Feasibility Study of a Polarized ^{6}Li ion Source

RCNP P-PAC, Nov. 10, 2003

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Collaborators

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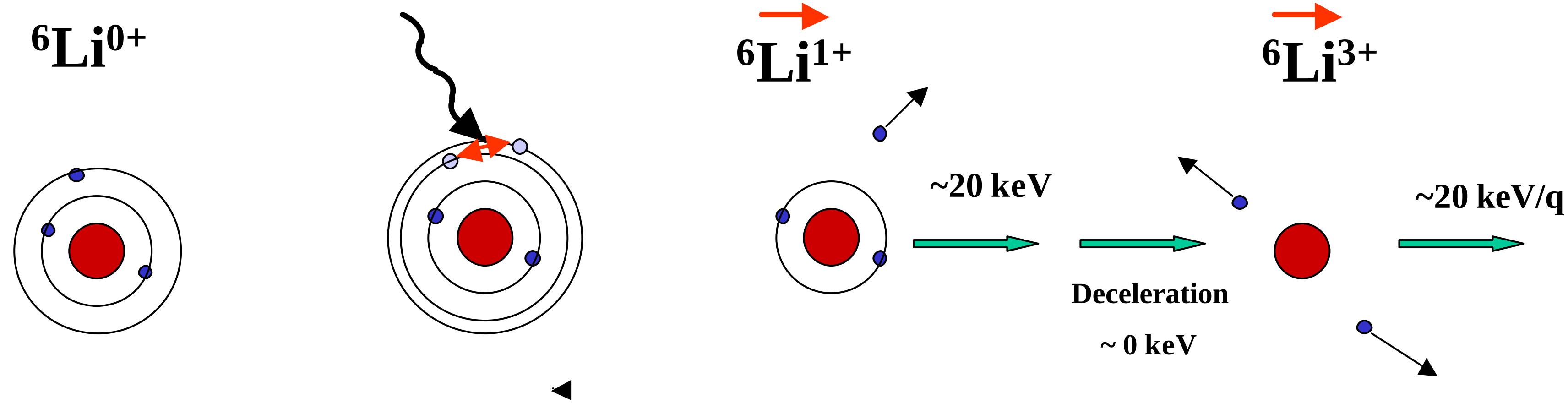
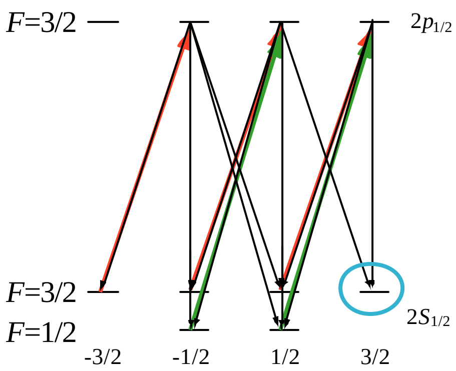


Atomic source (Oven) | **Optical pumping (diode laser)** | **Surface ionization** | **Ionization (ECR)**



Level Diagram of a ^{6}Li atom

High efficiency

No depolarization

(Heidelberg, FSU)

<Charge breeder>

Depolarization ?

Efficiency ?

cf. stripping

E ~ MeV

Physics Motivation

- **Study of the pion field in nuclei**

  excitation of 0⁻ states by (^{6}Li, ^{6}He) Reaction

  - **Tensor analyzing power at 0°: A_{zz} = -2**
  - **Selective excitation of ΔT=1, ΔS=1**
  - **High resolution measurement by dispersion matching**

    ⇔(d,^{2}He), (p,n)
- **Study of the reaction mechanism of composite particle**
  - **Elastic Scattering, inelastic scattering, (^{6}Li, ^{6}He) Reaction**

    (diff. cross section and analyzing powers)
- **Study of the break up mechanism with a polarized beam**
- **Study of the spin structure of ^{6}Li**

If the coordinate system is chosen as $\vec{z} \,//\, \vec{k}_i$, and $\vec{y} \,//\, \vec{k}_i \times \vec{k}_f$,

T-matrix element for a A(a,b)B reaction satisfies

$$\langle \vec{k}_f ; I_B M_B I_b M_b | T | \vec{k}_i ; I_A M_A I_a M_a \rangle$$
$$= (-)^{I_B - M_B + I_b - M_b + I_A - M_A + I_a - M_a} \pi_B \pi_b \pi_A \pi_a \times \langle \vec{k}_f ; I_B\, -M_B\, I_b\, -M_b | T | \vec{k}_i ; I_A\, -M_A\, I_a\, -M_a \rangle$$

from requirement of invariance under the reflection in *x*-*y* plane.

For reactions with spin-parity: $I_a^{\pi} = 1^+, I_A^{\pi} = 0^+, I_b^{\pi} = 0^+, I_B^{\pi}$

[for example, (d,^{2}He), (d,^{4}He), (^{6}Li,^{6}He) reaction on even-even target]

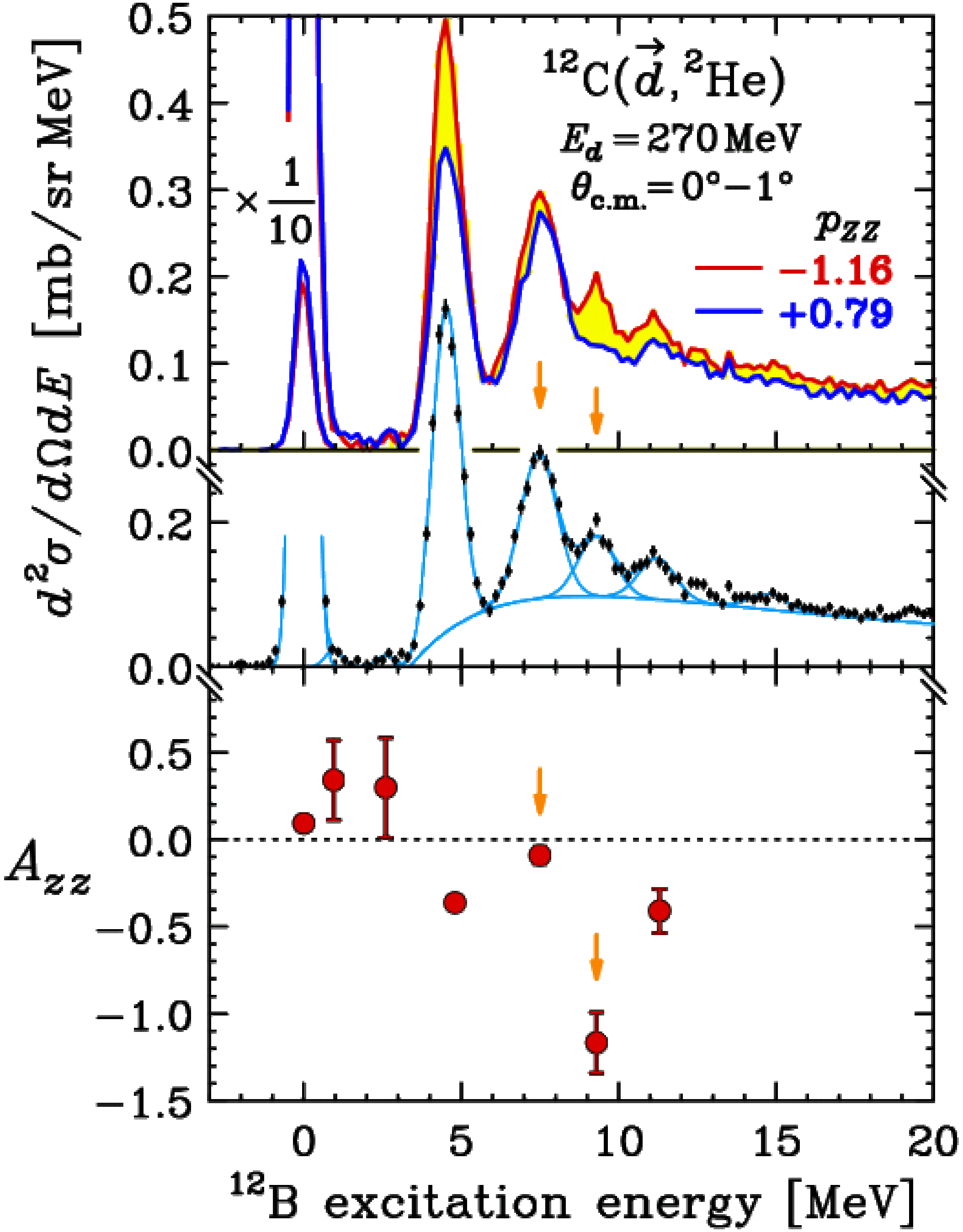
$$A_{ij} = \frac{Tr(TP_{ij}T^{+})}{Tr(TT^{+})} = \frac{1}{\sum_{M_B M_a} |\langle M_B | T | M_a \rangle|^2} \sum_{M_B M_a M'_a} \langle M_B | T | M_a \rangle \langle M_a | P_{ij} | M'_a \rangle \langle M'_a | T | M'_B \rangle^*$$

For $I_B^{\pi} = 0^-$, $\langle M_B = 0 | T | M_a = 1 \rangle = -\langle M_B = 0 | T | M_a = -1 \rangle$.

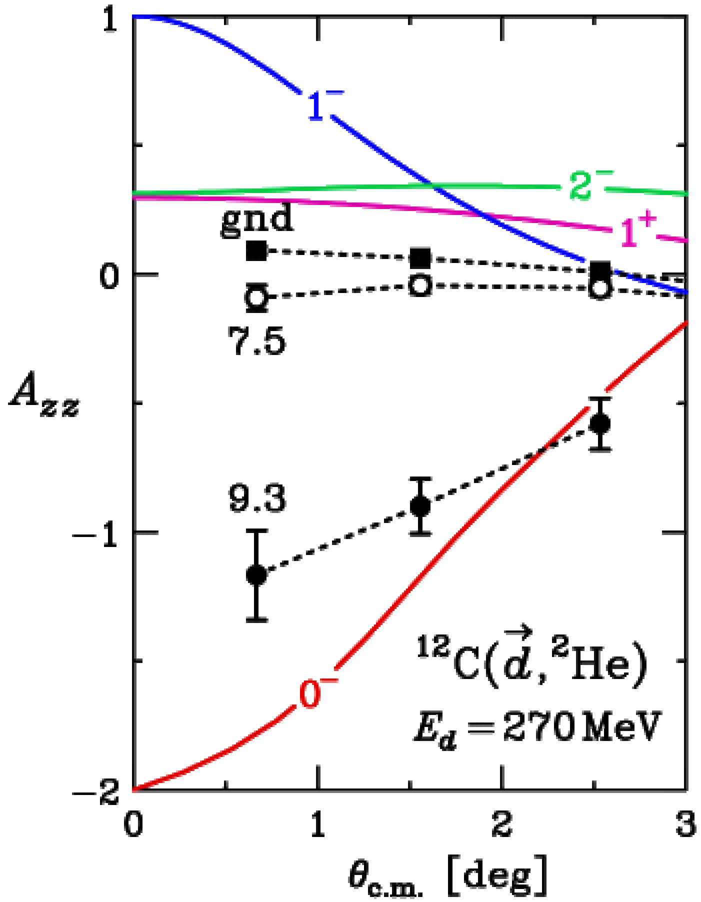
There are two independent elements $\langle 0 | T | 1 \rangle = A$ **and** $\langle 0 | T | 0 \rangle = B$**, then**

$$A_{yy} = \frac{1}{2|A|^2 + |B|^2} \frac{1}{2} \begin{pmatrix} A & B & -A \end{pmatrix} \begin{pmatrix} -1 & 0 & -3 \\ 0 & 2 & 0 \\ -3 & 0 & -1 \end{pmatrix} \begin{pmatrix} A^* \\ B^* \\ -A^* \end{pmatrix} \equiv 1$$

At 0 deg., $A_{zz} = -2$. **(model independent)**



$$\sigma = \sigma_0\left(1 + \tfrac{1}{2} P_{ZZ} A_{ZZ}\right) \xrightarrow{A_{ZZ}(0^-)=-2} \begin{cases} 3\sigma_0 & (P_{ZZ} = -2) \\ 0 & (P_{ZZ} = +1) \end{cases}$$



$A = 12$ 系で初めて 0^- を発見

H. Okamura *et al*. Phys. Rev. C 66 (2002) 054602

from parity conservation and rotational invariance

for reactions with spin-parity: $1^+ + 0^+ \rightarrow 0^+ + I^\pi$

— (d,^{2}He), (d, α), (^{6}Li,^{6}He) etc. —

$$A_{zz}(0°) = \begin{cases} +1 & \text{for} \quad \text{natural parity}\,[p = (-)^I] \\ -2 & \text{for} \quad 0^- \end{cases}$$

(extreme value of A_{zz})

Reaction cross section (if spin quantization axis is parallel to the beam direction)

$$\sigma = \sigma_0\left(1+\tfrac{1}{2}P_{ZZ}A_{zz}\right) = \begin{cases} \sigma_0\left(1-A_{zz}\right) & \cdots P_{ZZ} = -2 \\ \sigma_0\left(1+\tfrac{1}{2}A_{zz}\right) & \cdots P_{ZZ} = +1 \end{cases}$$

σ_0 : unpolarized cross section

cf. if spin quantization axis is parallel to the beam direction

$$\sigma = \sigma_0\left(1+\tfrac{1}{4}P_{ZZ}A_{zz}\right)$$

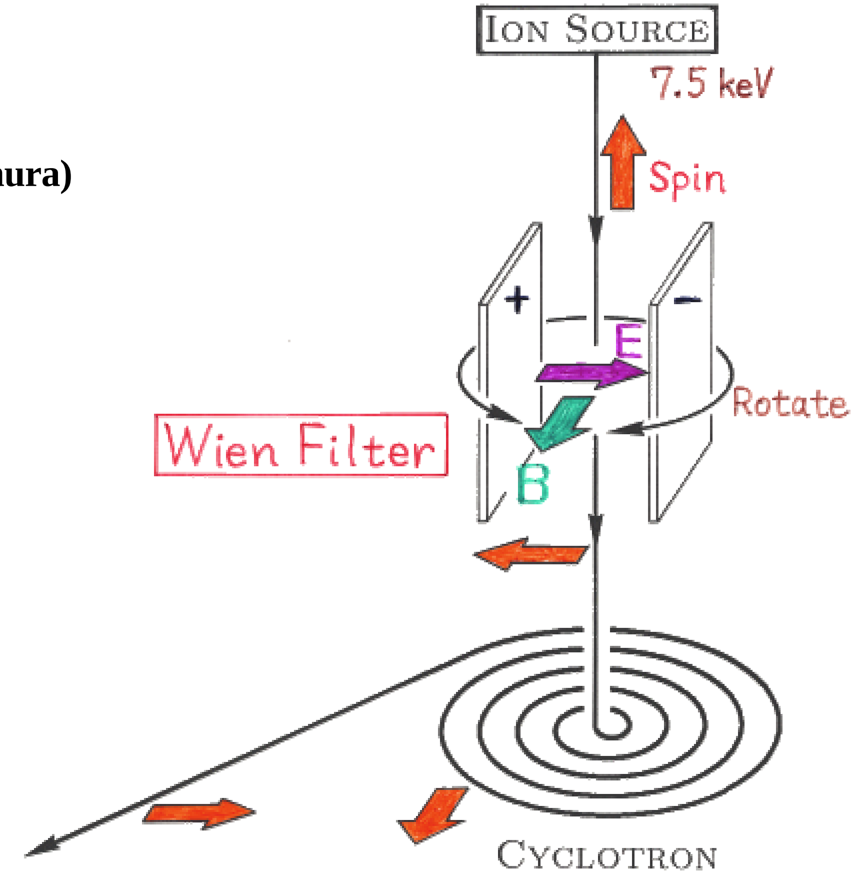
➡ **It is important to align the spin to the beam direction**

スピン回転方法

RIKEN

(H. Okamura)

サイクロトロン入射前に
低エネルギーでスピン回転
⇒ 加速中に歳差運動



バン・デ・グラフでは一般的だが…

- サイクロトロンでは特定のターンのみを引き出す必要有り
  ⇒ Thanks to RIKEN Accelerator Staff
- 加速後のスピンの向きを高効率でモニターする偏極度計必要

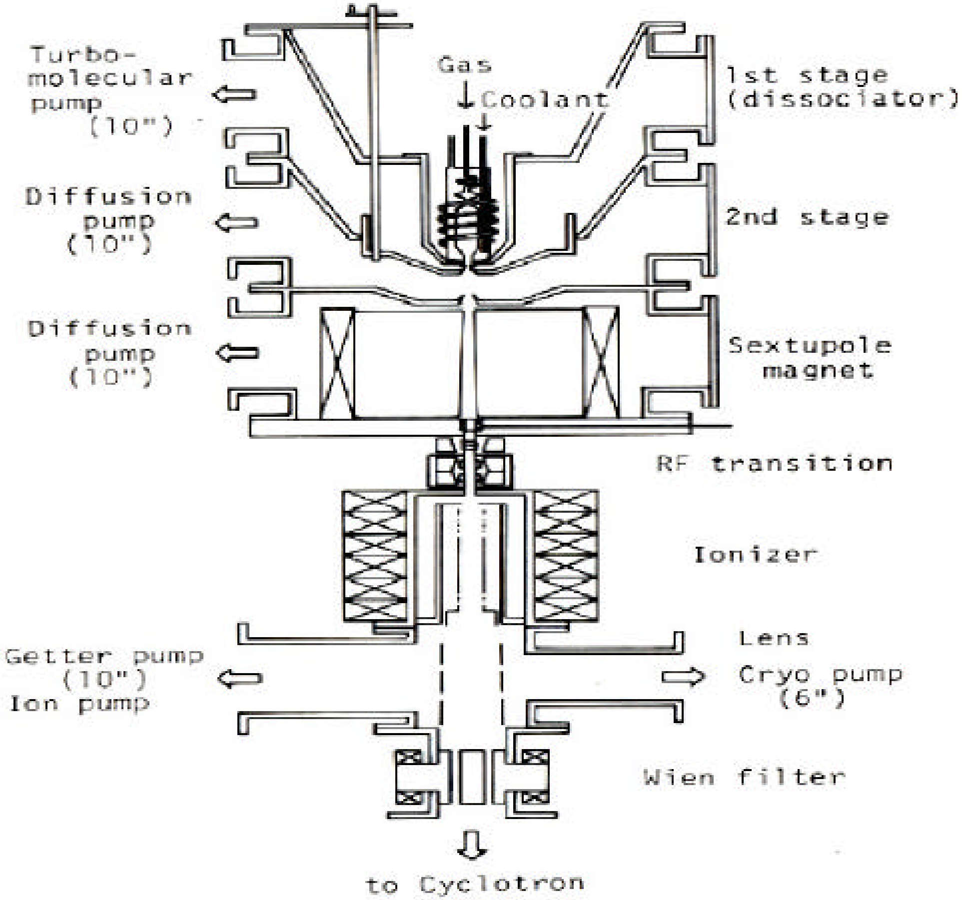


Fig. 1. Schematic diagram of the RCNP atomic beam polarized ion source.

(K. Hatanaka et al., NIM 217 (1983) 397-404)

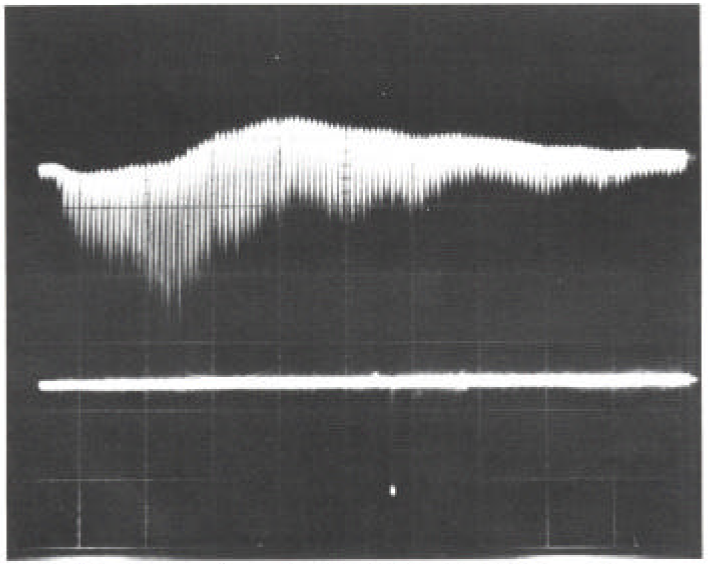


Fig. 6. Distribution of the turn numbers at a duty cycle of 1/115 observed for 56 MeV deuterons. The upper curve indicates signals from the plastic scintillator in the beam path, and the lower curve shows the trigger signal from the frequency divider. The horizontal scale is 1 μs/division.

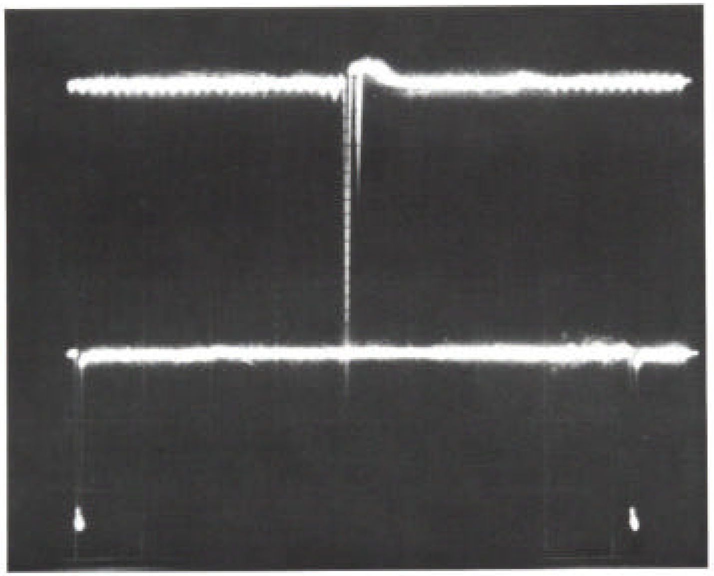


Fig. 7. Distribution of the turn numbers of the extracted deuterons restricted by the phase defining slit. The duty cycle is 1/48 and the horizontal scale is 0.5 μs/division. See the caption for fig. 6.

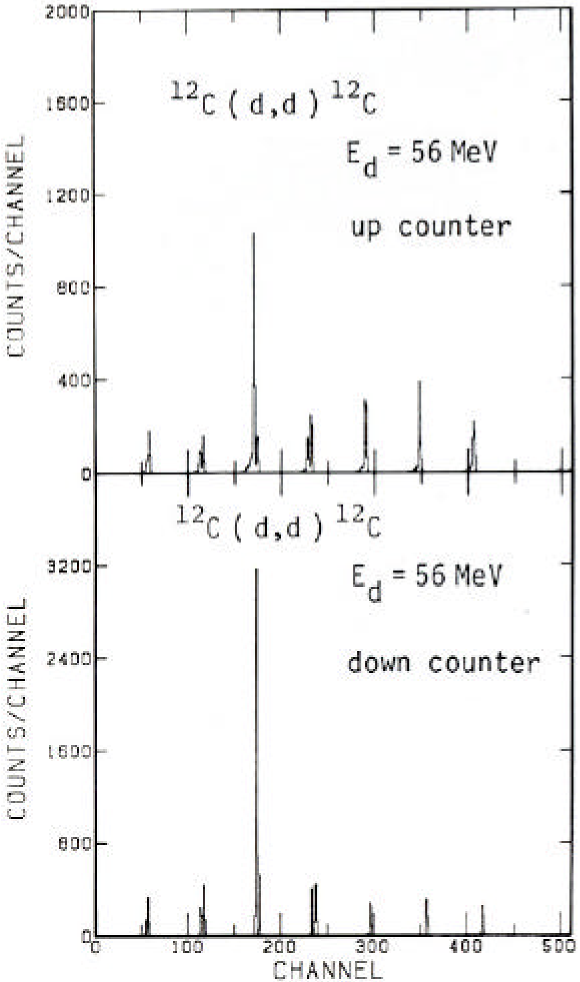


Fig. 9. TAC spectra in the case of 56 MeV deuterons. Each peak corresponds to a different turn number of the extracted beam.

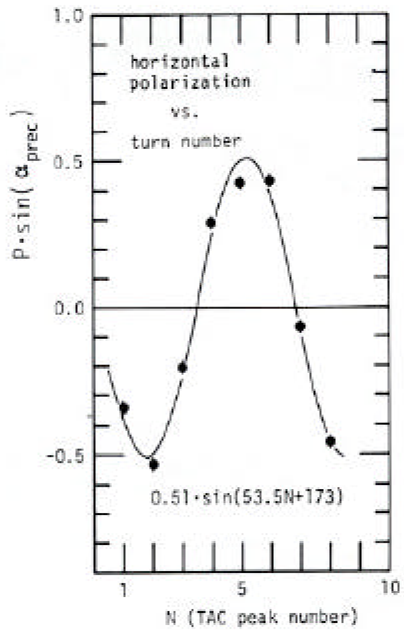


Fig. 10. Horizontal polarization as a function of the turn number in the TAC spectrum for 65 MeV protons.

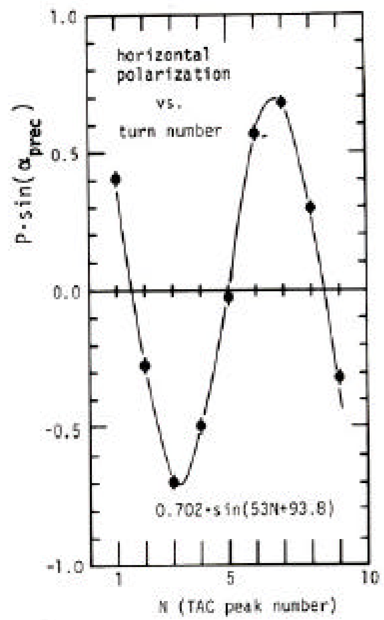


Fig. 11. Same as fig. 10, but for 56 MeV deuterons. The polarization is represented as a ratio to the ideal value, 2/3.

Development of Polarized ^{6}Li ion Sources at Other Laboratories.

- **Max Plank Institute, Heidelberg**

  Stern-Gerlach + Surface Ionizer (+ Charge Exchange+Tandem)

  (Optical Pumping)

  $^6Li^{1+}$: 20-30mA

- **Florida State University**

  Optical Pumping + Surface Ionizer (+ Charge Exchange+Tandem+LINAC)

- **Saturne**

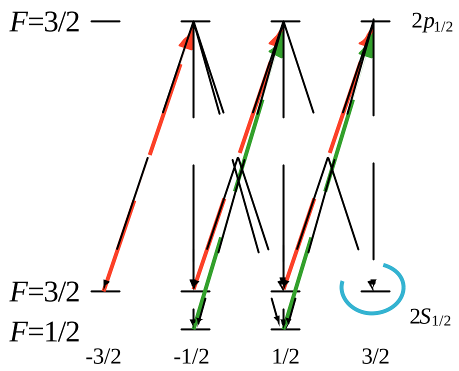
  Optical Pumping + Surface Ionizer (+ EBIS+Accum. Ring+Synchrotron)

  $^6Li^{1+}$: 20-35mA

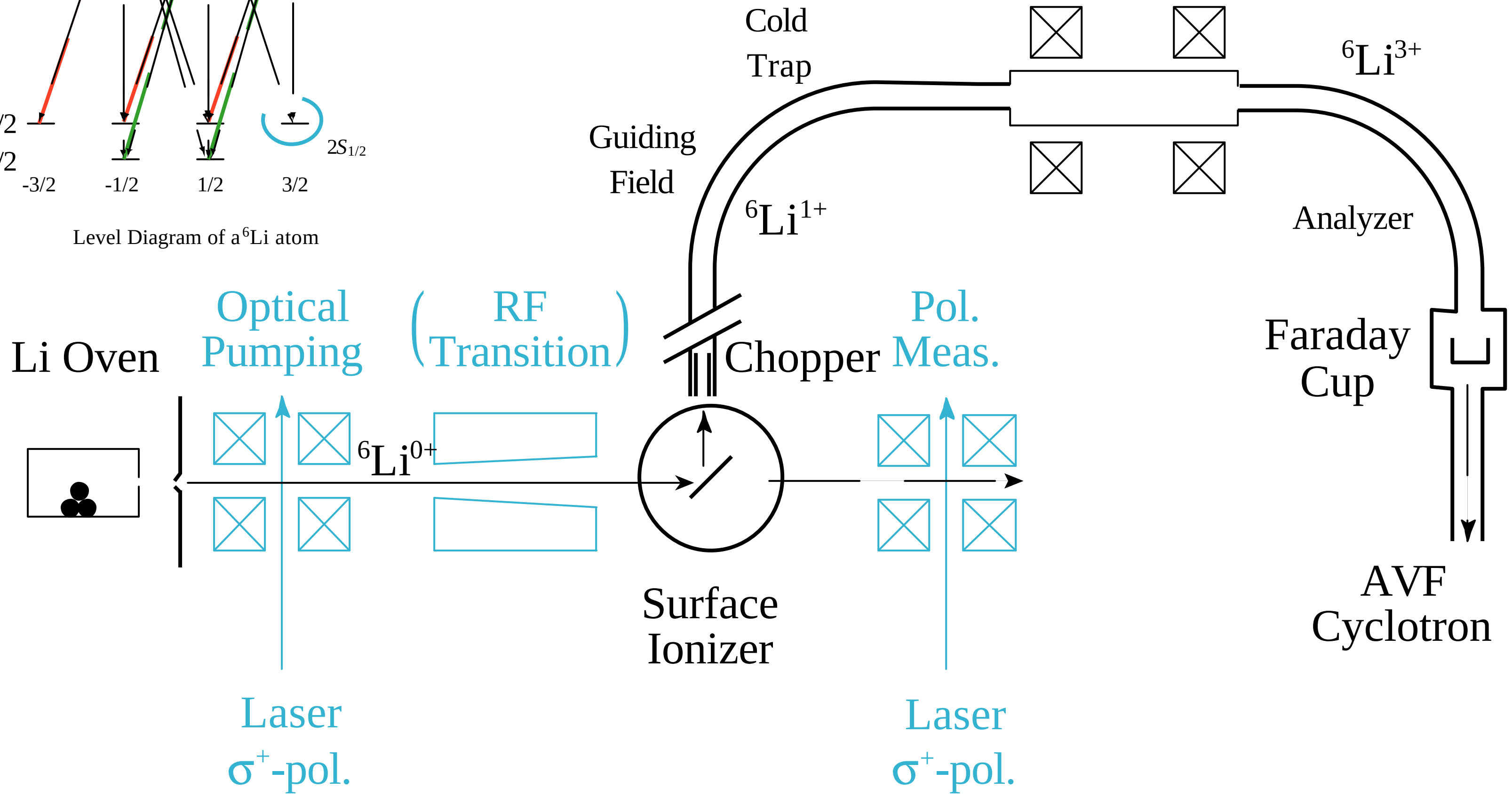
  $^6Li^{3+}$: 7×10^8 particles/spill

  P_{zz} = 70% at 187.5 keV/A

Plan of the polarized ^{6}Li ion source



Level Diagram of a ^{6}Li atom



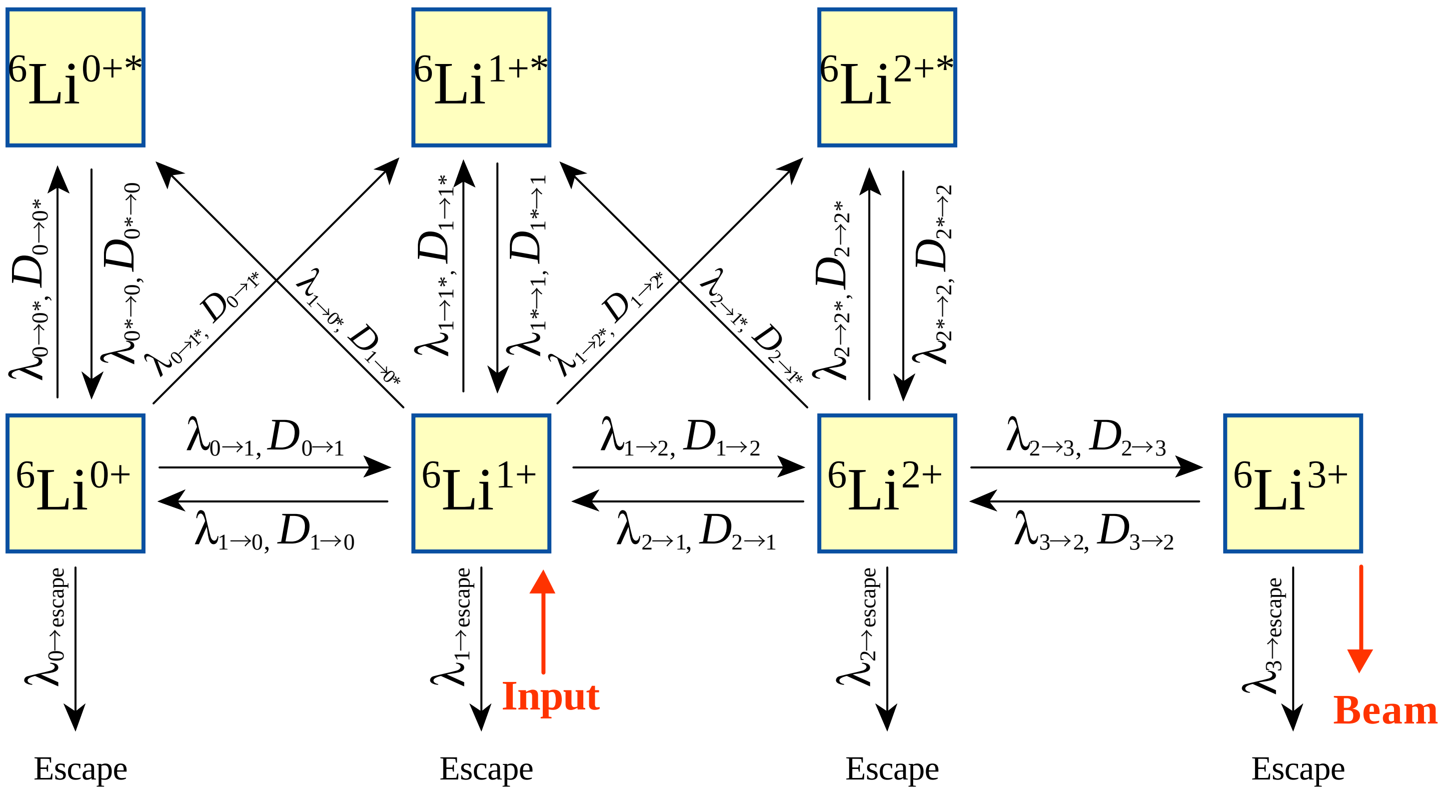
$^6Li^{1+}$: 20-30mA

Pol. 80-90%

Simulation of the Depolarization in the ECR Ionizer

by A. Tamii (extension of the simulation by Prof. M. Tanaka)

- **Fractions and polarizations of escaped ions are calculated by assuming the initial conditions, transition rates, and magnetic-substate transition matrix.**
- **The rate equations are analytically solved.**



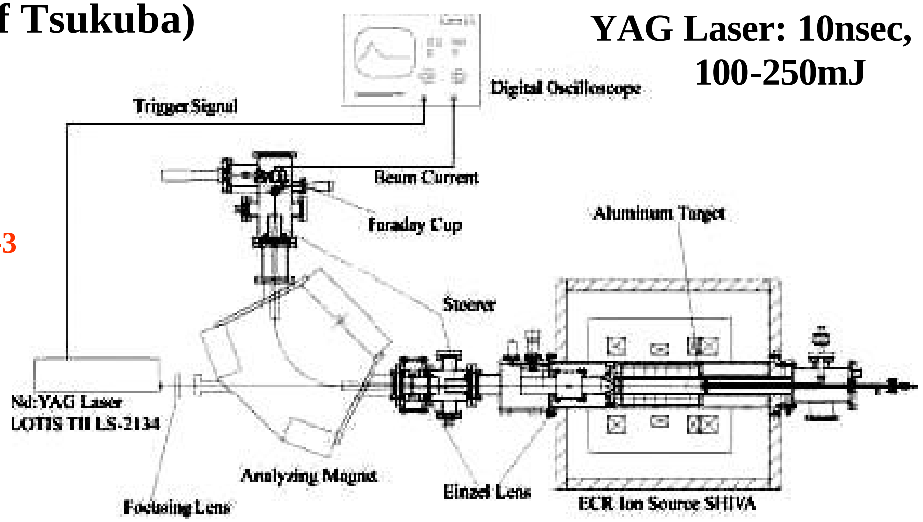
$\lambda_{i\to j}$: Transition Rate from i to j [s^{-1}]

$D_{i\to j}$: Transition Matrix of Magnetic Substates from i to j ($0 \leqq D_{ji} \leqq 1$)

Assumption of the Plasma Condition

The following plasma condition is assumed according to the empirical analysis of the laser abraded Al ion intensities from a 14.5 GHz ECR ionizer (SHIVA). **(M. Imanaka, PhD thesis, Univ. of Tsukuba)**

YAG Laser: 10nsec, 100-250mJ



RF Power: 250 W

Buffer Gas: Oxygen

Neutral Oxygen Gas Density (n_{gas}): 1.44×10^{10} cm^{-3}

Electron Density (n_e): 2.23×10^{11} cm^{-3}

Electron Temperature (T_e) : 582 eV

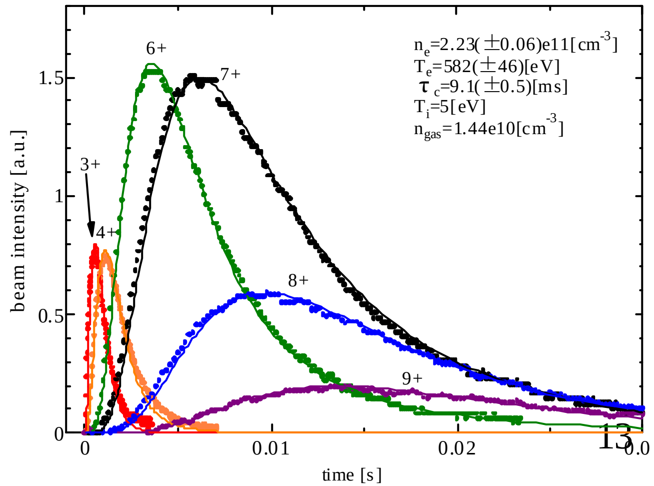
Ion Temperature (T_i) : 5 eV

Ionization Rate: Voronov's empirical Fit

Charge Exchage Rate: Muller and Saltzborn

Confinement time of Al: $t_i \propto \frac{i}{i_{max}} t_c$ **for the i+ ions, t_c=10msec**

n_e, T_e, t_c, T_i are fitted to the data.



Possible depolarization processes

- **Charge exchange process (ionization, electron capture)**

  incomplete hyperfine decoupling ◀▶ magnetic field

- **Atomic excitation and de-excitation**

  Atoms and ions are excited by electron impact and spontaneously de-excited to the ground state. The process is considered to proceed fast compared to the mixing time among hyperfine states. Depolarization occurs only when the electron spin flips.

- **Electron Spin Resonance (ESR) of $^{6}Li^{2+}$ ions in ECR**

- **Inhomogeneous magnetic field of ECR source**

  → **not included in the present estimation**

Magnetic-Substate Transition Matrix (1/2)

(according to the calc. of ^{3}He by M. Tanaka and Y. Plis)

- **The wave functions $\Psi_i(t)$ of the electron-nucleus system in a magnetic field system are written as a linear conbination of |IJ> states as**

$$\Psi_{\mathrm{I}}(0) = |\uparrow +1\rangle$$
$$\Psi_{\mathrm{II}}(0) = \sin\beta_+ |\uparrow 0\rangle + \cos\beta_+ |\downarrow +1\rangle$$
$$\Psi_{\mathrm{III}}(0) = \sin\beta_- |\uparrow -1\rangle + \cos\beta_- |\downarrow 0\rangle$$
$$\Psi_{\mathrm{IV}}(0) = |\downarrow -1\rangle$$
$$\Psi_{\mathrm{V}}(0) = -\cos\beta_- |\uparrow -1\rangle + \sin\beta_- |\downarrow 0\rangle$$
$$\Psi_{\mathrm{VI}}(0) = -\cos\beta_+ |\uparrow 0\rangle + \sin\beta_+ |\downarrow +1\rangle$$

$$\sin\beta_\pm \equiv \sqrt{\frac{1}{2}(1+\delta_\pm)} \quad \cos\beta_\pm \equiv \sqrt{\frac{1}{2}(1-\delta_\pm)}$$

$$\delta_\pm \equiv \frac{\pm\frac{1}{3} + x}{\sqrt{1 \pm \frac{2}{3}x + x^2}}$$

$$x \equiv \frac{B}{B_c} \qquad B_c: \text{critical magnetic field}$$

- **The time revolution of the |↓ +1> state is**

$$\begin{aligned}
|\downarrow +1\rangle_t &= \cos\beta_+ \Psi_{\mathrm{II}}(t) + \sin\beta_+ \Psi_{\mathrm{IV}}(t) \\
&= \cos\beta_+ \Psi_{\mathrm{II}}(0)\exp(-iE_{\mathrm{II}}t) + \sin\beta_+ \Psi_{\mathrm{IV}}(0)\exp(-iE_{\mathrm{IV}}t) \\
&= \cos\beta_+ \left(\sin\beta_+ |\uparrow 0\rangle + \cos\beta_+ |\downarrow +1\rangle\right)\exp(-iE_{\mathrm{II}}t) \\
&\quad + \sin\beta_+ \left(-\cos\beta_+ |\uparrow 0\rangle + \sin\beta_+ |\downarrow +1\rangle\right)\exp(-iE_{\mathrm{IV}}t)
\end{aligned}$$

- **The probability to find |↓ +1> and its time average (after sufficient time) is**

$$\begin{aligned}
P(t) &= \left|\cos^2\beta_+ \exp(-iE_{\mathrm{II}}t) + \sin^2\beta_+ \exp(-iE_{\mathrm{IV}}t)\right|^2 \\
&= \cos^4\beta_+ + \sin^4\beta_+ + 2\cos^2\beta_+ \sin^2\beta_+ \cos\left((E_{\mathrm{II}} - E_{\mathrm{IV}})t\right)
\end{aligned}$$

$$\overline{P} = \cos^4\beta_+ + \sin^4\beta_+ = \frac{1}{2}(1+\delta_+^2)$$

Magnetic-Substate Transition Matrix (2/2)

- By similar calculations we obtain

$$
\begin{pmatrix} |\uparrow\ +1\rangle' \\ |\uparrow\ 0\rangle' \\ |\uparrow\ -1\rangle' \\ |\downarrow\ -1\rangle' \\ |\downarrow\ 0\rangle' \\ |\downarrow\ +1\rangle' \end{pmatrix}
=
\begin{pmatrix}
\frac{1}{2}\left(1+d_+^2\right) & & & & \frac{1}{2}\left(1-d_+^2\right) \\
 & \frac{1}{2}\left(1+d_-^2\right) & & \frac{1}{2}\left(1-d_-^2\right) & \\
 & & 1 & & \\
 & \frac{1}{2}\left(1-d_-^2\right) & & \frac{1}{2}\left(1+d_-^2\right) & \\
\frac{1}{2}\left(1-d_+^2\right) & & & & \frac{1}{2}\left(1+d_+^2\right)
\end{pmatrix}
\begin{pmatrix} |\uparrow\ +1\rangle \\ |\uparrow\ 0\rangle \\ |\uparrow\ -1\rangle \\ |\downarrow\ -1\rangle \\ |\downarrow\ 0\rangle \\ |\downarrow\ +1\rangle \end{pmatrix}
$$

- We are not interested in the electron spin.

  In the case that the orientation of the electron spin is random at t=0, by taking the average for the initial state and sum for the final state concerning the electron spin, we obtain

$$
\begin{pmatrix} |+1\rangle' \\ |0\rangle' \\ |-1\rangle' \end{pmatrix}
=
\begin{pmatrix}
\frac{1}{4}\left(3+d_+^2\right) & \frac{1}{4}\left(1-d_+^2\right) & 0 \\
\frac{1}{4}\left(1-d_+^2\right) & \frac{1}{4}\left(2+d_+^2+d_-^2\right) & \frac{1}{4}\left(1-d_-^2\right) \\
0 & \frac{1}{4}\left(1-d_-^2\right) & \frac{1}{4}\left(3+d_-^2\right)
\end{pmatrix}
\begin{pmatrix} |+1\rangle \\ |0\rangle \\ |-1\rangle \end{pmatrix}
$$

- When x=5/3, the matrix is

$$
D_{\mathrm{dep}} = \begin{pmatrix} 0.955 & 0.045 & 0 \\ 0.045 & 0.871 & 0.083 \\ 0 & 0.083 & 0.917 \end{pmatrix}
$$

Critical Magnetic Field

Calc. by H. Okamura

atom	state	calc. ν	calc. B_C	exp. ν	exp. B_C	μ_I/μ_N
^{1}H	$1s$	1422.586	508.204	1420.406	507.591	+2.7928
	$2s$	177.823	63.525	177.557	63.450	
^{2}H	$1s$	327.564	117.019	327.384	116.842	+0.8574
	$2s$	40.945	14.627	40.924	14.605	
^{3}H	$1s$	1517.387	542.071	1516.702	542.059	+2.9790
	$2s$	189.673	67.759	189.594	67.759	
^{3}He$^+$	$1s$	8669.430	3097.062			−2.1275
	$2s$	1083.679	387.133			
^{6}Li^{2+}	$1s$	8479.169	3029.093			+0.8220
	$2s$	1059.896	378.637			
		(MHz)	(Gauss)	(MHz)	(Gauss)	

Depolarization due to the electron spin resonance (ESR) effect

We take SHIVA as a model case.
If micro-wave with a power of 250W is applied in a (non-resonating) cylinder with a diameter of 72mm.

$$u = \frac{W}{\pi r^2 c} = 2.0 \times 10^{-10}\ \text{J/cm3}$$

$$B_1 = \sqrt{\mu_0 u} = 0.16\ \text{Gauss}$$

The thickness of the ESR region is

$$\Delta R = 4.0\ \mu m \quad \text{at } R = 5.0\text{cm (in axial direction)}$$

$$\Delta R = 0.9\ \mu m \quad \text{at } R = 1.9\text{cm (in radial direction)}$$

The effective thickness averaged for isotropic ion velocity distribution and averaged half-length between the ECR points are

$$L \cong \frac{4.0 + 0.9 \times 2}{3} \times \frac{1}{2}\left(1 + \ln \frac{2R}{\Delta R}\right) = 12\ \mu m$$

$$\overline{R} = \frac{1}{2}\,\frac{5.0 + 1.9 \times 2}{3} = 1.5\ cm$$

The spin rotation angle of the electron calculated with random-walk approximation is

$$\omega = \Delta\omega \times \sqrt{N} = \gamma_e B_1 \frac{L}{v} \times \sqrt{\frac{v}{\overline{R}}\tau_i} = 6.2 \times 10^{-2}\ \text{rad} = 3.6°$$

The nuclear depolarization is caused by the hyper-fine coupling between the electron and the nucleus.
Hence depolarization is negligible. Note that the calculation depends on the assumed plasma parameters.

Depolarization due to the inhomogeneous magnetic field

The *T1* relaxation is calculated by the following formula by Schearer et al., Phys. Rev. 139 (1965) A1398.

$$\frac{1}{T1} = \frac{2}{3}\frac{v^2}{\gamma_I^2 \tau_c H_0^4}\left(\frac{\partial H_y}{\partial y}\right)^2$$

For ions by putting the following numbers we obtain

$$\gamma_I = 3.94 \times 10^7\ \mathrm{rad}/s/T$$
$$\tau_c = 1.2 \times 10^{-6}\ \mathrm{sec}$$
$$v = 1.3 \times 10^6\ \mathrm{sec}$$
$$H_0 = 0.5T$$
$$\frac{\partial H_y}{\partial y} = 0.15T/\mathrm{cm}$$

$$T1 = 4.5\,\mathrm{msec\ for\ ions}$$

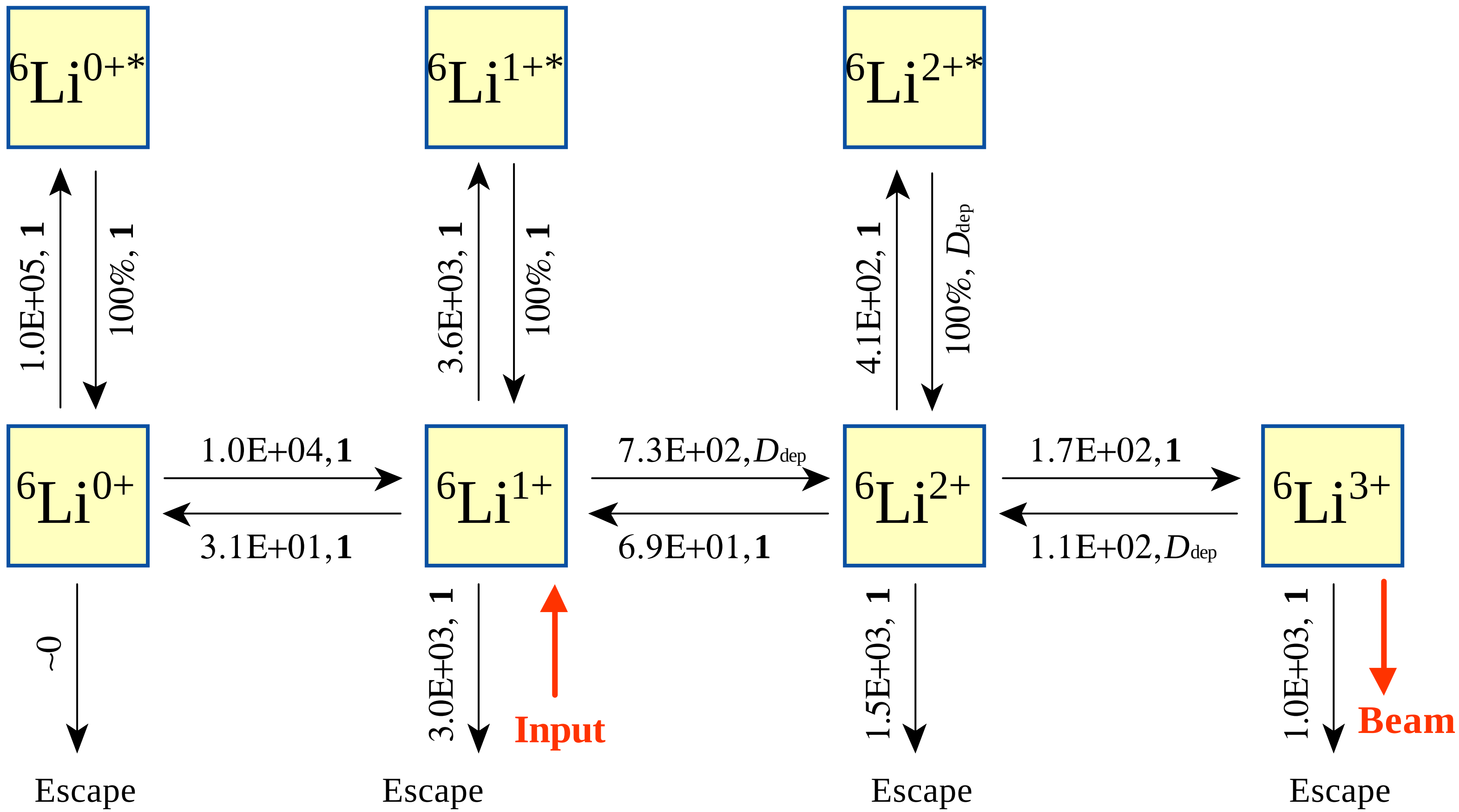
For neutral lithium atoms, by putting the numbers we obtain

$$\gamma_I = 3.94 \times 10^7\ \mathrm{rad}/s/T$$
$$\tau_c = 3.7 \times 10^{-5}\ \mathrm{sec}$$
$$v = 9.7 \times 10^4\ \mathrm{sec}$$
$$H_0 = 0.5T$$
$$\frac{\partial H_y}{\partial y} = 0.3T/\mathrm{cm}$$

$$T1 = 6.3\ \mathrm{for\ neutral\ atoms}$$

The *T1* relaxation time for ions has large depolarization effect when we consider the confinement time of $^{6}Li^{3+}$ (1 msec) and should be carefully taken care of.

Summary of the Processes in the ECR Ionizer



Results of the simulation

The result of the simulation is

$$P_{3+,escape} = \begin{pmatrix} 0.0165 & 0.0010 & 0.0000 \\ 0.0010 & 0.0148 & 0.0017 \\ 0.0000 & 0.0017 & 0.0157 \end{pmatrix} P_{1+,in}$$

The polarization of escaped 3+ ions when we feed 1+ ions with pure magnetic substate population is summarized as follows

Table 2: Calculated depolarization and efficiency for the $^6Li^{1+} \to {}^6Li^{3+}$ ionization in the ECR ionizer.

Initial State ($^6Li^{1+}$)			Final Sate ($^6Li^{3+}$)		
state	vector pol.	tensor pol.	vector pol.	tensor pol.	efficiency
pure $\|+1>$	1.00	1.00	0.94	0.84	0.017
pure $\|\ 0>$	0.00	-2.00	-0.05	-1.54	0.017
pure $\|-1>$	-1.00	1.00	-0.90	0.70	0.017

(by A. Tamii)

Note that depolarization due to the inhomogeneous magnetic field is not included in the present calculation.

Dependence on plasma parameters

Table 3: Calculated depolarization and efficiency for the $^6Li^{1+} \rightarrow {}^6Li^{3+}$ ionization in the ECR ionizer when the assumed confinement is increased by a factor of 10 (10 msec for $^6Li^{3+}$).

Initial State ($^6Li^{1+}$)			Final Sate ($^6Li^{3+}$)		
state	vector pol.	tensor pol.	vector pol.	tensor pol.	efficiency
pure $\|+1>$	1.00	1.00	0.86	0.68	0.23
pure $\|0>$	0.00	-2.00	-0.07	-1.14	0.23
pure $\|-1>$	-1.00	1.00	-0.79	0.46	0.23

Table 4: Calculated depolarization and efficiency for the $^6Li^{1+} \rightarrow {}^6Li^{3+}$ ionization in the ECR ionizer when the assumed neutral gas density increased by a factor of ten (1.44×10^{11} cm^{-3}).

Initial State ($^6Li^{1+}$)			Final Sate ($^6Li^{3+}$)		
state	vector pol.	tensor pol.	vector pol.	tensor pol.	efficiency
pure $\|+1>$	1.00	1.00	0.94	0.83	0.007
pure $\|0>$	0.00	-2.00	-0.05	-1.53	0.007
pure $\|-1>$	-1.00	1.00	-0.90	0.70	0.007

(by A. Tamii)

Feasibility tests at RIKEN

1. **Basic information by laser ablation method with the 18GHz superconducting ECR ion source**

   measurements of confinement times and ionization efficiencies

   parameters: mirror ratio, neutral gas density, RF power

2. **Measurements by injecting $^{6}Li^{1+}$ ions into the ECR plasma**

   parameters: deceleration voltage

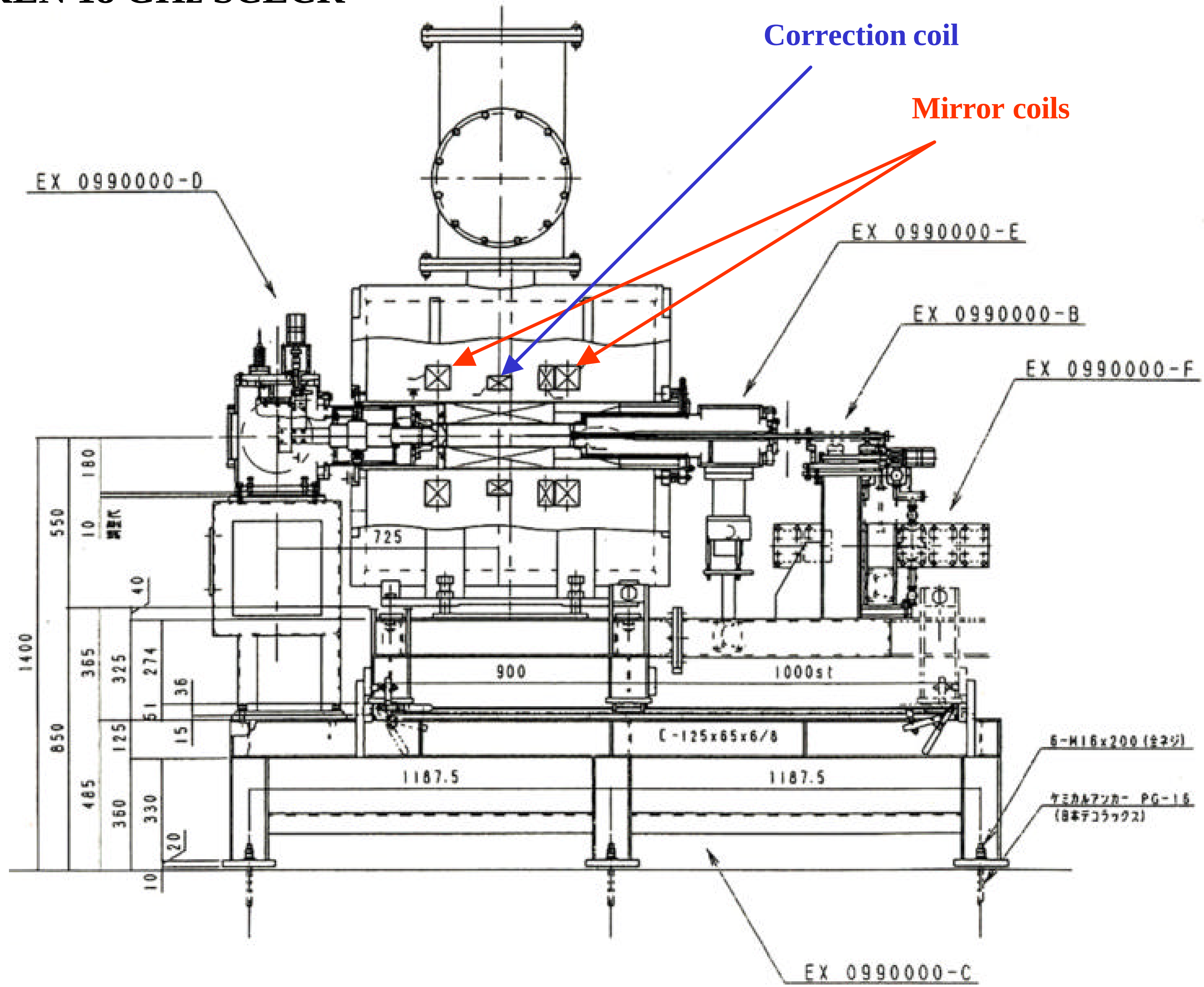
3. **Polarization measurements of $^{6}Li^{3+}$ ions**

   $^{2}H(^{6}Li,a)^{4}He$ reaction at low energy
   Q=22.372 MeV

   $A_{yy}[^{6}Li(d,a)^{4}He] = A_{yy}[^{2}H(^{6}Li,a)^{4}He]$ ~ 0.5 at 0 deg.

   → **$A_{zz} = -1$**

RIKEN 18 GHz SCECR



F. Seiler, NP A286 (1977) 1

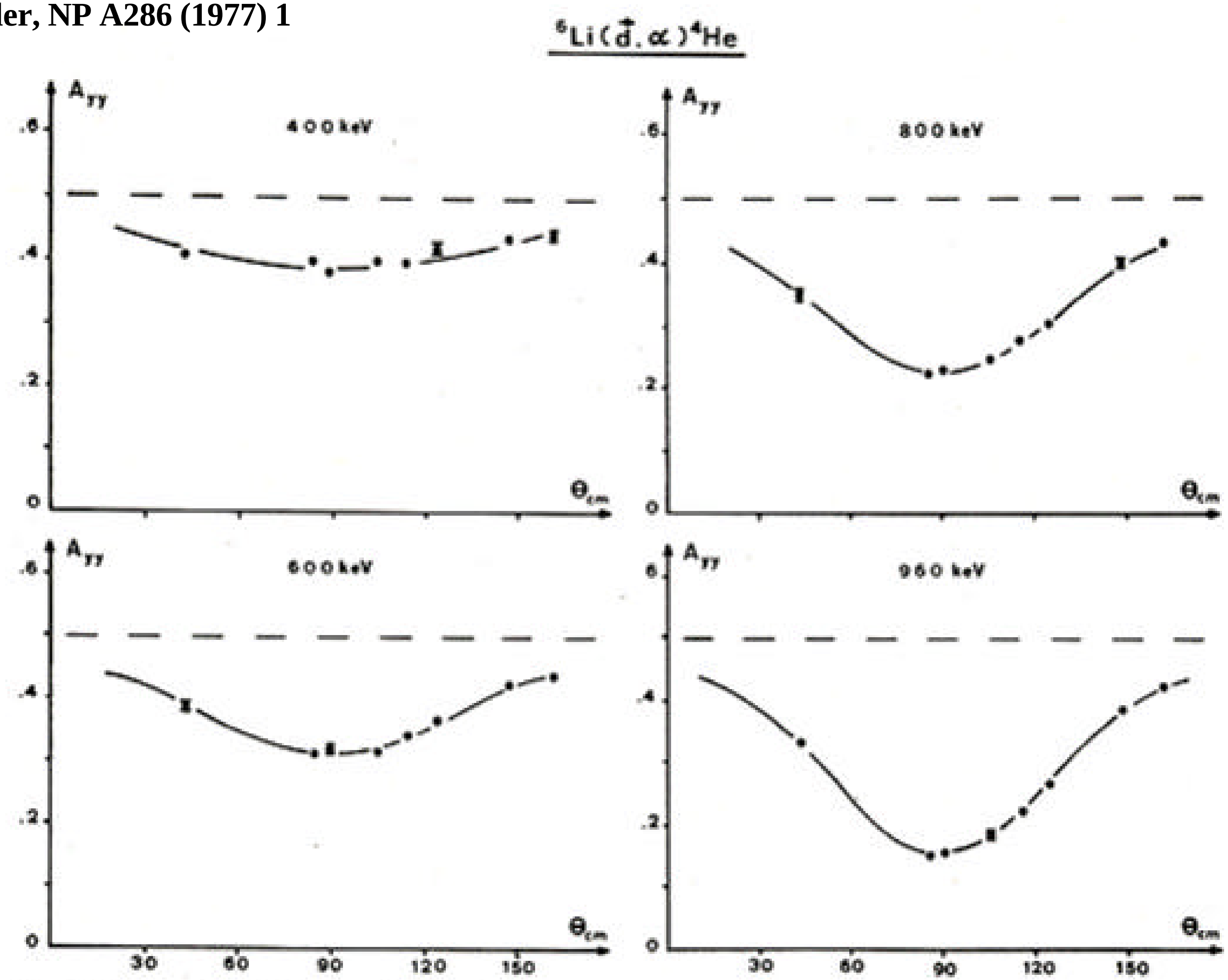


Fig. 3. Values of $A_{yy}(\theta)$ for the ^{6}Li($\vec{d}$, α)^{4}He reaction. The data plotted were computed from the measurements of Neff and collaborators [17]). The symmetry of the solid curves reflects the symmetries imposed by the presence of two identical bosons in the outgoing channel. Where the errors are not shown, they are smaller than the dot. The solid curve is drawn merely to guide the eye.

For reactions with spin-parity: $1^+ + 1^+ \rightarrow 0^+ + 0^+$,

$$\langle 00|T|+1\,+1\rangle = \langle 00|T|-1\,-1\rangle = A$$
$$\langle 00|T|0\,+1\rangle = -\langle 00|T|0\,-1\rangle = B$$
$$\langle 00|T|-1\,+1\rangle = \langle 00|T|+1\,-1\rangle = C$$
$$\langle 00|T|+1\,0\rangle = -\langle 00|T|-1\,0\rangle = D$$
$$\langle 00|T|0\,0\rangle = E$$

$$\sigma A_{yy}\left[{}^2H\left({}^6Li,\alpha\right){}^4He\right] = Tr\left(T^+ P^{Li}_{yy} T\right)$$
$$= Tr\left[\begin{pmatrix} A^* & B^* & C^* \\ D^* & E^* & -D^* \\ C^* & -B^* & A^* \end{pmatrix} \frac{1}{2}\begin{pmatrix} -1 & 0 & -3 \\ 0 & 1 & 0 \\ -3 & 0 & -1 \end{pmatrix} \begin{pmatrix} A & D & C \\ B & E & -B \\ C & -D & A \end{pmatrix}\right]$$
$$= -|A|^2 - 3\,\Im\left(AC^*\right) + 2|B|^2 - |C|^2 + 2|D|^2 + |E|^2$$
$$= Tr\left[\begin{pmatrix} A^* & D^* & C^* \\ B^* & E^* & -B^* \\ C^* & -D^* & A^* \end{pmatrix} \frac{1}{2}\begin{pmatrix} -1 & 0 & -3 \\ 0 & 1 & 0 \\ -3 & 0 & -1 \end{pmatrix} \begin{pmatrix} A & B & C \\ D & E & -D \\ C & -B & A \end{pmatrix}\right]$$
$$= Tr\left(T^+ P^{d}_{yy} T\right) = \sigma A_{yy}\left[{}^6Li\left(d,\alpha\right){}^4He\right]$$

At 0 deg., from rotational invariance

$$\langle 00|\left[T,J_z\right]|M_a M_A\rangle = 0 - (M_a + M_A)\langle 00|T|M_a M_A\rangle = 0$$

$\langle 00|T|M_a M_A\rangle = 0$ **if** $M_a + M_A \neq 0$ **, then** $A = B = D = 0$

$$A_{zz}\left[{}^2H\left({}^6Li,\alpha\right){}^4He\right]\left(0^\circ\right) = \frac{2\left(|C|^2 - |E|^2\right)}{2|C|^2 + |E|^2}$$

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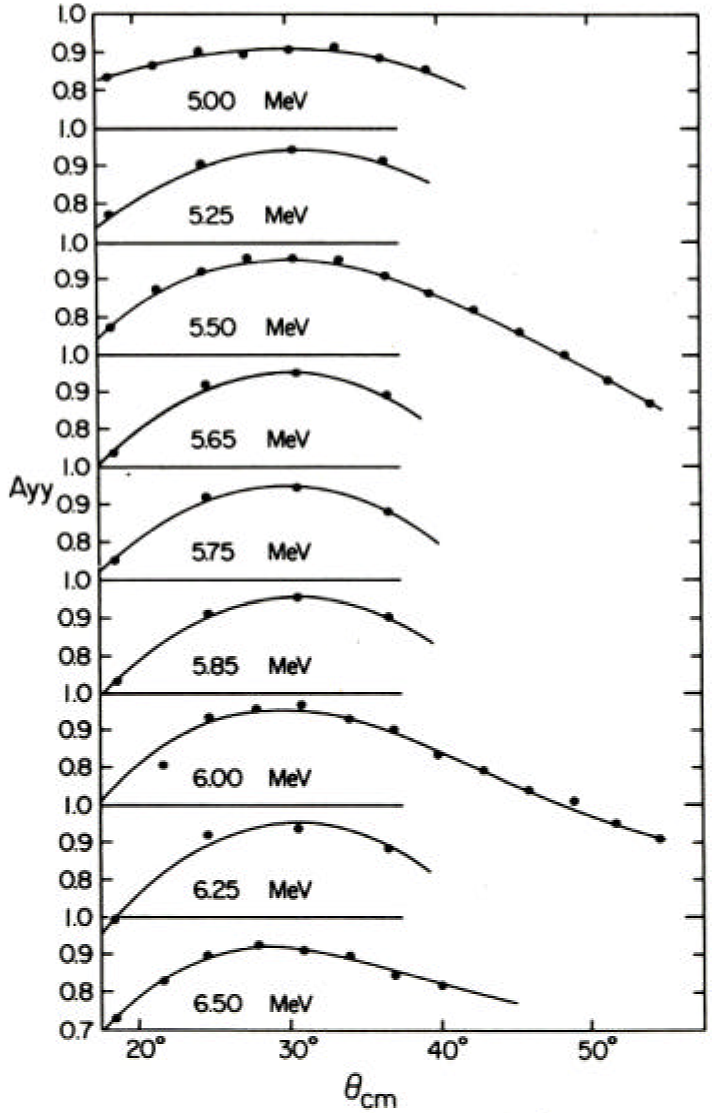

Fig. 1. The tensor analysing power A_{yy} between 5.0 and 6.5 MeV. The statistical errors are smaller than the dot size. The curves are polynomial fits.

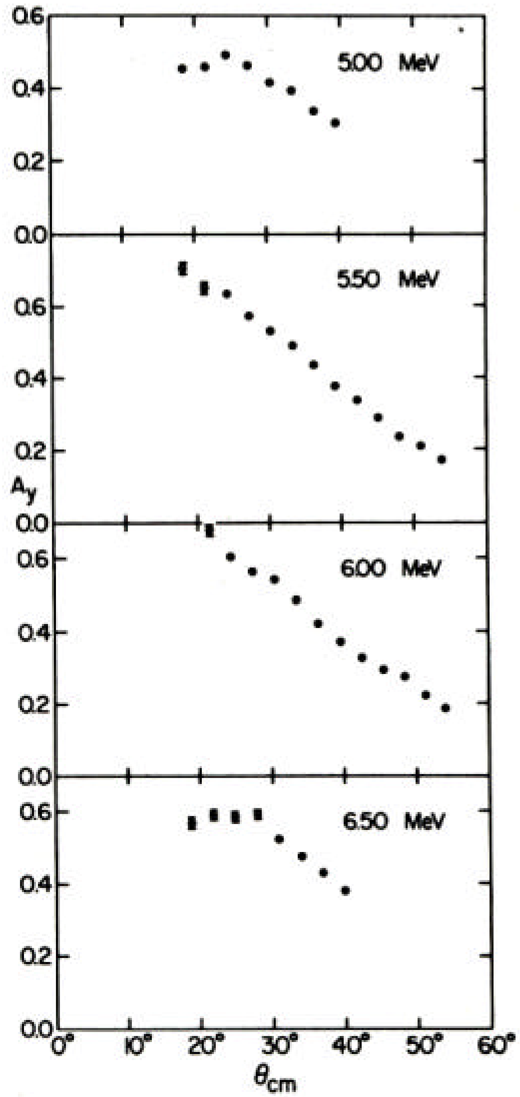

Fig. 2. The vector analysing power A_y between 5.0 and 6.5 MeV. The statistical errors are smaller than the dot size.

Budget request

First step		**0**
Second step	**Li oven**	**2,000,000**
	accelerating system	**1,000,000**
	electro-static lenses, insulations	**1,000,000**
	Subtotal	**4,000,000**
Third step	**diode lasers (x2)**	**8,000,000**
	optical components	**2,500,000**
	Subtotal	**10,500,000**
	Total	**14,500,000**