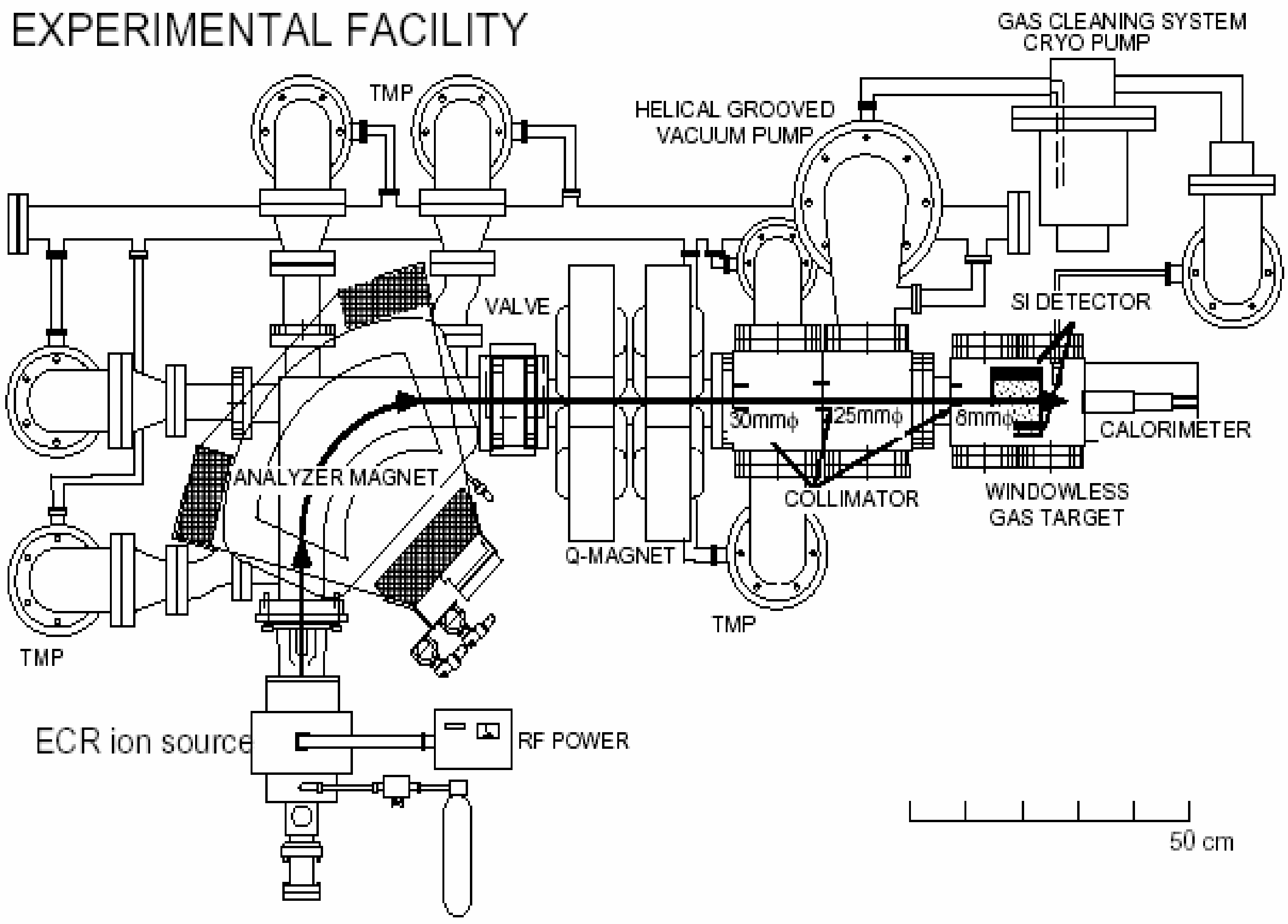
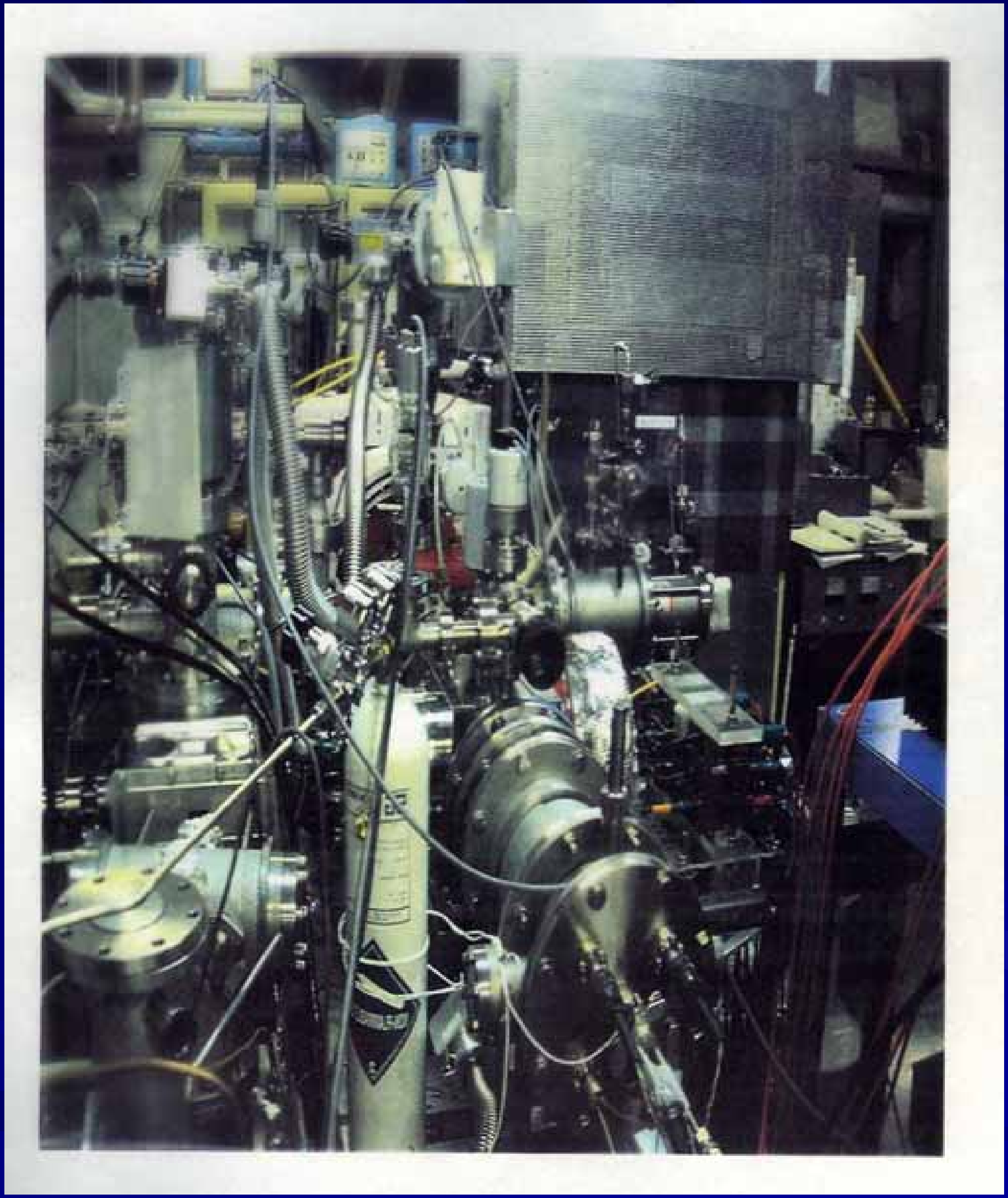
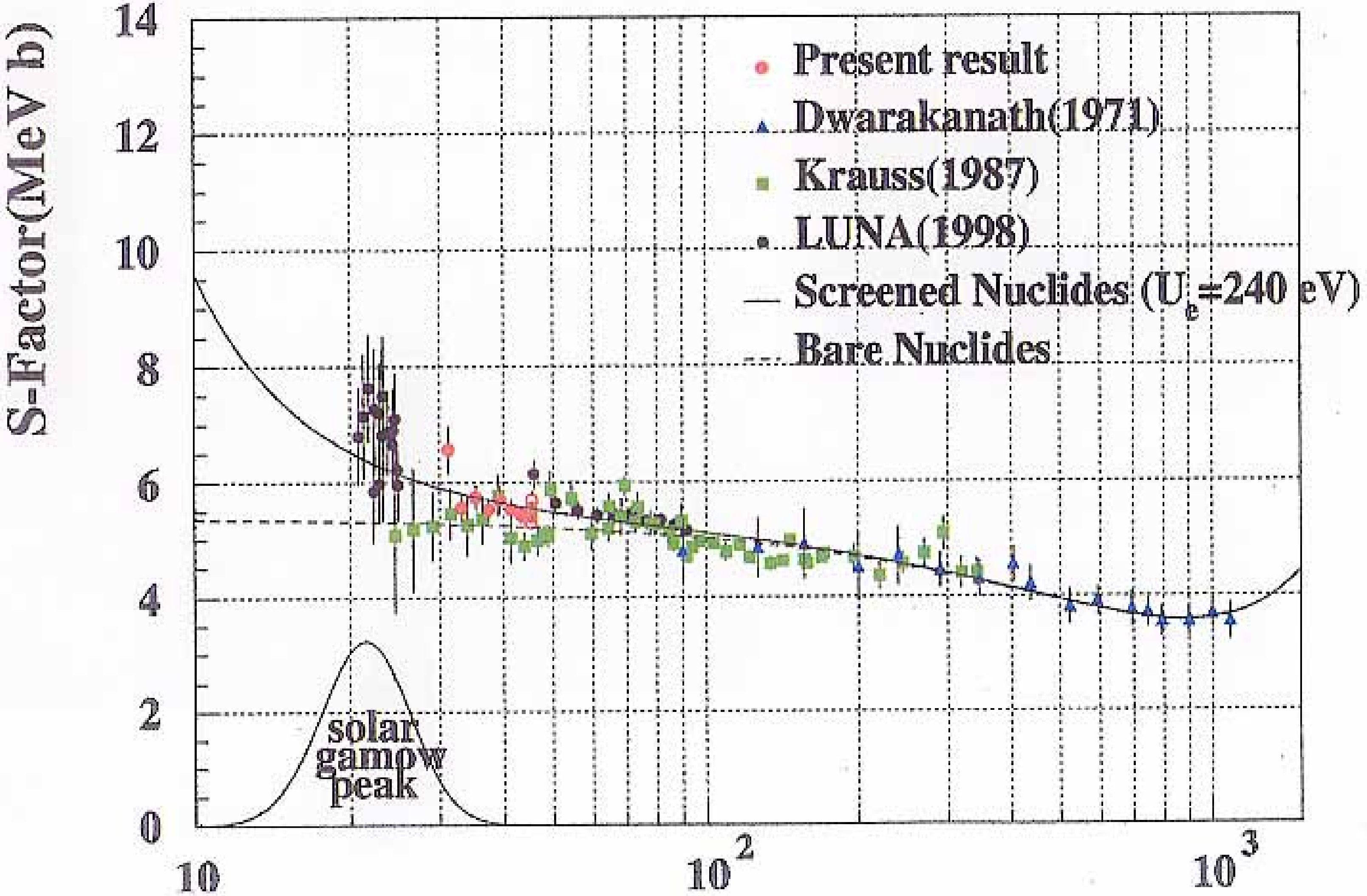


FIG. 1: Complete layout of Osaka University Cosmological Experimental Apparatus for Nuclear Physics, OCEAN .





S-Factor(MeV b)
14
12
10
8
6
4
2
0
10
10^2
10^3
Present result
Dwarakanath(1971)
Krauss(1987)
LUNA(1998)
Screened Nuclides (U_e=240 eV)
Bare Nuclides
solar
gamow
peak

New experimental approach to determine the electron screening potential of various atomic configurations for fusion reaction

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Our claim(2)

- Theoretical estimate for screening potential (Ue)

  should be usually considered as a constant.

But it should be as a energy dependent term

Charge state during transmitting the gas target would affect the screening potential Takigawa and Kato, to be published

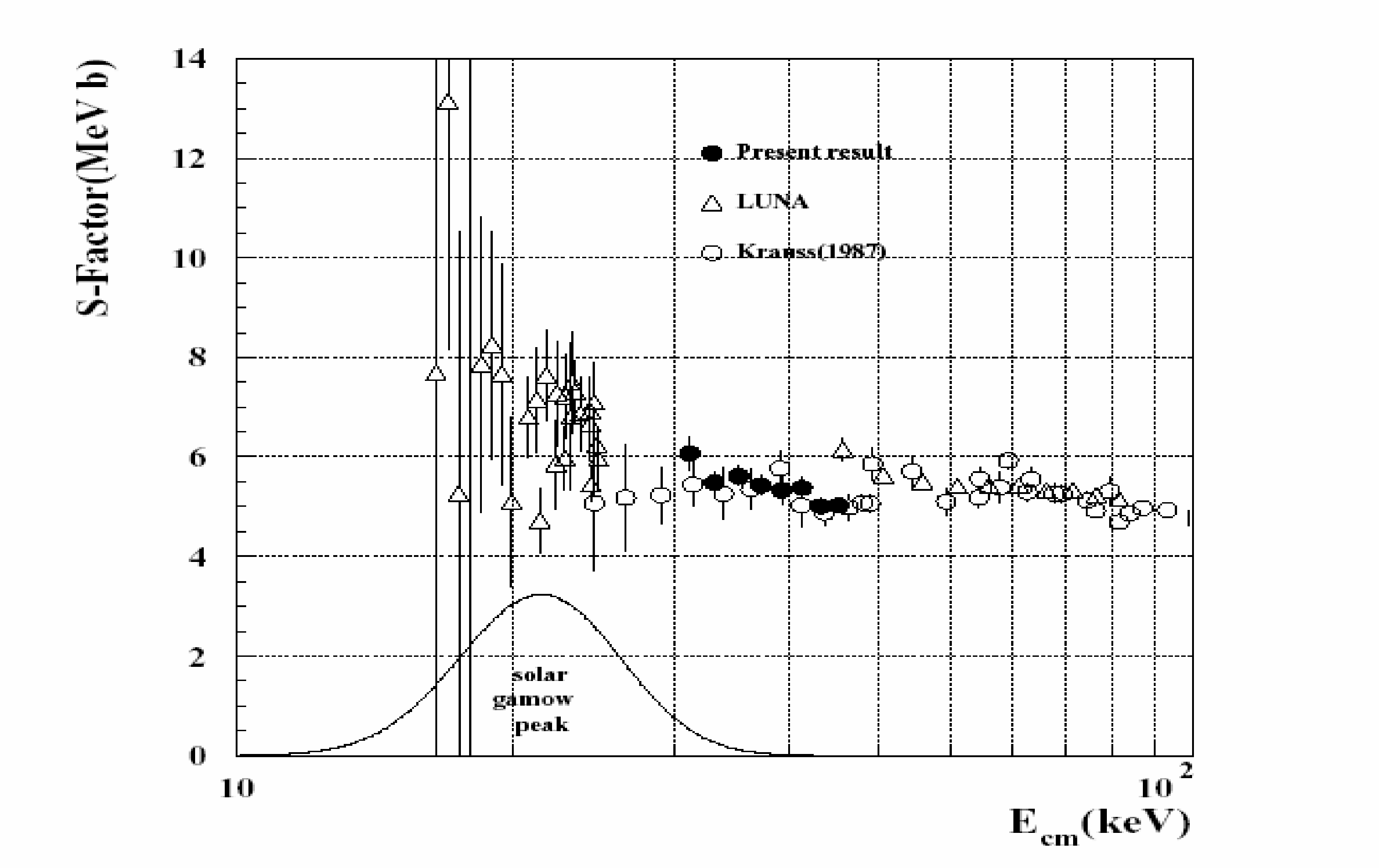
- $^3He + ^3He – 2p + a$ reaction
-
- charge state of incident beam
- screening potential for each beam
- $^3He(2+)$ + 3He gas target adiabatic limit 171 eV
- $^3He(1+)$ + 3He gas target 254 eV
- $^3He(0+)$ + 3He gas target 241 eV
- exp 432 +/-29 eV

Claim(3)

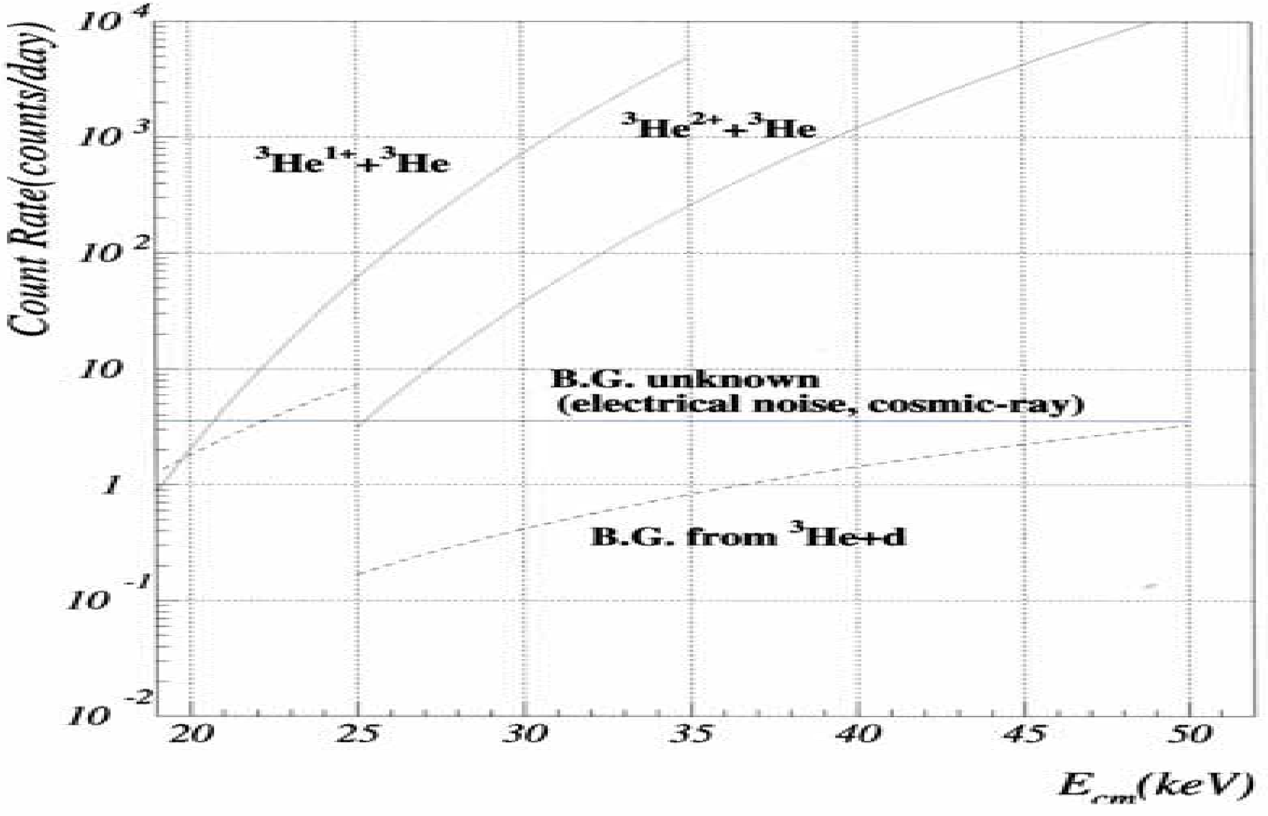
- Maximum enhancement or medium or incomplete enhancement has happened or not (this is not clear so far)
- After effects from time dependent collision phenomena with appropriate electronic states of ions and atoms would be measured

we could extrapolate S(E) factor to the value at required energy(Gamow energy)

Osaka Univ. Cosmological Experimental Apparatus for Nuclear Physics



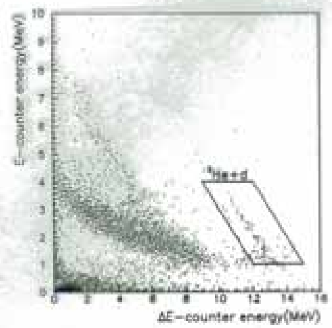
Counting rates



Background

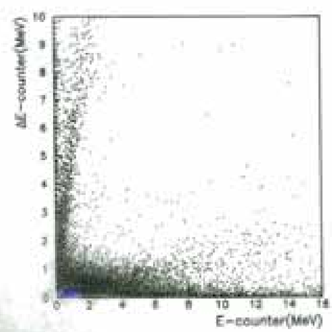
deuteron contamination in the target

^{3}He + d in ^{3}He + ^{3}He experiment ⇒ 0.2 ppm



no gas target
gas circulation
⇓
~10^{-4} Torr at target
~~assume~~ measured water component
⇓
0.1 ppm

other B.G. (electronic noise, cosmic-ray)

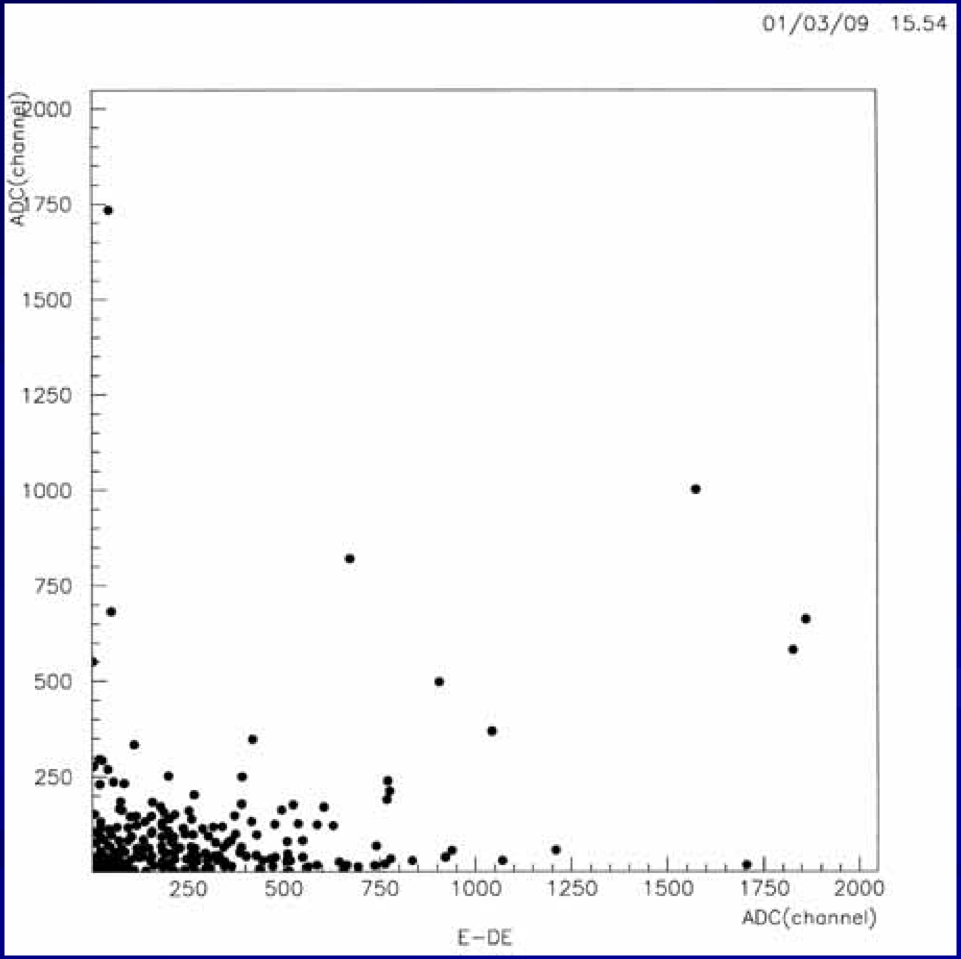


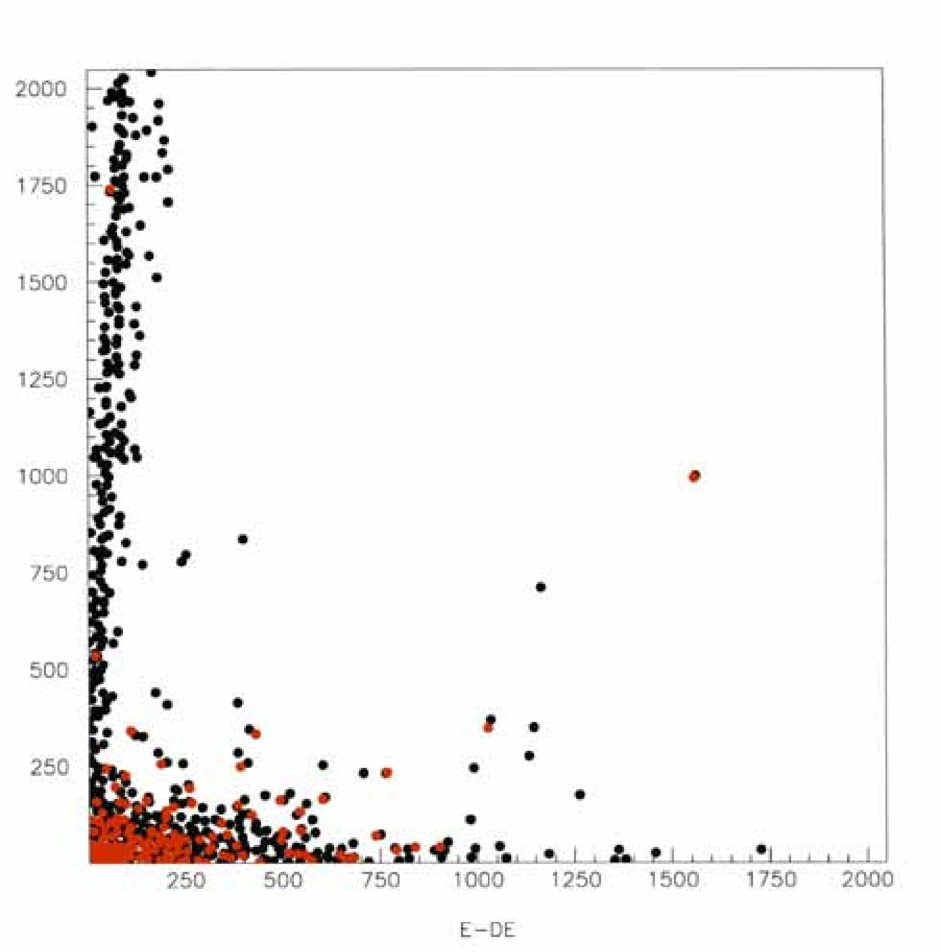
live time ~ 38 days

μ-on 2 MeV cm^2 /g

ΔE 70 keV

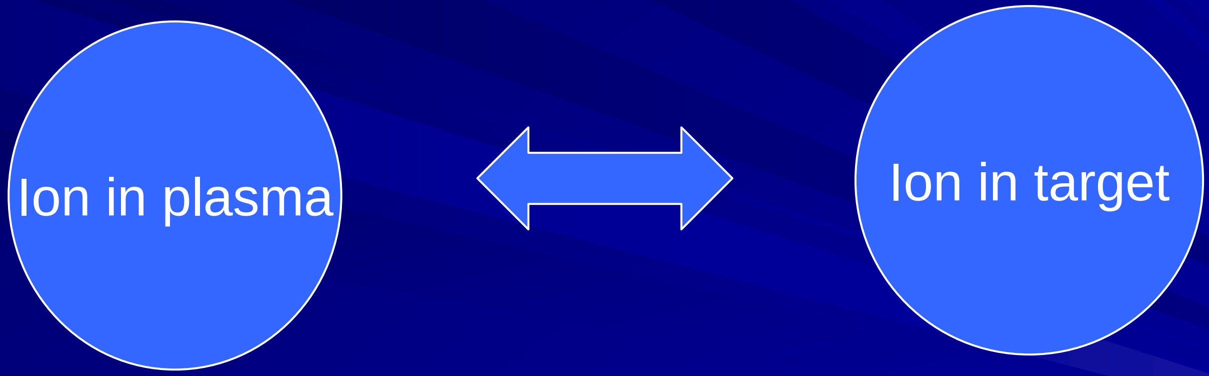
E 450 keV


01/03/09 15.54
ADC(channel)
2000
1750
1500
1250
1000
750
500
250
250
500
750
1000
1250
1500
1750
2000
ADC(channel)
E-DE


2000
1750
1500
1250
1000
750
500
250
250
500
750
1000
1250
1500
1750
2000
E-DE

Plasma (ion production) ---- beam----- gas (neutral)
ECR Ion Source   Target

- ***Plasma diagnositics***
- ***Photon observation***



Visible light(1s4s-1s2p) observation

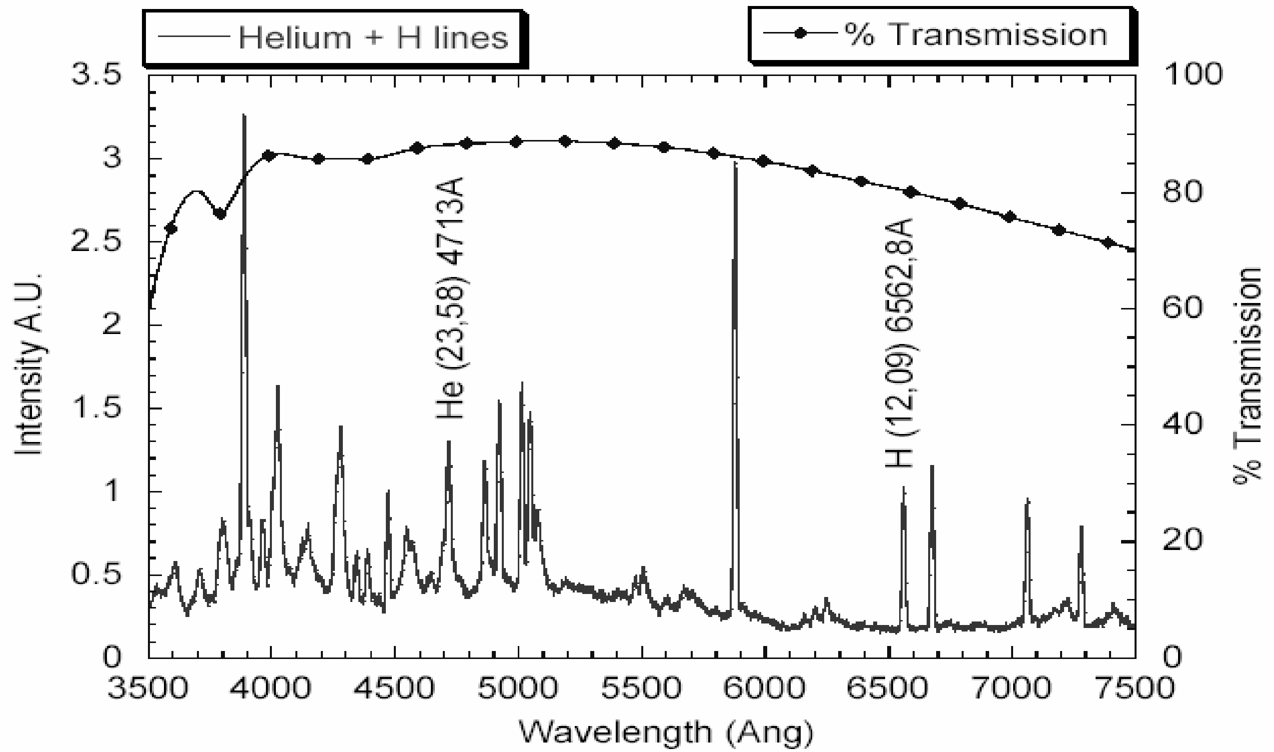


Fig. 1 First order of diffraction of the atomic lines produced inside the ECRIS. One can see the name of the element, the energy needed to reach the initial state and the wavelength of the radiative de-excitation in angström. The dot line shows the transmission of the glass windows.

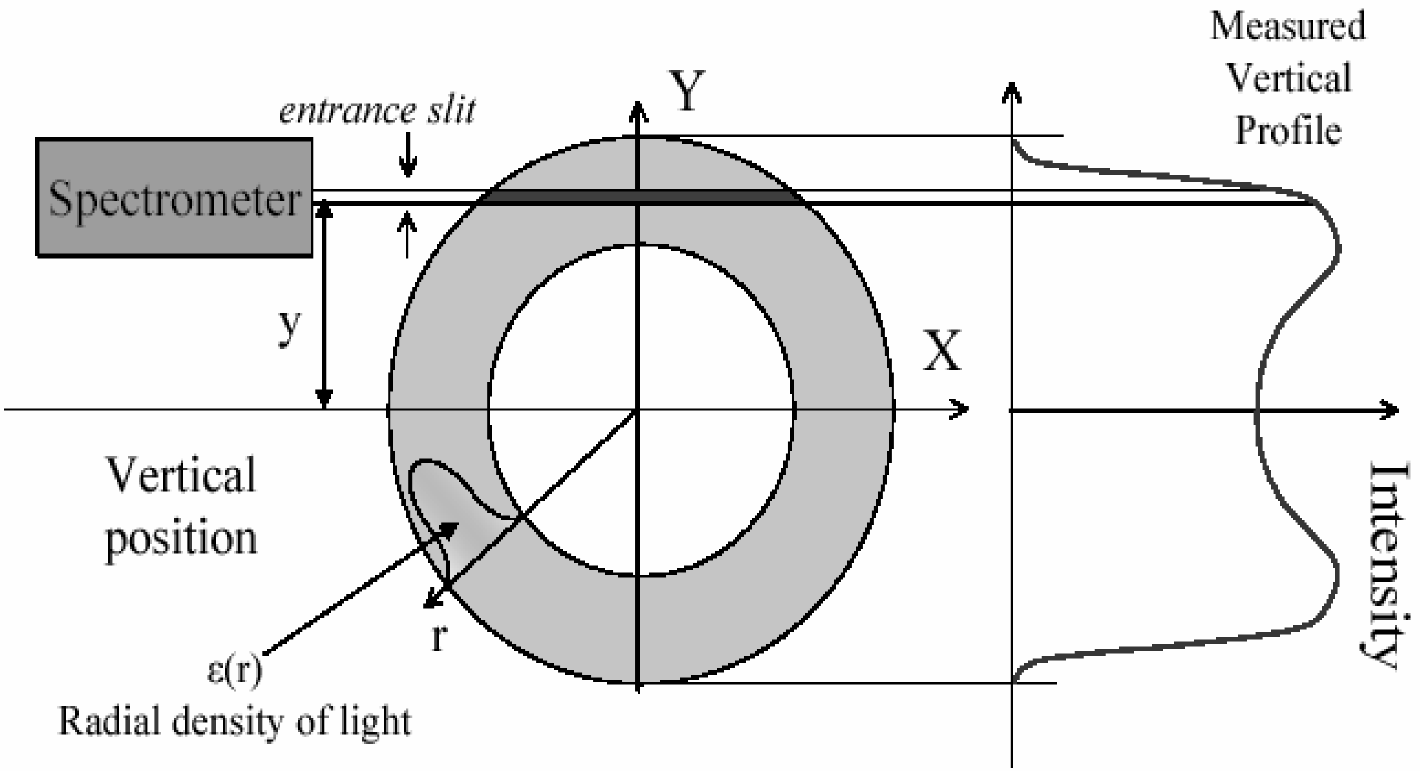
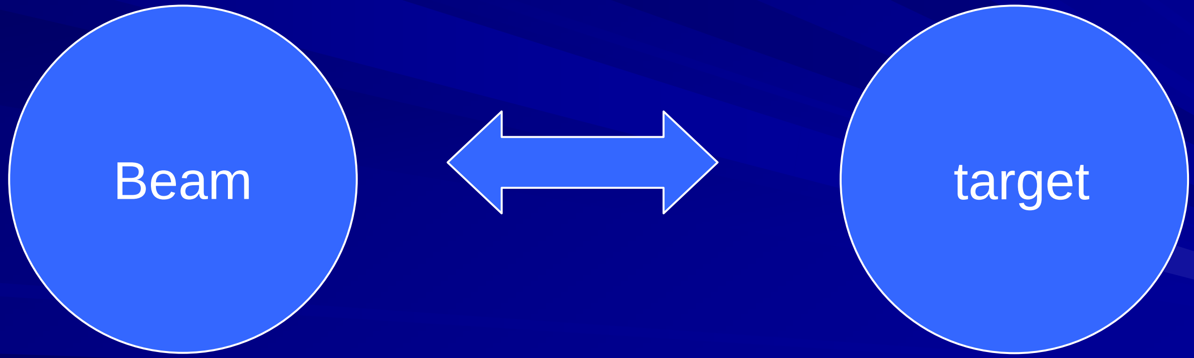
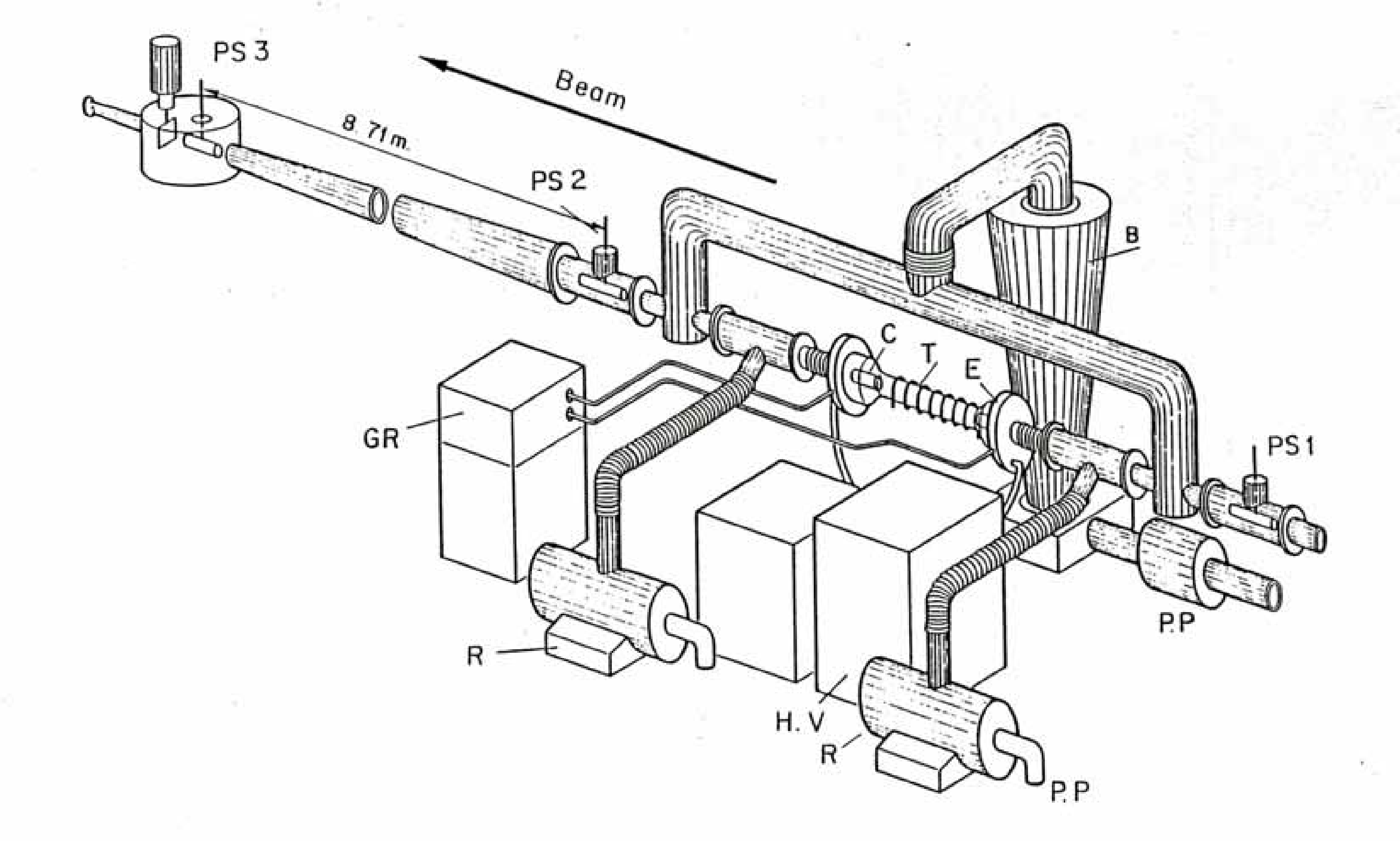


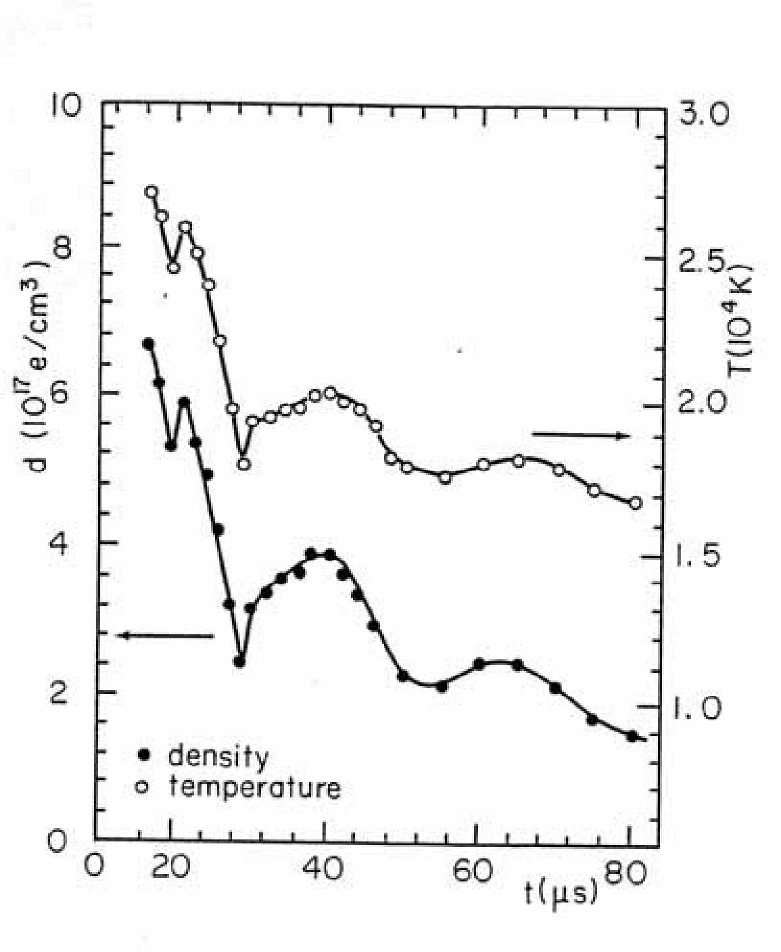
Fig. 4 Vertical cut of the "hollow" heating zone. The spectrometer at the y vertical position measured the intensity of the atomic lines emitted from a thin slice of plasma.

Nuclear Reaction at very low energy ~ At stellar condition

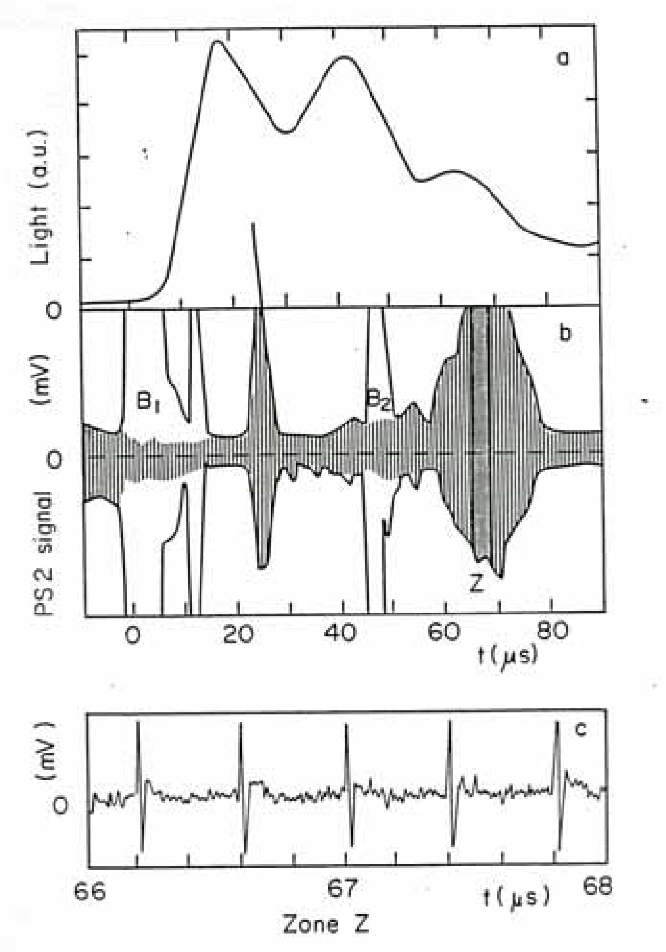
With Z_{1e} + Z_{2e}



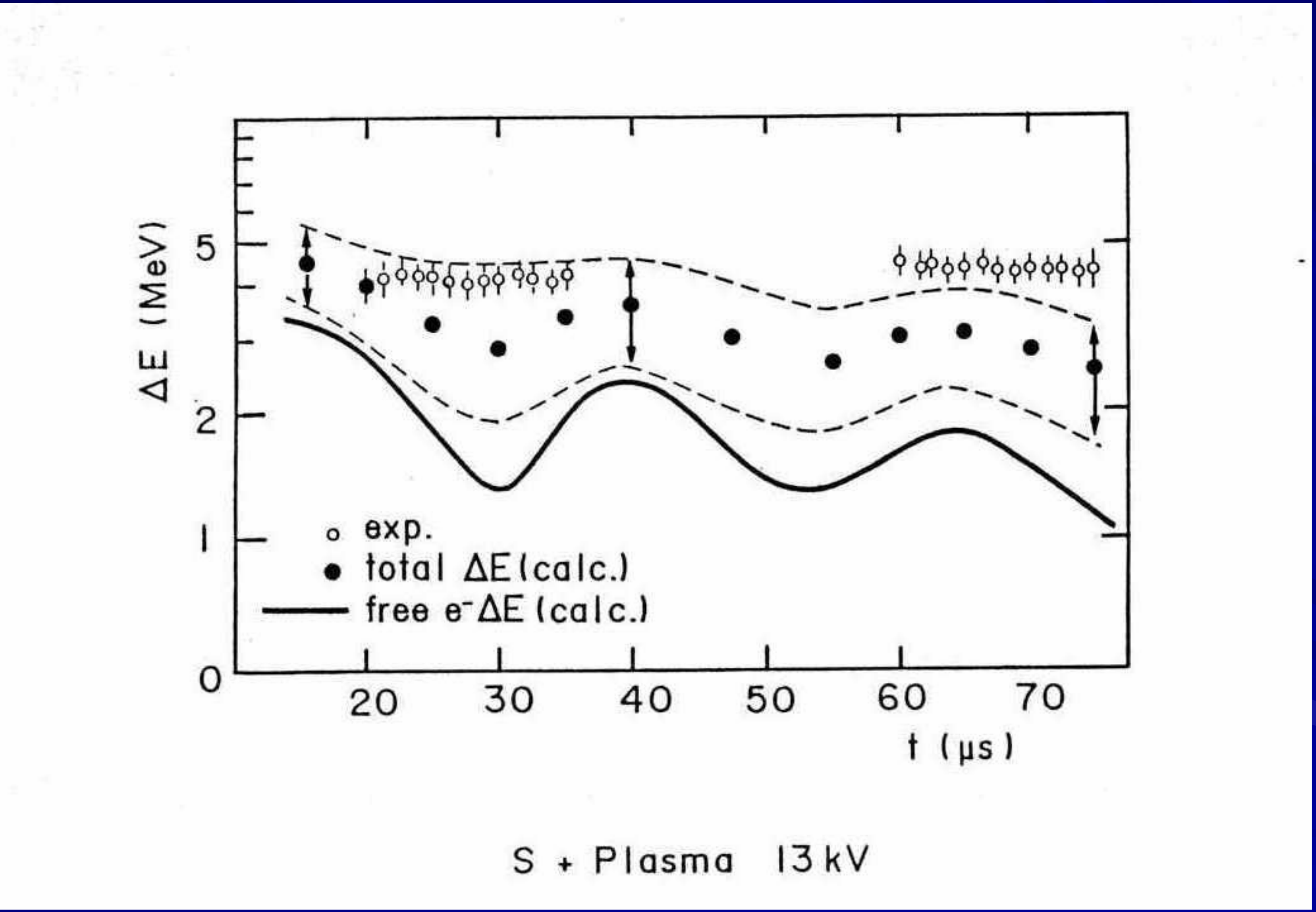

PS 3
Beam
8.71m.
PS 2
B
C
T
E
GR
PS 1
P.P
R
H.V
R
P.P



10
8
6
4
2
0
d (10^17 e/cm^3)
3.0
2.5
2.0
1.5
1.0
T(10^4 K)
0
20
40
60
80
t(μs)
density
temperature



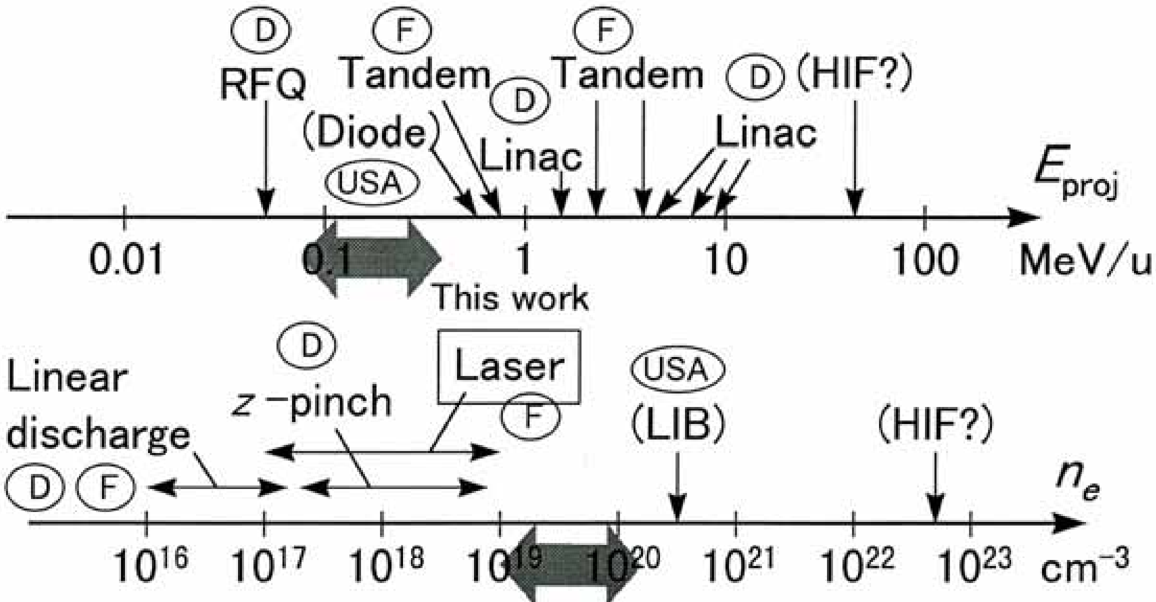
a
b
c
Light (a.u.)
PS2 signal (mV)
(mV)
O
O
O
B_1
B_2
Z
0
20
40
60
80
t (μs)
66
67
68
t (μs)
Zone Z



ΔE (MeV)
5
2
1
0
20
30
40
50
60
70
t (μs)
o exp.
● total ΔE (calc.)
free e⁻ ΔE (calc.)
S + Plasma 13 kV

Beam–plasma interaction research (1982–) :
No data exist at ~100 keV/u, $n_e > 10^{19}$ cm^{-3}.

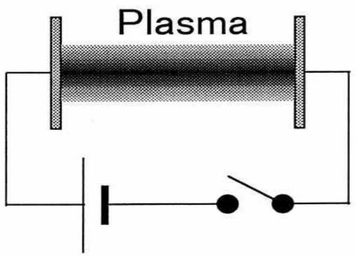
- Scope of projectile energy E_{proj} / electron density n_e

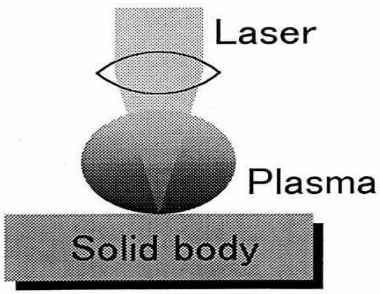


Application of a laser plasma is suitable to obtain higher electron densities.

- **Discharge plasma:**
  - Long lifetime
  - Large size
  - Complicated vacuum pumping system
  - Large discharge current

- **Laser plasma:**
  - High density
  - Short lifetime
  - Small size
  - Large density gradient
  - No discharge current





98/03/23

Stopping power for projectile ions in a cold/plasma target

- Modified Bethe formula ;

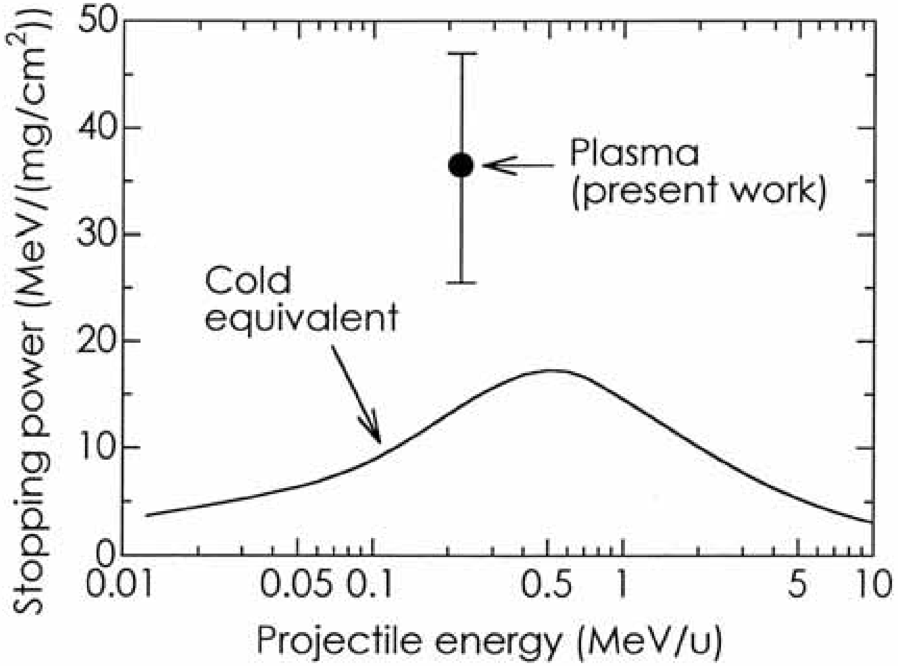
$$-\frac{dE}{dx} \propto {Z_{\text{eff}}}^2 \cdot \ln\left(\frac{b_{\max}}{b_{\min}}\right)$$

(Z_{eff} = effective charge = averaged charge state n)

- Expectation :

$$-\frac{dE}{dx}(\text{cold}) < -\frac{dE}{dx}(\text{Plasma})$$

Preliminary result : Stopping power of a LiH plasma ($n_e \sim 10^{18}$ cm^{-3}) for 225 keV/u ^{16}O ions.



Clear and definite answer for this entangled problem

- *Ion trap apparatus for nuclear astrophysics*
- *Larger capacity than existing installation*
- *Bare beam and bare target*
- *Higher luminosity than storage ring*
- *Stable operation in a few months*

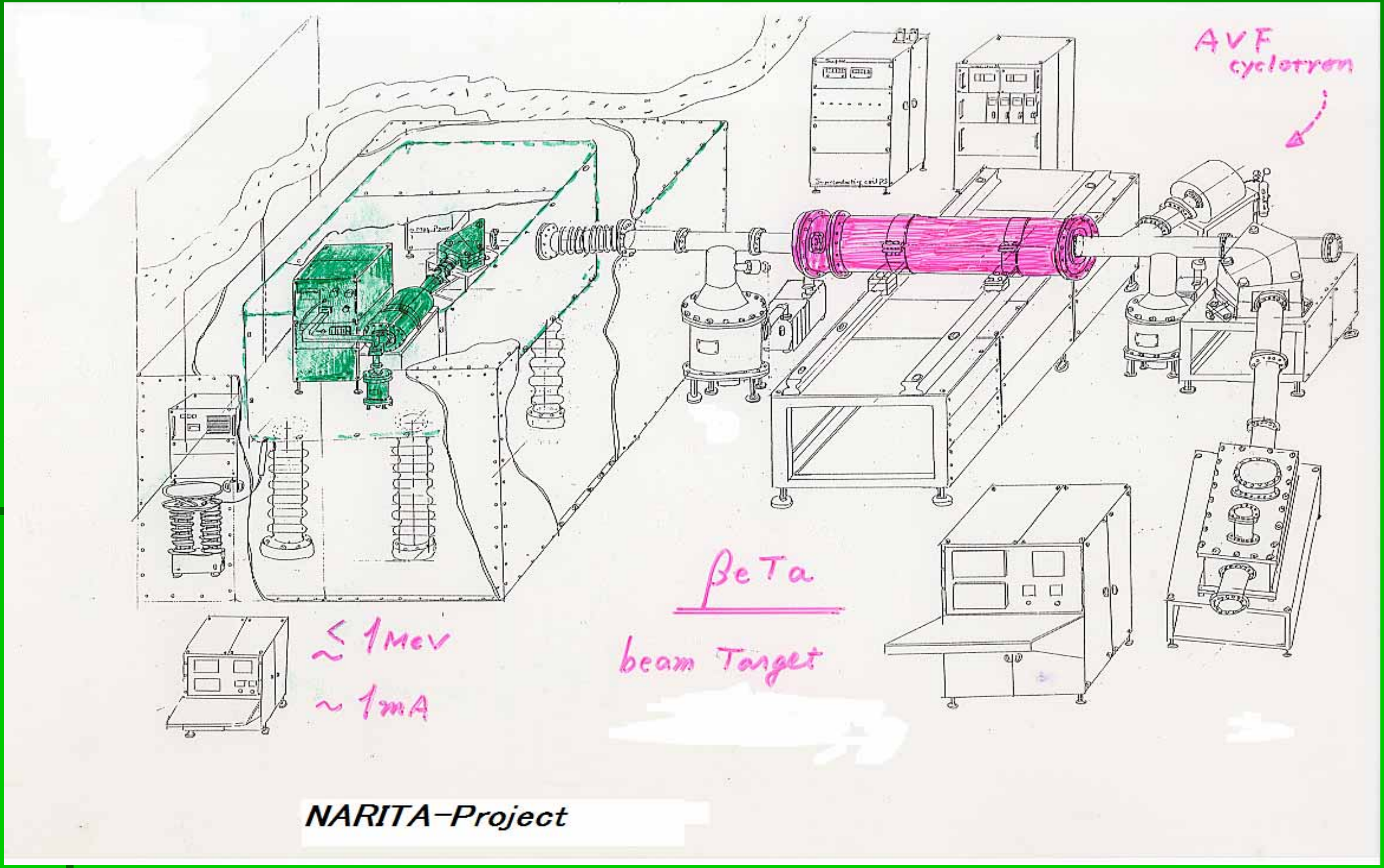
We prefer to realize terrestrial experiments as it is at stellar condition

Nature		*Laboratory*
Core of the sun or	-------	*high density*
Interior of supernovae		*high temp*
		plasma
		atomic state

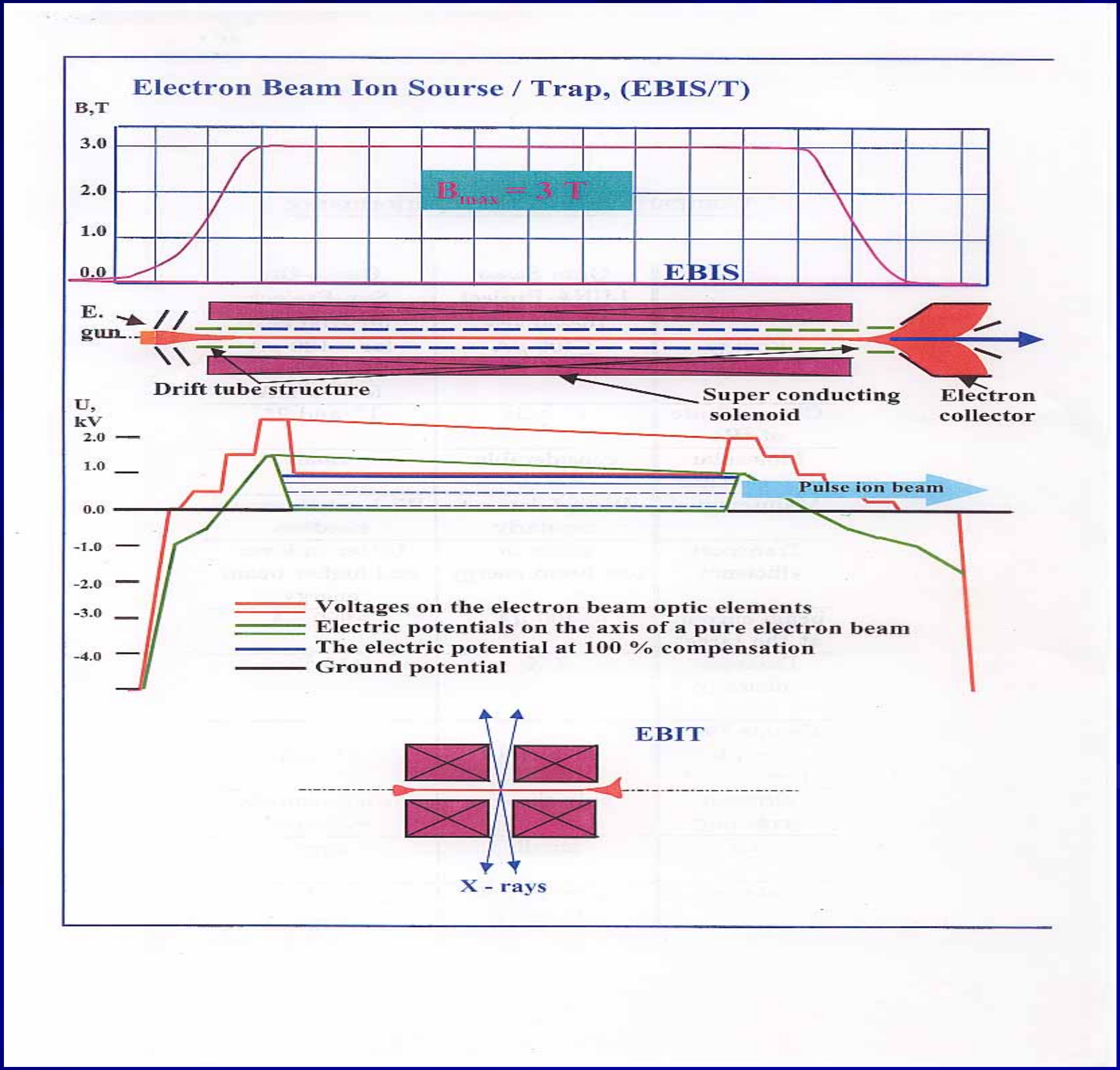
Nuclear Astrophysics Researches in Ion Trap Apparatus NARITA

- ***Consists of***
- ***BeTa***
- ***Ion Source with High Brightness at high voltage platform***
- ***RI production stage by AVF cyclotron***

Beam -Target Experiment in RCNP Osaka Univ.



Electron beam ion trap



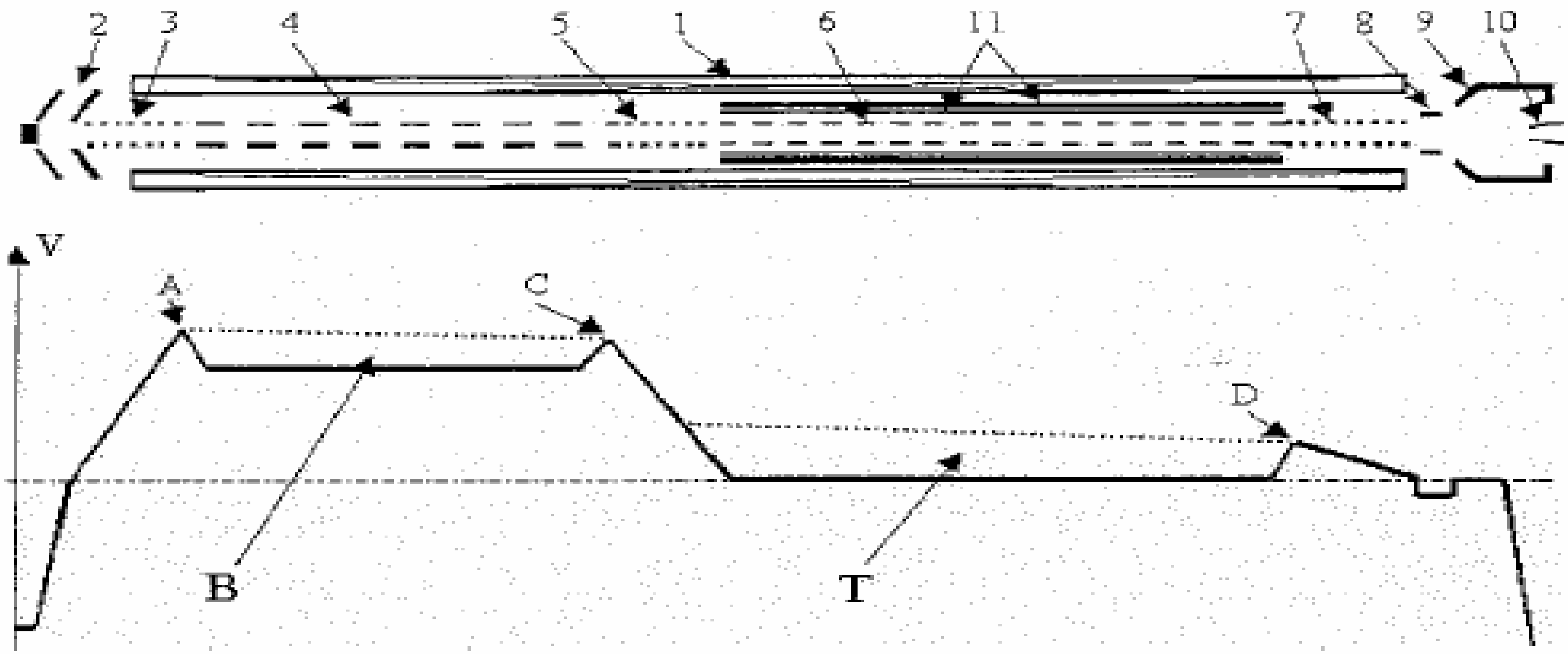


FIG. 1. Schematic view of the BeTa apparatus (up) and of the voltage (V) distribution along its axis (down): (1) super conducting solenoid, (2) electron gun, (3) electron accelerating tube and gun vacuum separator, (4) drift tube section for a beam nuclei trap, (5) ion accelerating tube and a middle vacuum separator, (6) drift tube sections for target nuclei trap, (7) electron collector vacuum separator, (8) electron suppressor, (9) electron collector, (10) ion extractor; (A), (C), (D) potential barriers of ion traps, (B) beam nuclei potential trap, (T) target nuclei potential trap.

- *the ion capacity of the trap(the maximum number of elementary positive charge in the trap)*

- $C^{+} = 3.36 \times 10^{11} I_e L E_e^{-1/2}$

I_e ; *beam current in amperes*

L; length of the trap in meters

E_e; *electron energy in keV*

Compensation time; the positive space charge of the residual gas ions completely compensates the electron beam space charge
n; density of the residual gas
E_e; electron energy
I_e; ionization potential of the residual gas

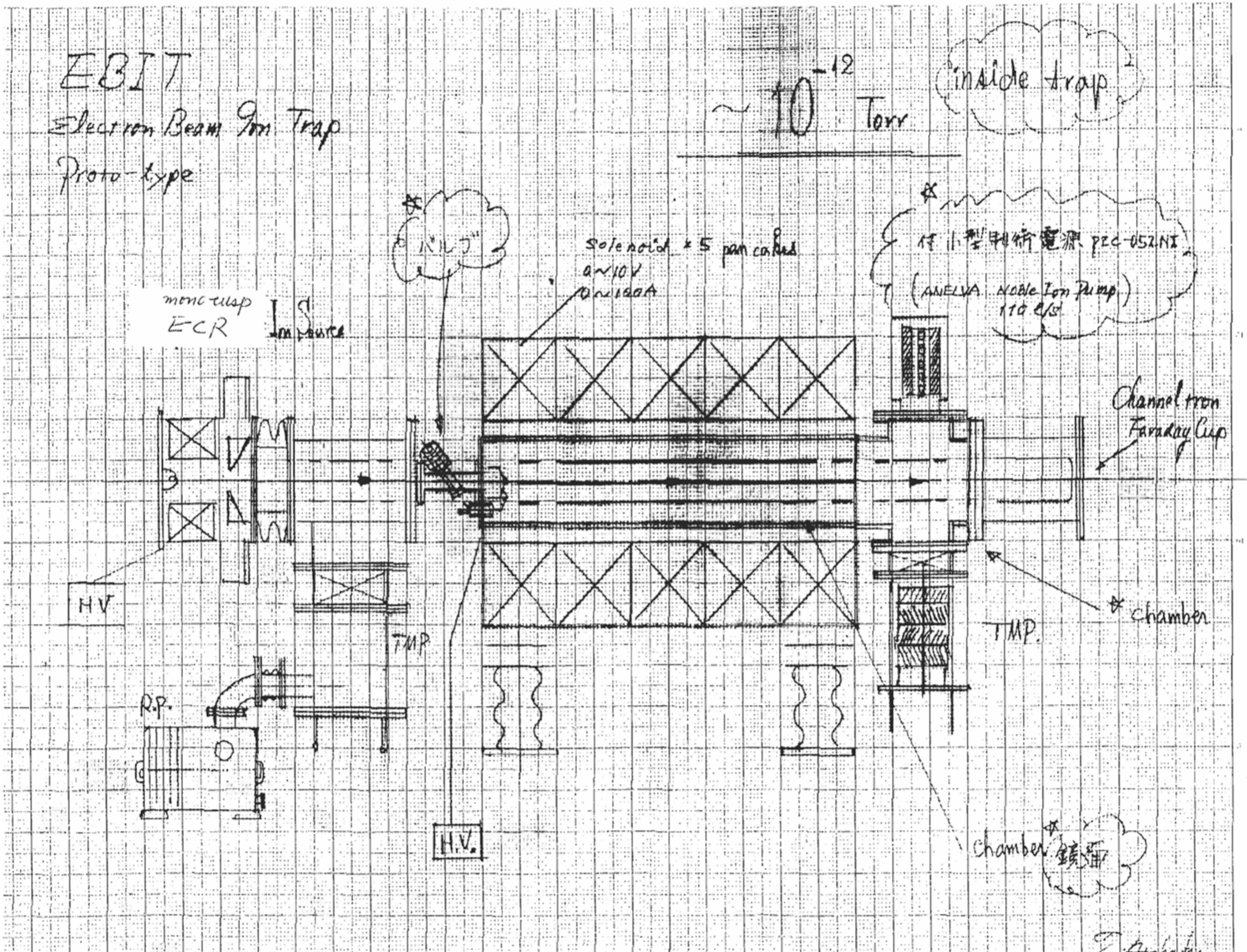
$$\tau_c = 7.5 \times 10^4 \frac{E_e^{1/2}}{n \ln(E_e/I_e)} I_e$$

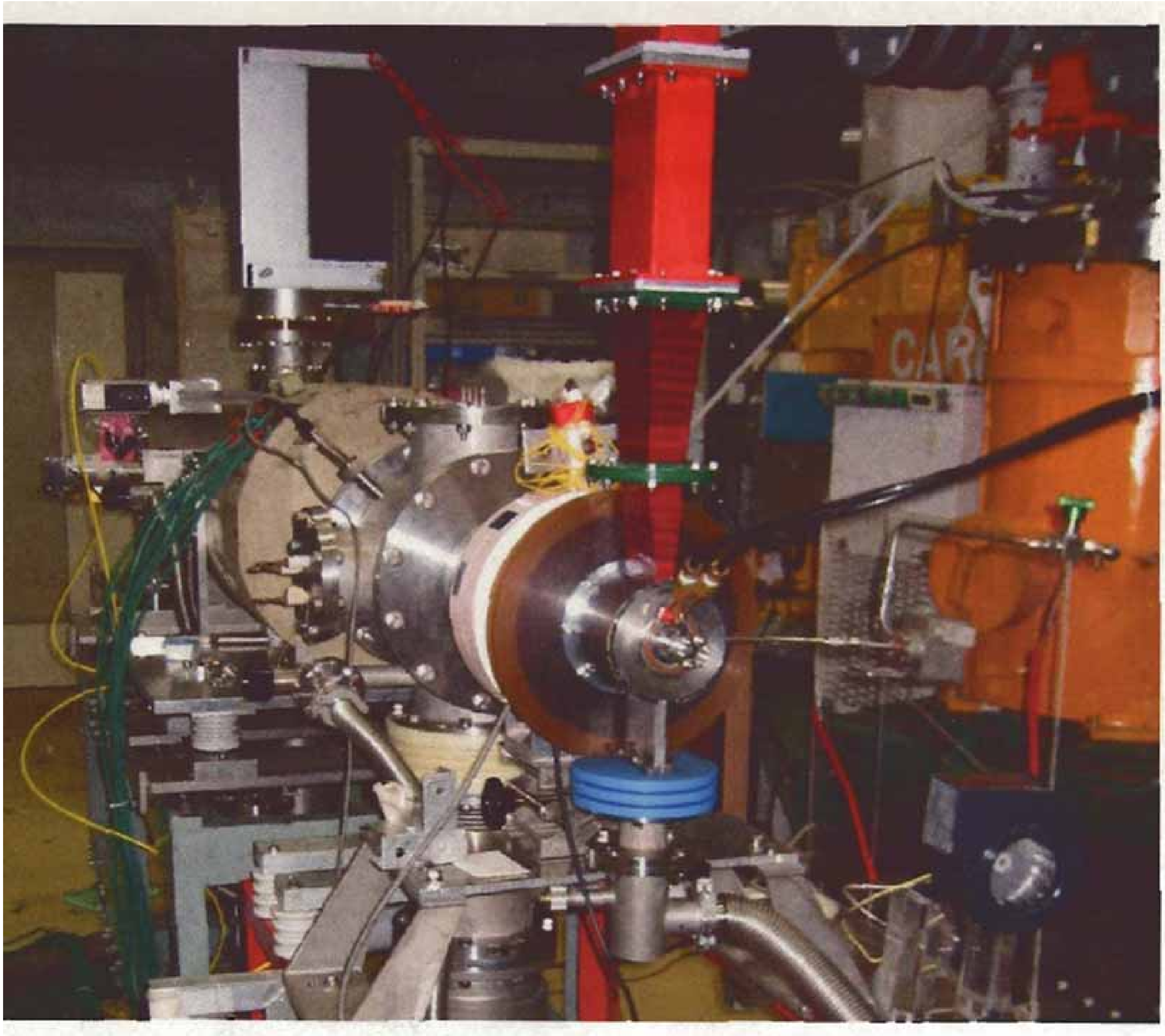
Proto-type experimental apparatus

- ***E_e=10 keV, I_e=14.2 eV,***
  if we assume compensation time is 5 sec.

- ***n = ~10^{-8}Pa (very low pressure)***
  will be required pressure inside the trap,

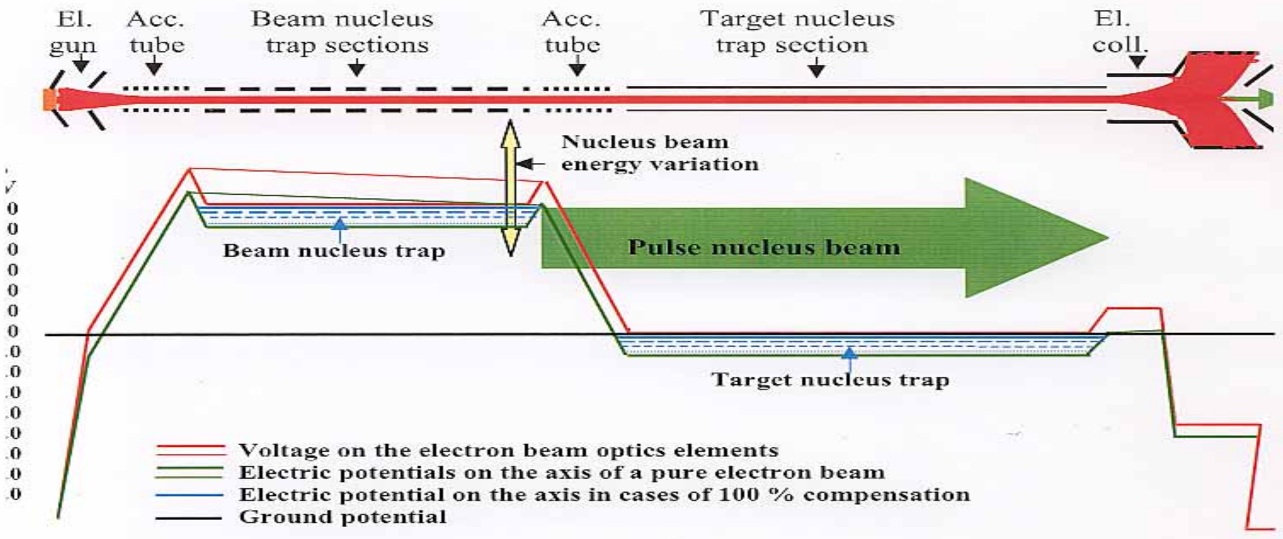
Now we are testing the proto-type apparatus, by using ANAC ionizer.


EBIT
Electron Beam Ion Trap
Proto-type
~ 10^-12 Torr
inside trap
"バルブ"
solenoid × 5 pancakes
0~10V
0~100A
(ANELVA Noble Ion Pump)
110 ℓ/s
mono cusp
ECR
Ion Source
Channeltron
Faraday Cup
HV
TMP
TMP.
chamber
R.P.
H.V.
Chamber



Electron Beam Mode of the BeTa Operation

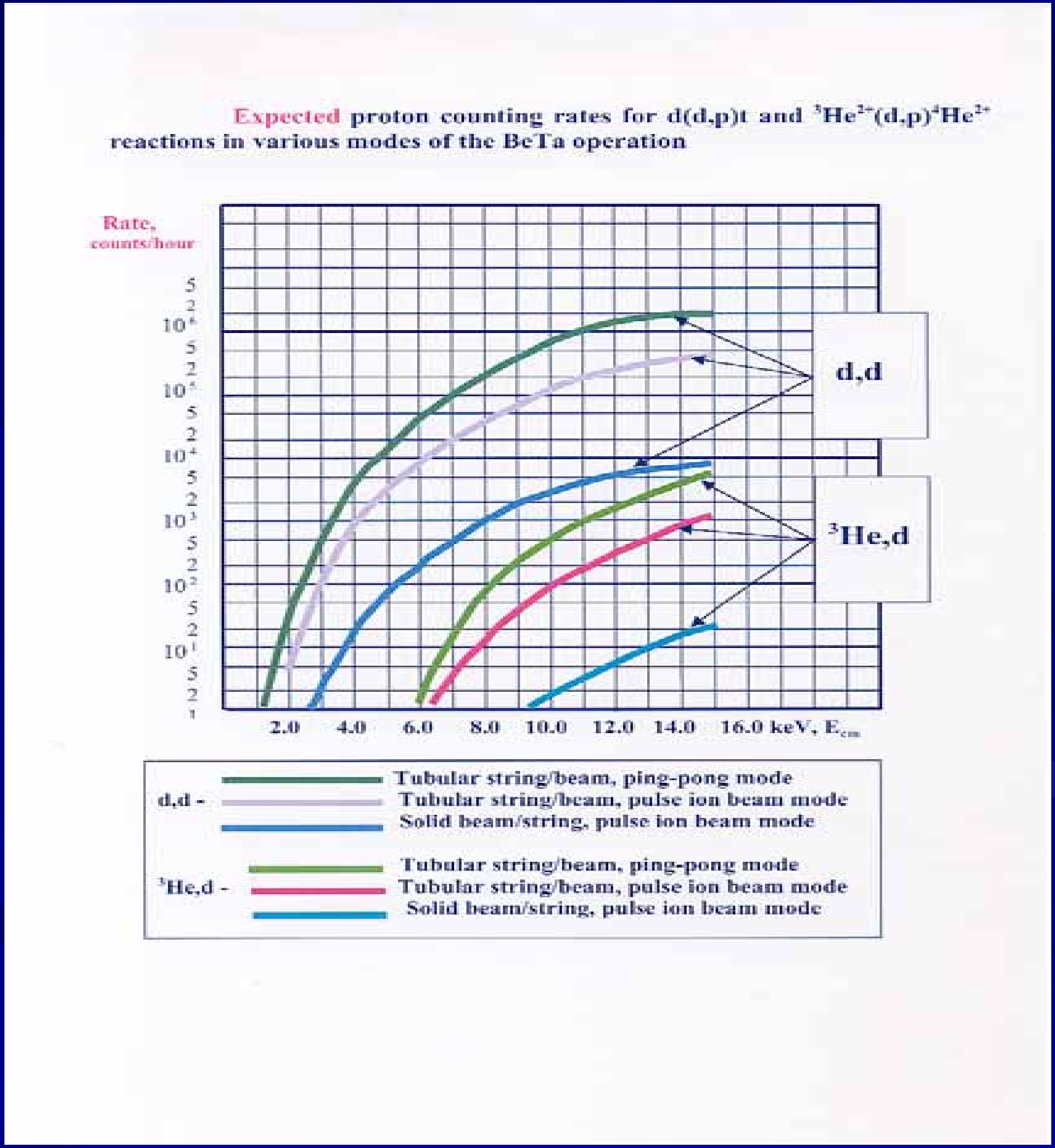
a) Pulse nucleus beam mode



beam —target overlap

Along the axis cross sections of
a nucleus beam trap, of a nucleus beam and of a nucleus target trap,
in an electron beam.

Expected counting rates



Proposal on studies of $p + {}^7Be^{4+}$ reaction at low energy

- *1) the electron beam(or string) of $10^3 A/cm^2$, of 100A current of 1.4 m length and of 3cm radius is used for ionization ${}^7Be^{4+}$ as a target*
- *2) $2.5*10^{12}$ of ${}^7Be$ nuclei at the target thickness $2.5*10^{13}$ length/cm^2*
- *3) cross section = $1*10^{-34}$ cm^2 and 50% efficiency*
- *4) proton beam 40mA at 70 keV*

$^{7}Be(p,gamma)^{8}B$ is the most important and the most uncertain nuclear physics input used in solar neutrino calculation

p + $^{7}Be^{4+}$ reaction

at low energy

2counts/hour

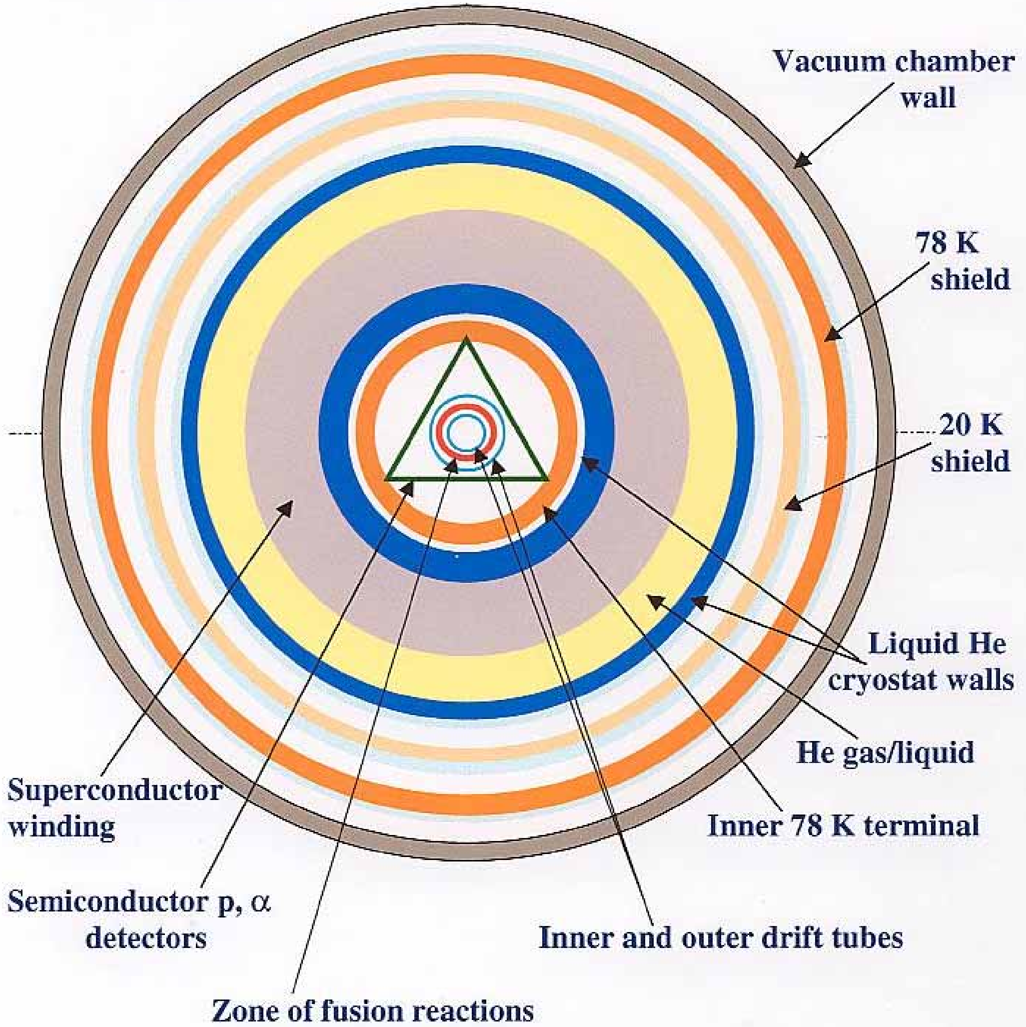
expected

Conclusion

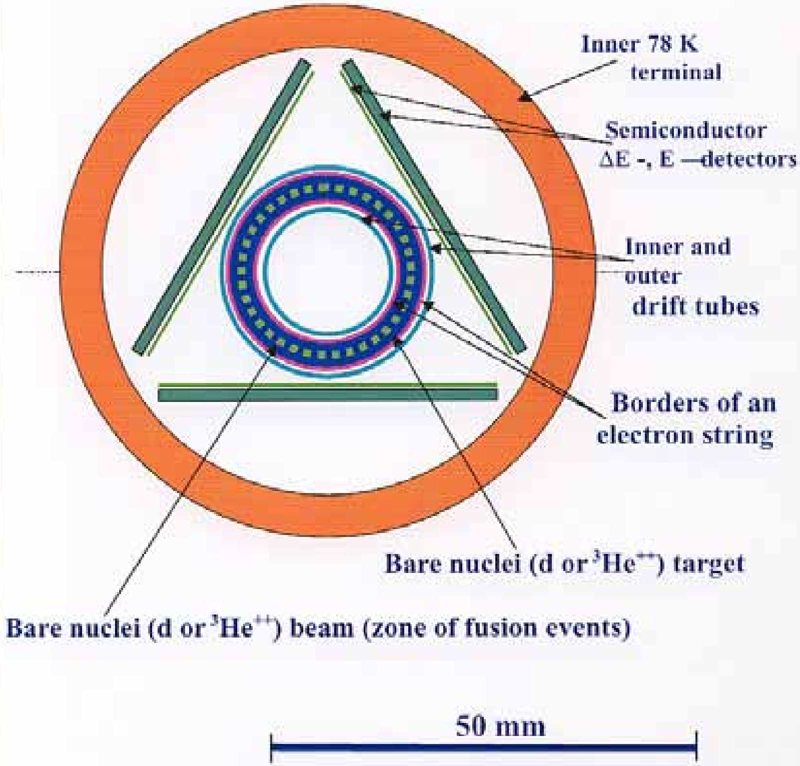
1) To meet terrestrial experiment as stellar condition we will be able to select Temperature, density, pressure, atomic state and also do material such as solid, liquid, gas, plasma
2) On going experiment will be the state selective experiment for interacting particles in atomic states
3) We showed feasibility of meas. for bare to bare nuclear reaction at similar condition as stellar state,
3) Proposed BeTa and NARITA installation (It seems sophisticated apparatus for nuclear astrophysics)

They will be possible tool to study astrophysical S-factor free from the enhancement of screening potential.

Schematic view of a transverse cross section of the BeTa apparatus



Transversal cross section view of the inner region of the BeTa apparatus



Experimental approach, related to this problem

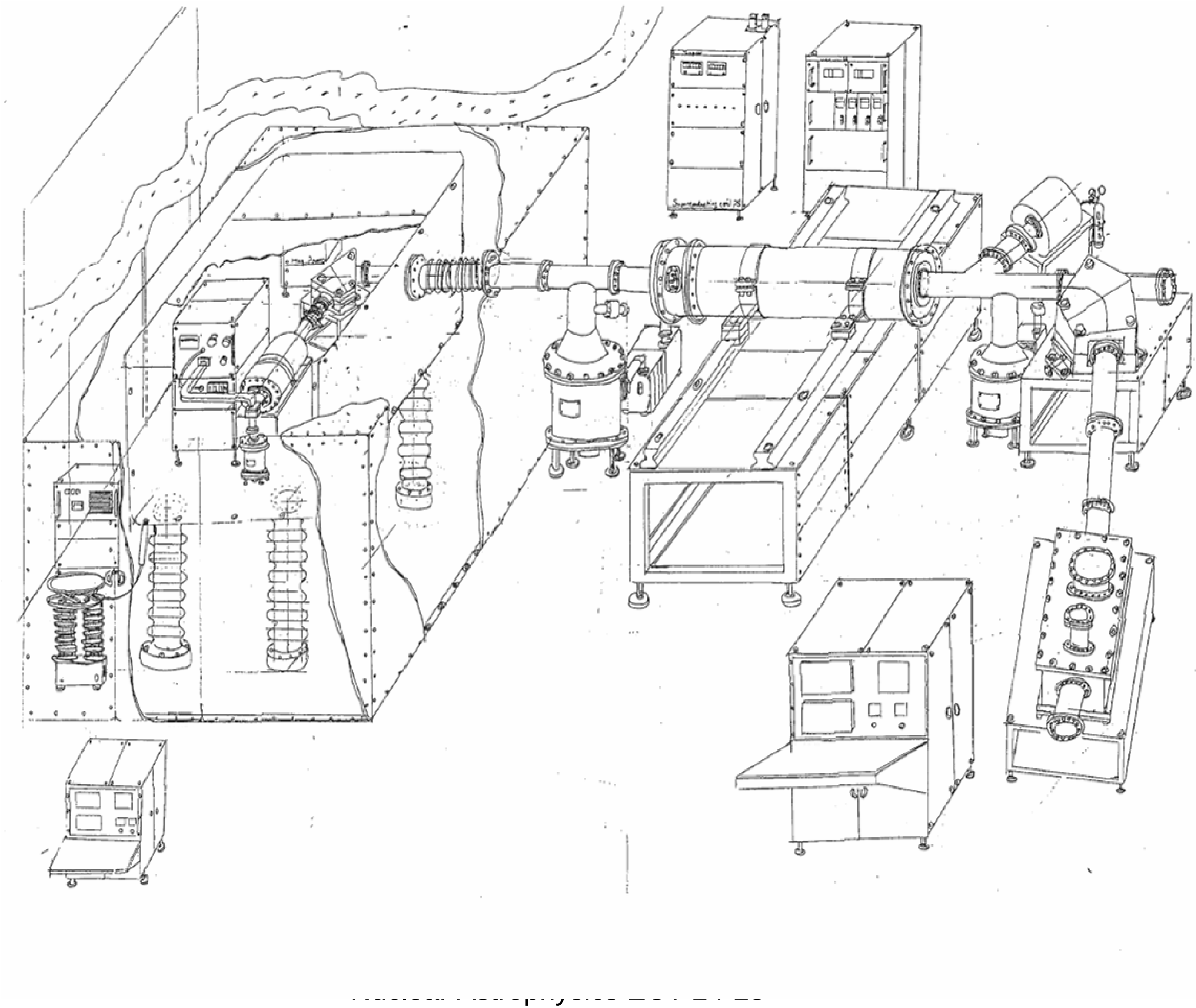
iii) For electron configuration of target and incident particles

combination between various target and incident particle: atom and molecule

Ingenious experimental devices; storage ring

Nuclear Astrophysics Researches in Ion Trap Apparatus

- ***Consists of***
- ***BeTa***
- ***Ion Source with High Brightness at high voltage platform***
- ***RI produced by AVF cyclotron***



Plasma (ion production) ---- beam----- gas (neutral ECR Ion Source Target

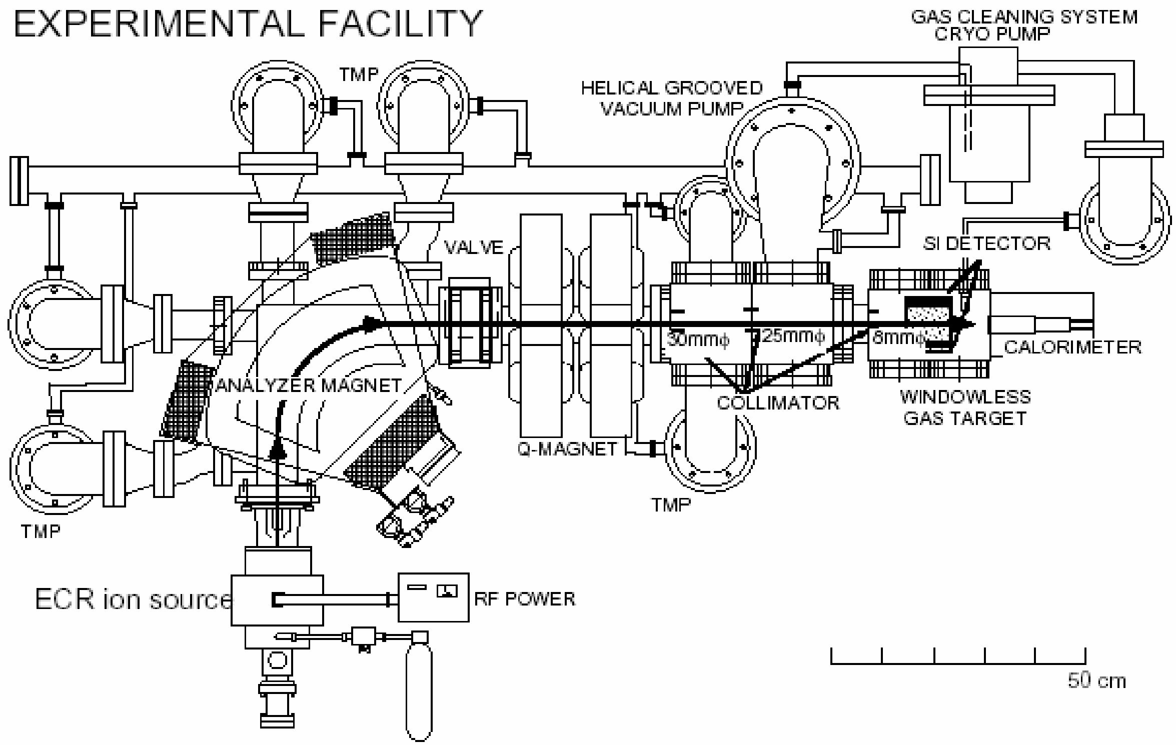


FIG. 1: Complete layout of Osaka University Cosmological Experimental Apparatus for Nuclear Physics, OCEAN .

The shielding effect reduces the Coulomb potential and eases the penetration of the coulomb barrier. During the discussion we use following expressions for astrophysical S-factor with screening potential Ue and enhancement factor f ;

$$\sigma(E) = \frac{S(E)}{E}\exp\left[-2\pi\eta(E)\right] \quad where, \eta(E) = Z_1 Z_2 \alpha \left(2E/\mu c^2\right)^{-\frac{1}{2}}$$

$S(E)$;	astrophysical $S(E) -$ *factor*
$\eta(E)$;	Sommerfeld parameter
Z_1 *and* Z_2;	initial nuclei charge
μ;	reduced mass

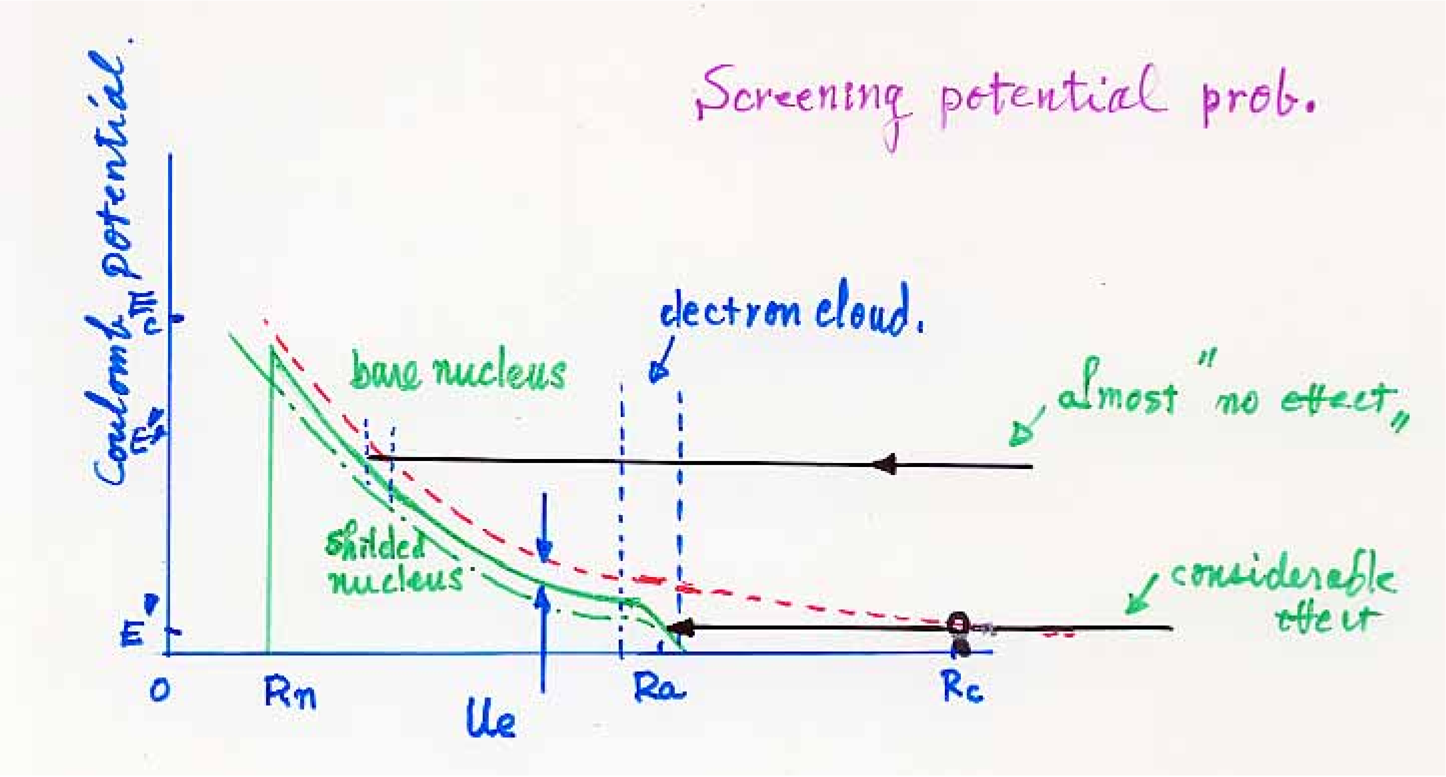
enhancement factor; f

$$f \equiv \frac{\sigma(E+U_e)}{\sigma(E)}$$

$$= \frac{S(E+U_e)}{S(E)} \frac{E}{E+U_e} \frac{\exp\left[-2\pi\eta(E+U_e)\right]}{\exp\left[-2\pi\eta(E)\right]}$$

$$\approx \exp\left\{\pi\eta(E)\frac{U_e}{E}\right\}$$

Screening Potential



Screening energies

(ref. K.Langanke and C.A.Barns, Advance of Nucl. Phys.)

Comparison of Screening Energies $\triangle E$ Determined by Best Fit from Experimental Data(19,24,25) with the Adiabatic Limits

Reaction	$\triangle E$ (eV) experiment	$\triangle E$ (eV) adiabatic limit
$d(^3\mathrm{He}, p)^4\mathrm{He}$	180 ± 30	119
$^6\mathrm{Li}(p, \alpha)^3\mathrm{He}$	470 ± 150	186
$^6\mathrm{Li}(d, \alpha)^4\mathrm{He}$	380 ± 250	186
$^7\mathrm{Li}(p, \alpha)^4\mathrm{He}$	300 ± 280	186
$^{11}\mathrm{B}(p, \alpha)2^4\mathrm{He}$	620 ± 65	348

(1) *Status of The Problem*

Experimental approach, related expts

i) For low energy beam collision expts. we have to avoid the ambiguity of energy loss from stopping power;

We need precise measurement of stopping power of various incident particles with different energies in various medium

Mobility of radio-active beams or PET might be available tools for this issue

Claim(3)

- ***Maximum enhancement or medium or incomplete enhancement has happened or not (this is not clear so far)***
- ***After effects from time dependent collision phenomena with appropriate electronic states of ions and atoms would be measured***

we could extrapolate S(E) factor to the value at required energy(Gamow energy)

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Improved information on the $^2H(^6Li,\alpha)^4He$ reaction extracted via the "Trojan horse" method

A. Musumarra,[1,2] R. G. Pizzone,[1,2] S. Blagus,[3] M. Bogovac,[3] P. Figuera,[1] M. Lattuada,[1,4] M. Milin,[3] Đ. Miljanić,[3] M. G. Pellegriti,[1,2,5] D. Rendić,[3] C. Rolfs,[6] N. Soić,[3] C. Spitaleri,[1,2,*] S. Typel,[7] H. H. Wolter,[8] and M. Zadro[3]

TABLE I. Parameters obtained from a second order polynomial fit of the THM data shown in Fig. 2. The extracted screening potential energy and the value predicted by the adiabatic approximation are also given.

S(0) [MeV b]	S_1 [b]	S_2 [MeV^{-1}b]	U_e [eV]	U_e^{ad} [eV]
16.9±0.5	-41.6	28.2	320±50	186