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

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Physics Motivation

- Study of the nuclear structure by the (^{6}Li, ^{6}He) Reaction
  - Selective excitation of ΔT=1, ΔS=1
  - Tensor analyzing power at 0 °

    → Selectivity for the 0^-,1^-, and 2^- states
  - High resolution measurement by dispersion matching

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

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

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

- Max Plank Institute, Heidelberg

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

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

- Florida State University

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

- Saturne

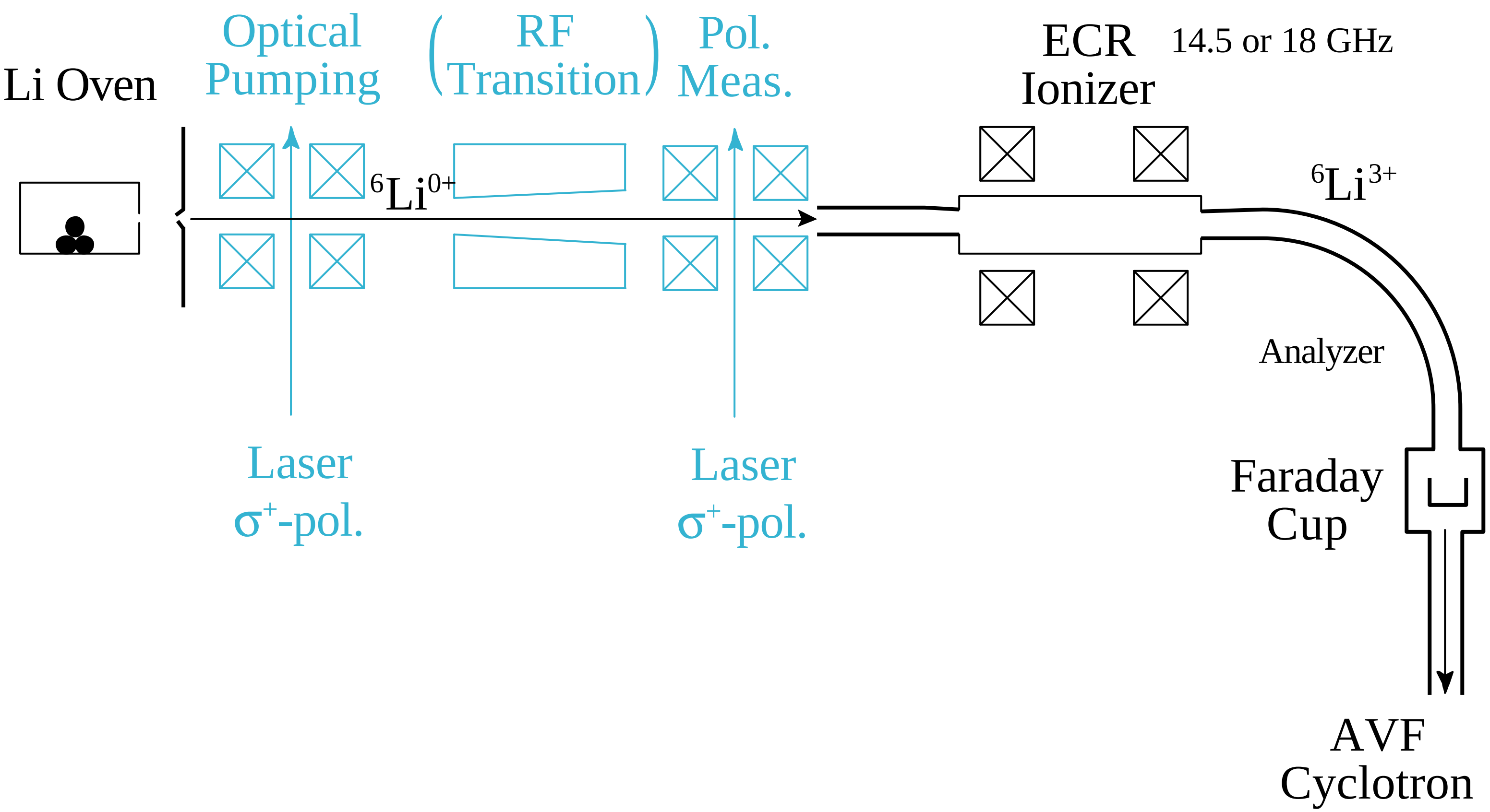
  Optical Pumping + Surface Ionizer (+ EBIS+Accum. Ring+Synchrotron)

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

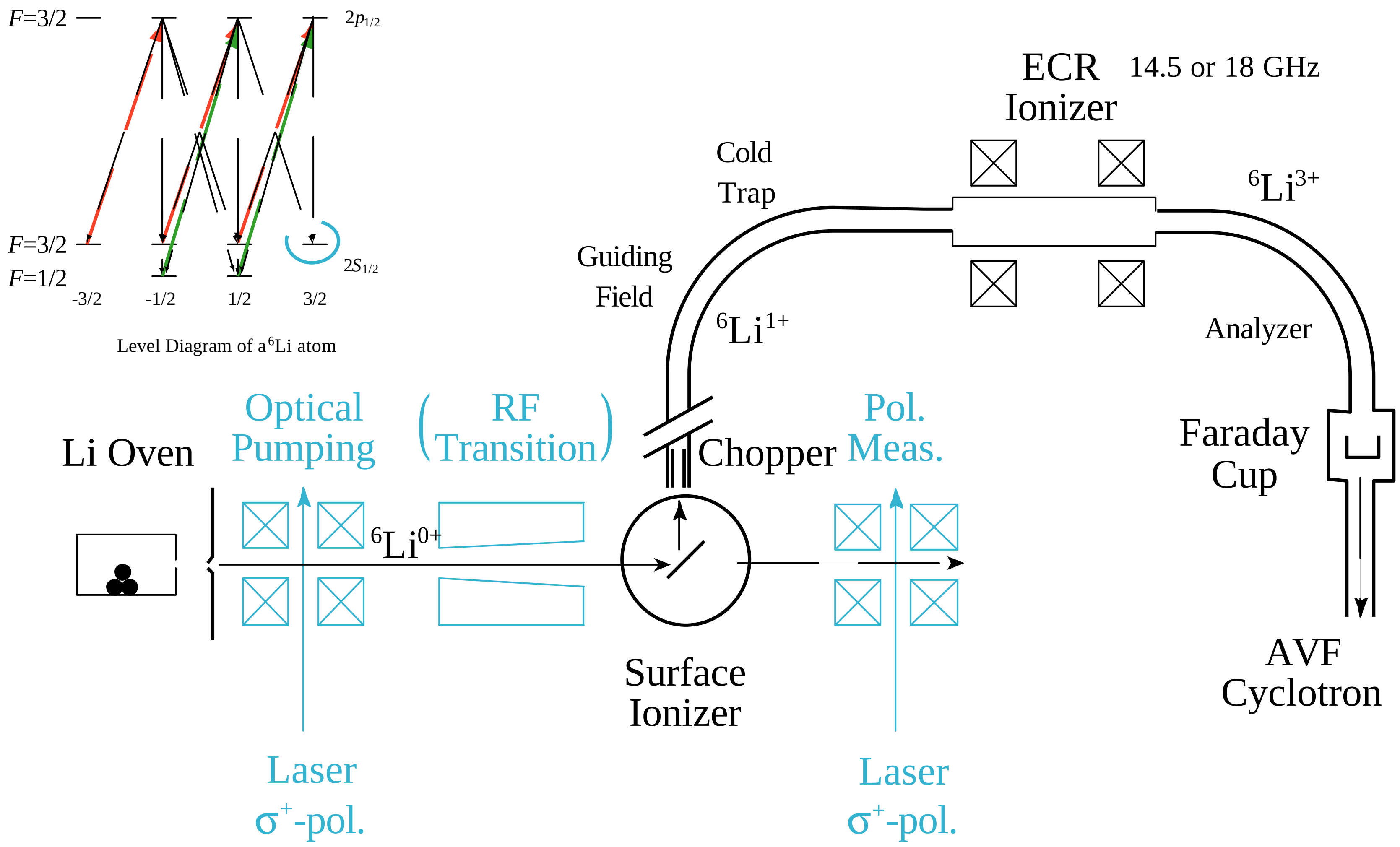
  $^6Li^{3+}$: 7×10^8 particles/spill

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

Plan of the polarized ^{6}Li ion source (I)



Plan of the polarized ^{6}Li ion source (II)



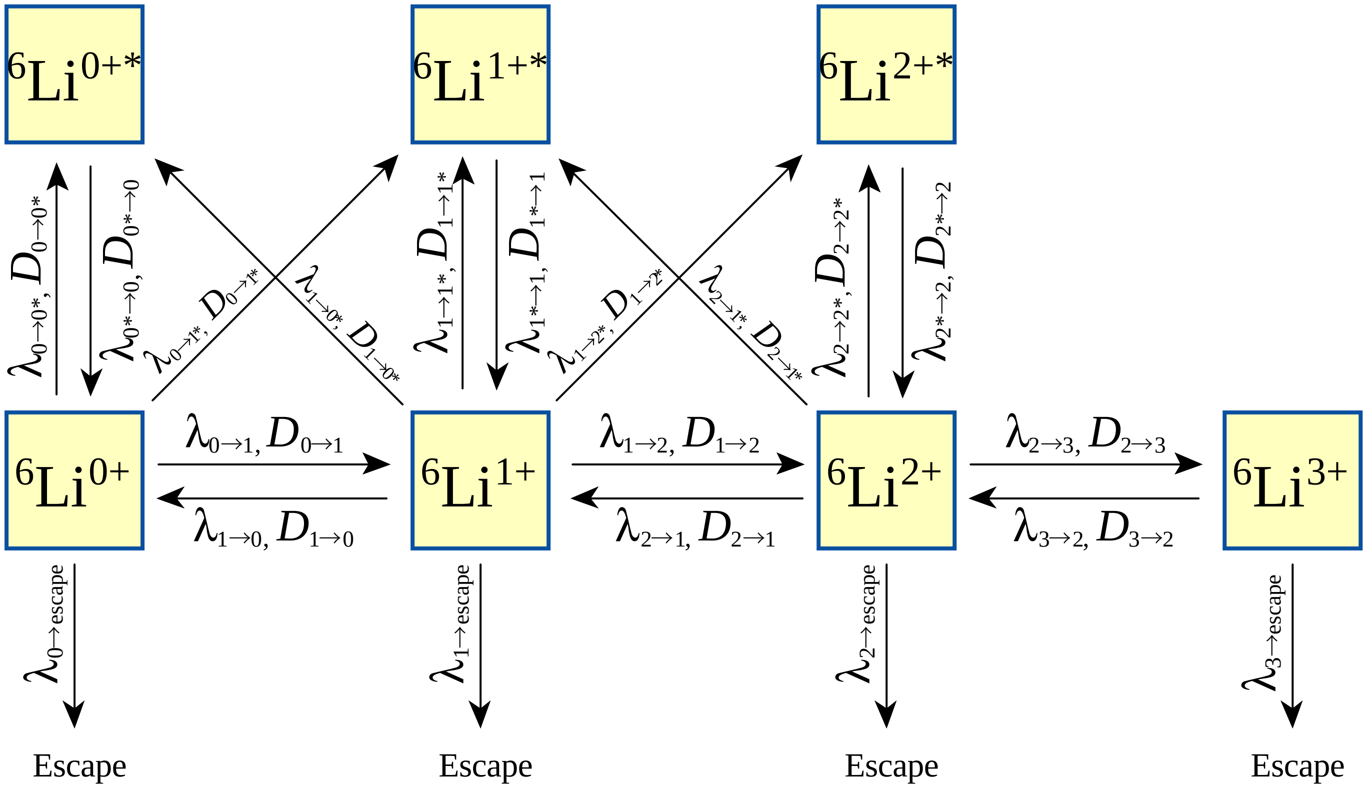
^{6}Li^{1+}: 20-30mA

Pol. 80-90%

Simulation of the Depolarization in the ECR Ionizer

(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}]

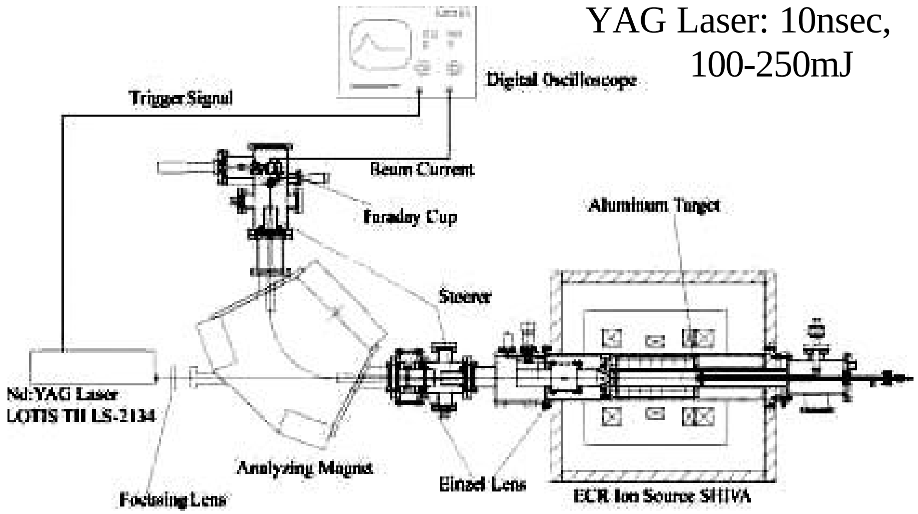
$D_{i\to j}$: Transition Matrix of Magnetic Substates from i to j ($0 \leqq D_{ji} \leqq 1$)

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



Buffer Gas: Oxygen

RF Power: 250 W

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

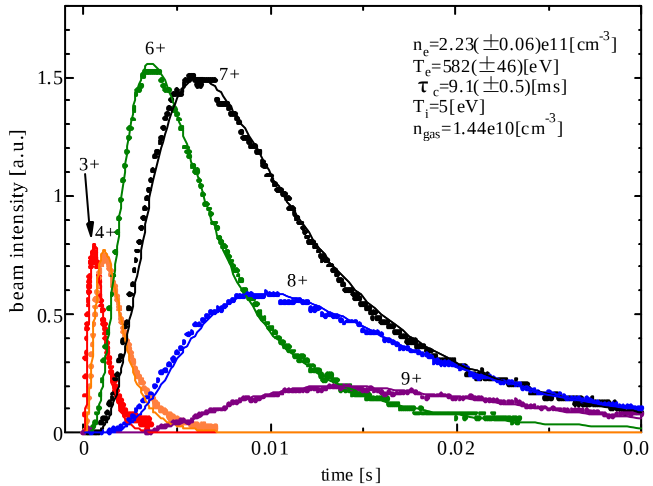
Ion Temperature (T_i) : 5 eV

Ionization Rate: Voronov's empirical Fit

Charge Exchange Rate: Muller and Saltzborn

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

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



Magnetic-Substate Transition Matrix (1/2)

(according to the calc. of 3He 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

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

$$\sin b_\pm \equiv \sqrt{\frac{1}{2}(1+d_\pm)} \qquad \cos b_\pm \equiv \sqrt{\frac{1}{2}(1-d_\pm)}$$

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

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

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

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

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

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

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

Magnetic-Substate Transition Matrix (2/2)

- By similar calculations we obtain

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

- 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

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

- 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.

$$u = \frac{W}{pr^2c} = 2.0\times10^{-10}\,\mathrm{J/cm3}$$

$$B_1 = \sqrt{m_0 u} = 0.16\,\mathrm{Gauss}$$

The thickness of the ESR region is

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

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

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

$$L \cong \frac{4.0 + 0.9\times2}{3}\times\frac{1}{2}\left(1+\ln\frac{2R}{\Delta R}\right) = 12\,mm$$

$$\overline{\mathrm{R}} = \frac{1}{2}\,\frac{5.0+1.9\times2}{3} = 1.5\,cm$$

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

$$w = \Delta w\times\sqrt{N} = g_e B_1 \frac{L}{v}\times\sqrt{\frac{v}{\overline{R}}t_i} = 6.2\times10^{-2}\,\mathrm{rad} = 3.6^\circ$$

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.

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

For ions by putting the following numbers we obtain

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

$$T1 = 4.5 \text{ msec for ions}$$

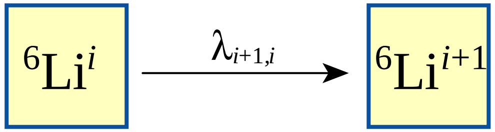
For neutral lithium atoms, by putting the numbers we obtain

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

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

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

Ionization Rate by Electron Impact



Voronov's empirical fit

G.S. Voronov, Atom. Data and Nucl. Data Tables 65 (1997)1.

$$c_{i\to i+1} = \langle s v_e \rangle = A \frac{1 + P U^{1/2}}{X + U} U^K e^{-U} \quad [\mathrm{cm^3 s^{-1}}]$$

$$U = \frac{I_i}{T_e}$$

I_i: Ionization Energy

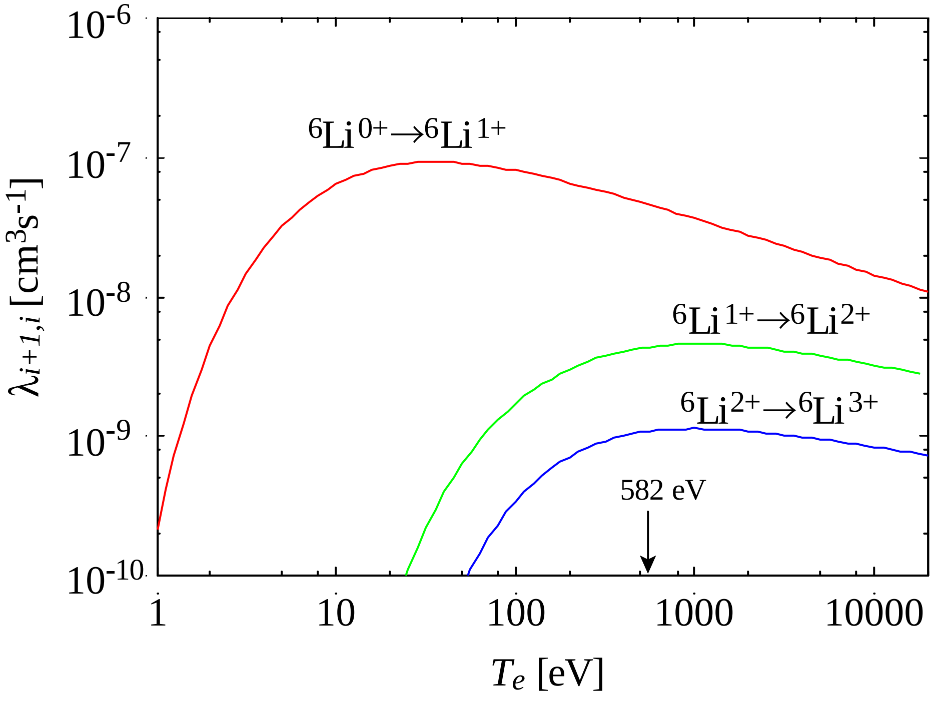
T_e: Electron Temperature

A, P, X, K: Fitting Parameters

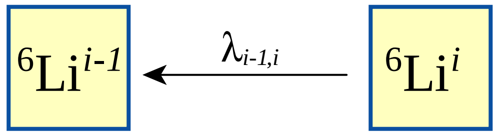
$^6Li^{0+} \longrightarrow {}^6Li^{1+}$: 4.52×10^{-8} cm^{3}s^{-1}
$^6Li^{1+} \longrightarrow {}^6Li^{2+}$: 3.26×10^{-9} cm^{3}s^{-1}
$^6Li^{2+} \longrightarrow {}^6Li^{3+}$: 7.53×10^{-10} cm^{3}s^{-1}

$$l_{i\to i+1} = c_{i\to i+1} n_e$$

n_e: 2.23×10^{11} cm^{-3}



Charge Exchange Reaction Rate with the Neutral Gas



Muller and Saltzborn Empirical Fit

A. Muller and E. Saltzborn, Phys. Lett. A62 (1977) 391.

$$s = 1.43 \times 10^{-12} i^{1.17} I_{gas}^{-2.76} \quad [\mathrm{cm}^2]$$

$$z_{i \to i-1} = \langle s v_i \rangle = 3.15 \times 10^{-6} i^{1.17} I_{gas}^{-2.76} \sqrt{\frac{T_i}{A_i}} \quad [\mathrm{cm}^3 \mathrm{s}^{-1}]$$

I_{gas}: Ionization Energy of the Neutral Gas (Oxygen: 13.6 eV)

T_i: Ion Temperature (5 eV)

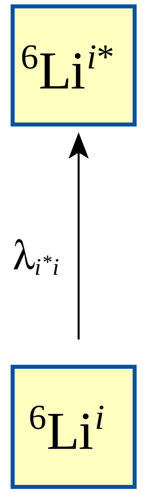
A_i: Ion Mass in AMU

$^{6}Li^{1+} \rightarrow {}^{6}Li^{0+}$: 2.14×10^{-9} cm^{3}s^{-1}
$^{6}Li^{2+} \rightarrow {}^{6}Li^{1+}$: 4.81×10^{-9} cm^{3}s^{-1}
$^{6}Li^{3+} \rightarrow {}^{6}Li^{2+}$: 7.72×10^{-9} cm^{3}s^{-1}

$$l_{i \to i-1} = V_{i \to i-1} n_{gas}$$

n_{gas}: 1.44×10^{10} cm^{-3}

Atomic Excitation Rate by Electron Impact (1/2)



- $^6Li^{0+} \longrightarrow {}^6Li^{0+*}$ 2s→2p (including cascade)

  D. Leep and A. Gallagher, Phys. Rev. A 10 (1974) 1082.

  $s \sim 3.5 p a_0^2 = 3.1 \times 10^{-16}$ [cm^2] at $T_e \sim 600$ eV

  $s v_e = 4.5 \times 10^{-7}$ [cm^{3}s^{-1}] $l_{0 \to 0^*} = s v_e n_e$

  a factor of ~10 larger than the ionization rate coefficient

- $^6Li^{1+} \longrightarrow {}^6Li^{1+*}$ 1s→2p

  assume that a factor of ~5 larger than the ionization rate coefficient

$s v_e = 1.6 \times 10^{-8}$ [cm^{3}s^{-1}] $l_{1 \to 1^*} = s v_e n_e$

Atomic Excitation Rate by Electron Impact (2/2)

- $^{6}Li^{2+} \rightarrow {}^{6}Li^{2+*}$ 1s→2p

  Fisher *et al.*, Phys. Rev. A 55 (1997) 329.

  Empirical fit of 1s→2p excitation cross sections of hydrogen-like atoms

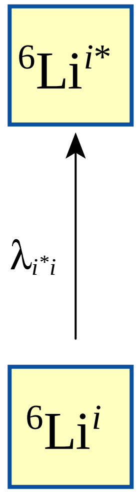
  $$\sigma \sim 1.0\pi a_0^2 Z_i^{-4} = 1.1\times10^{-18} \quad [\mathrm{cm}^2]\ \mathrm{at}\ T_e \sim 550\,\mathrm{eV}$$

  $$\sigma v_e = 1.6\times10^{-9} \quad [\mathrm{cm^3 s^{-1}}] \qquad \lambda_{2\rightarrow 2^*} = \sigma v_e n_e$$

  Summing up transitions 1s→2,…,6 and taking the Boltzmann distribution

  $$\langle \sigma v_e \rangle = 1.82\times10^{-9} \quad [\mathrm{cm^3 s^{-1}}]$$

  a factor of ~2 larger than the ionization rate coefficient



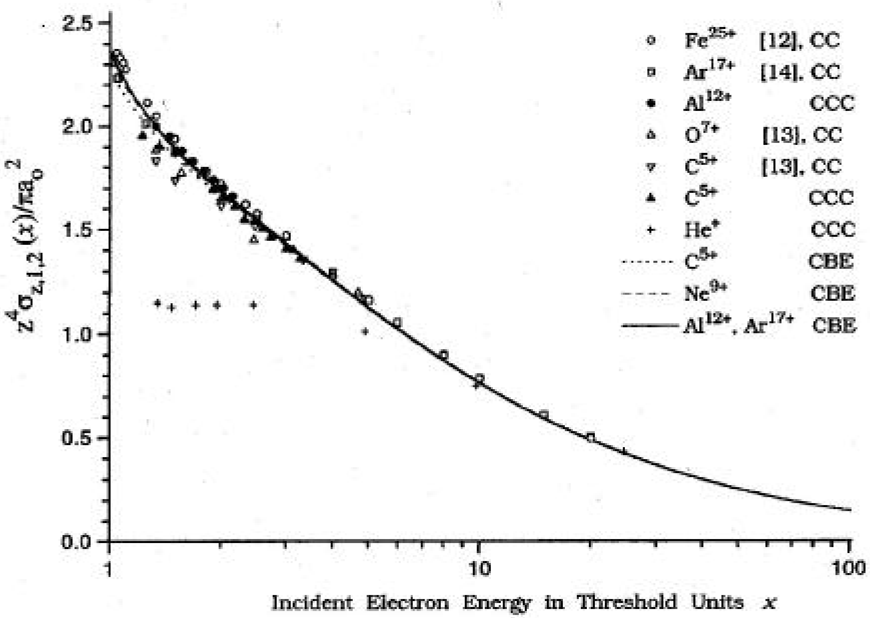


FIG. 3. Cross sections for transition 1→2 in hydrogenlike ions with $z = 2$–26.

Confinement Time of The Ions

- It is very difficult to estimate the confinement time of ions in an ECR plasma.

  If we assume (M.Imanaka, PhD Thesis; Shirkov, CERN/PS 94-13)

  $$t_i \propto i\sqrt{A_i}$$

  and scale the value of τ_{3+}=2.3msec, which was fitted to the Al data,

  $$t_{1+} = 0.33[\text{ms}]$$
  $$t_{2+} = 0.66[\text{ms}]$$
  $$t_{3+} = 0.99[\text{ms}]$$

  $$l_i = t_i^{-1}$$

$^{6}\text{Li}^{i}$

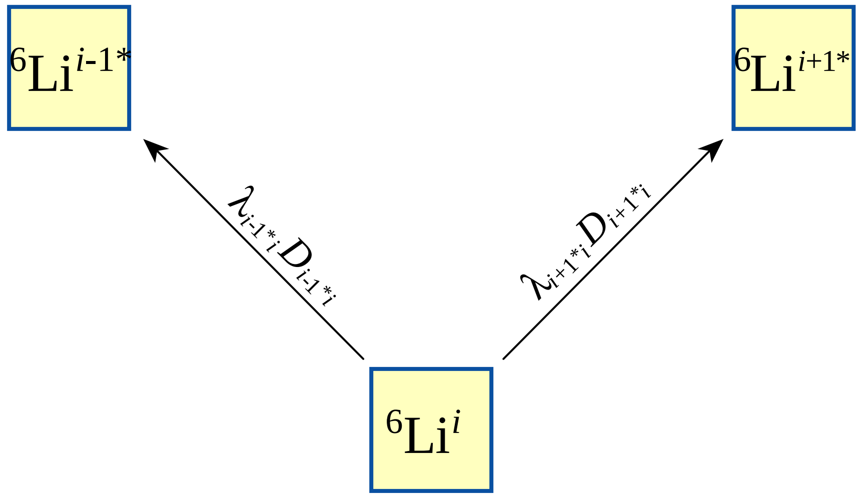
λ_i ↓

escape

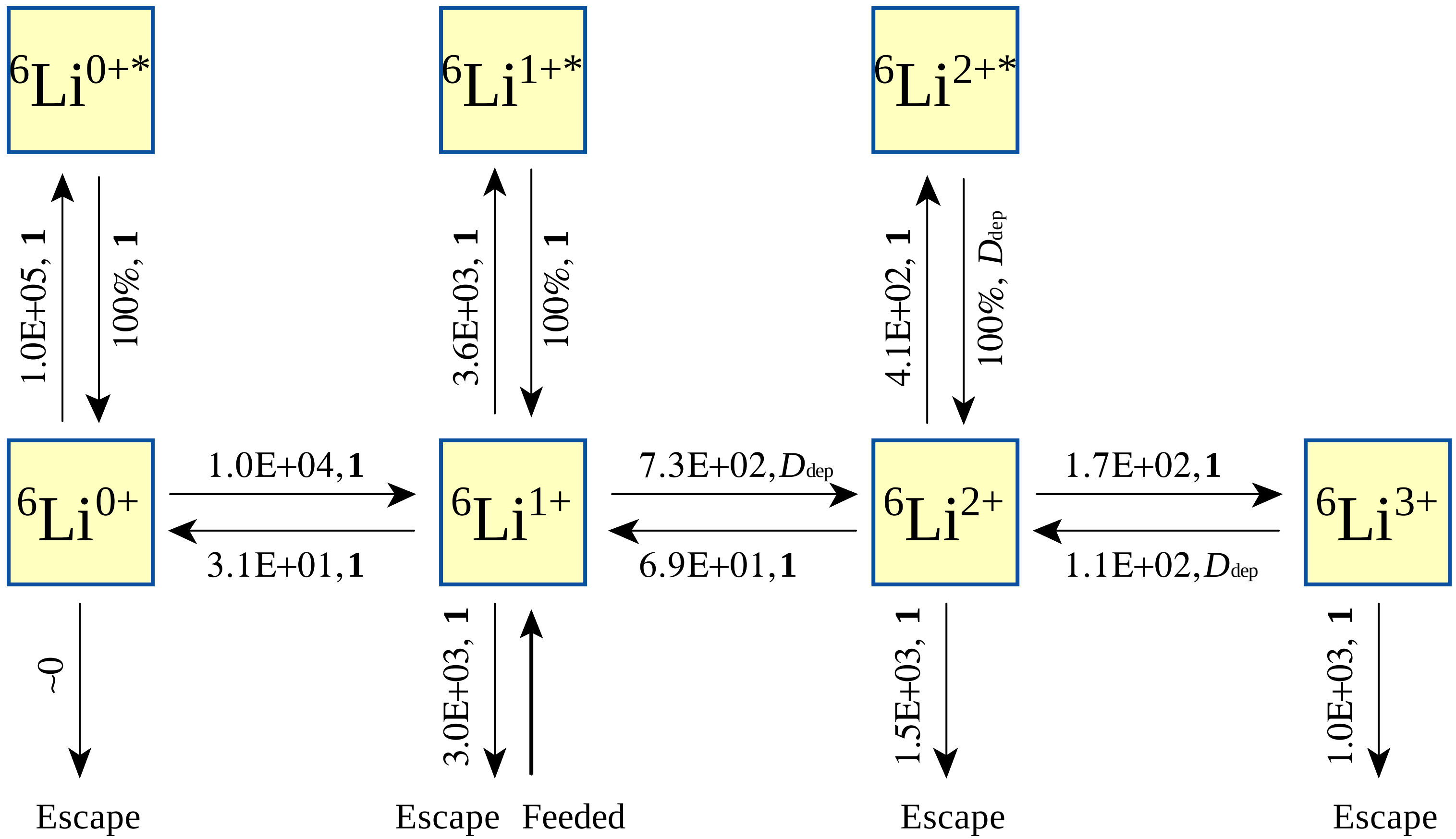
Other processes

Inelastic Ionization and Radiative Capture Processes

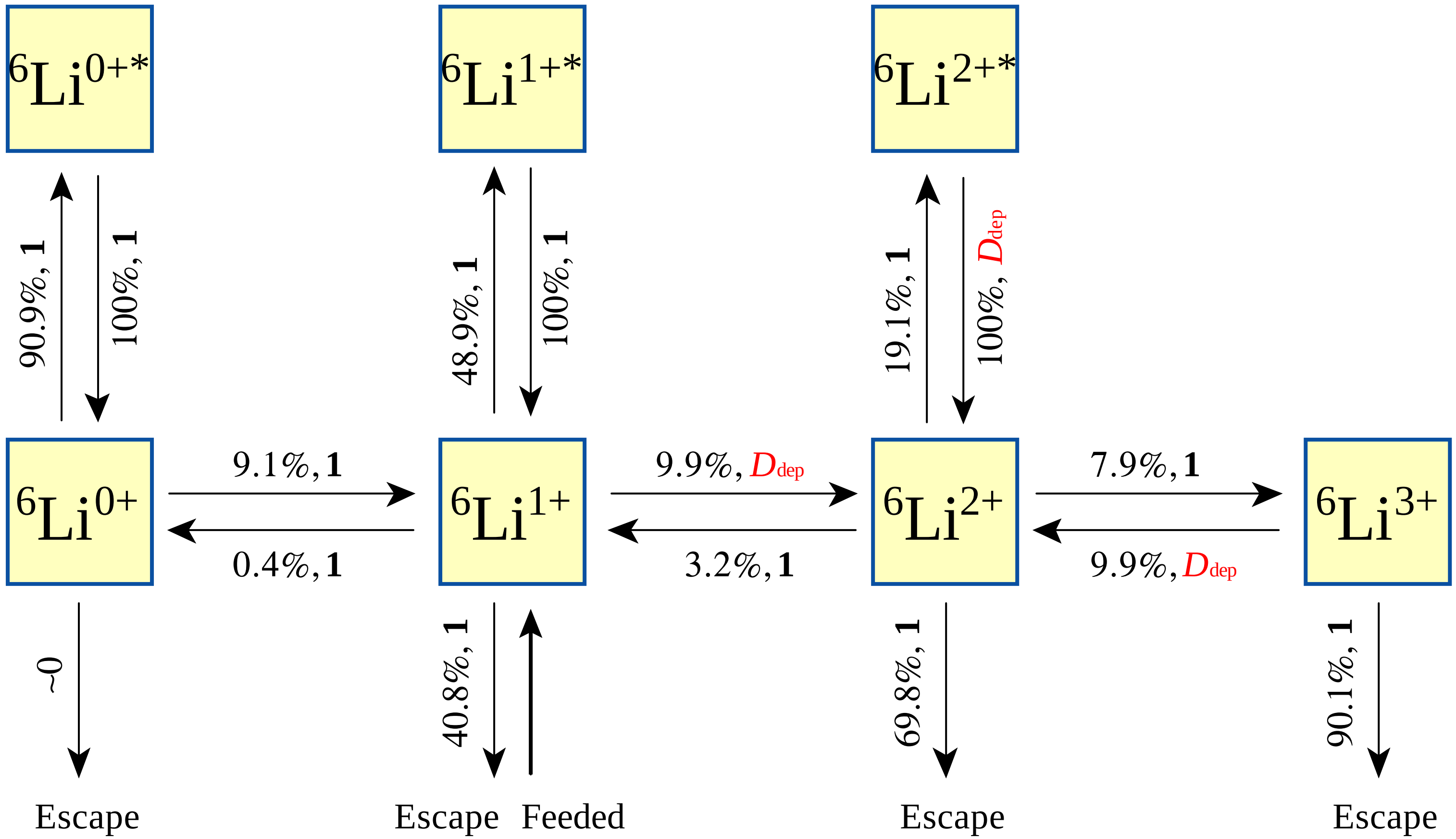
In the present calculation, these processes has no (or negligible) effect.



Summary of the Processes in the ECR Ionizer



Summary of the Processes in the ECR Ionizer



Results of the simulation

The result of the simulation is

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

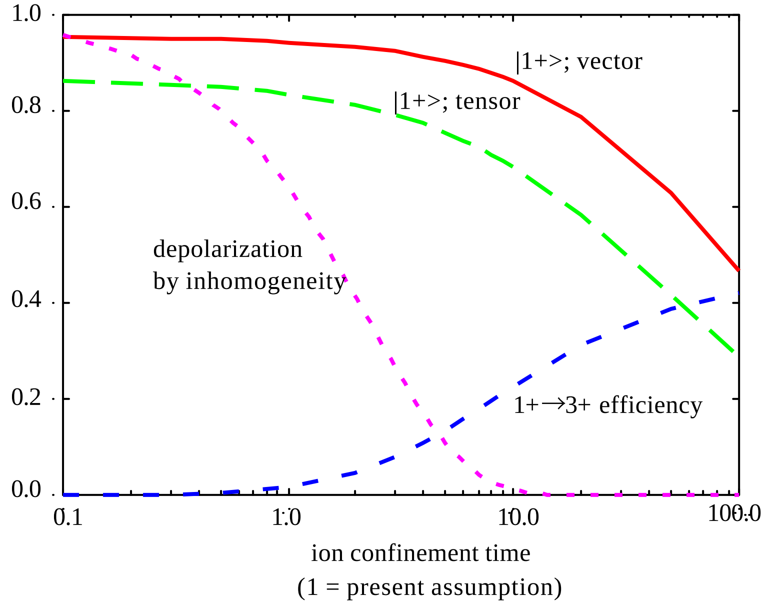
The polarization of escaped 3+ ions when we feed 1+ ions with pure magnetic substate population is summarized as follows

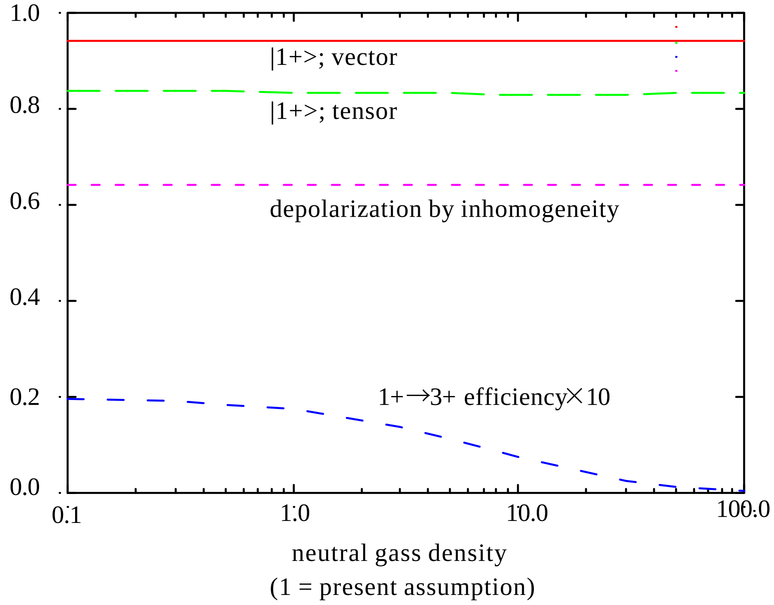
Table 2: Calculated depolarization and efficiency for the $^6Li^{1+} \to {}^6Li^{3+}$ ionization in the ECR ionizer.

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

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

Result of the simulation
(parameter dependence)





Polarization of the extracted beam from the ECR ionizer is approximately expressed as

(initial polarization) × (vector/tensor polarization in the figure) × (depolarization by inhomogeneity in the figure)

Ionization efficiency in the ECR ionizer is expressed as

(efficiency of feeding ions/atoms into the plasma) × (1+ →3+ efficiency in the figure) × (extraction efficiency)

Feasibility Test Plan

- Study of confinement time and ionization efficiency of Li is planed by using the 18GHz superconducting ECR ion source at RIKEN and the laser abration method.

- Optimization of the plasma condition:

  Mirror ratio, neutral gas density, RF power

- Development of the Li-oven, surface ionizer for testing the beam current.

- Laser pumping system for testing the polarization of the $^{6}Li^{3+}$ beam

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- Further simulation with more realistic parameters is required.