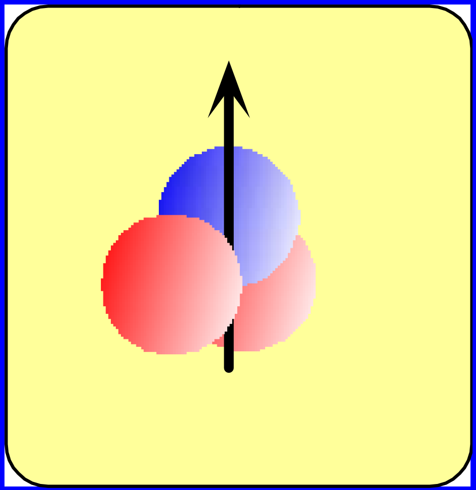
Development of polarized ^{3}He ion source and a design for practical use



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    a) Collaborators
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3) EPPIS (Electron pumping polarized ion source)

4) SEPIS (Spin-exchange polarized ion source)

5) Future plan

Collaborators

1. **RCNP, Osaka Univ:**
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   K. Abe, K. Katori, T. Ohshima

3. **Dept. Physics, Konan Univ.:**
   T. Takeuchi, Y. Yamamoto, T. Yamagata, K. Yonehara,

4. **Dept. Physics, Tokushima Univ.:**
   S. Nakayama

5. **Dept. Chemistry, Niigata Univ.:**
   N. Shimakura

6 **Dept. Physics, Wisconsin Univ., Madison, USA**
   L.W. Anderson

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   R. Morgenstern

8. **Dubna, Moscow, Russia:**
   Yu. Plis

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   A. Zelenski, C.P. Levy

10. **Centre d'Etudes Nucleaires de Grenoble, France:**
    R. Geller, G. Melin

11. **Dept. Physics, Sungkyunkwan Univ., Korea:**
    B. T. Kim

12. **Dept. Physics, Univ. Texas, USA:**
    T. Udagawa

13. **Kobe Tokiwa, Kobe:**
    M. Tanaka

13 Institutes
24 Participants

A List of refereed papers showing our activity on the development of polarized ^{3}He ion source at RCNP

[1] M. Tanaka et al., Colloque de Physique **C6** (1990).

[2] M. Tanaka et al., Phys. Rev. **A41** (1990) 496.

[3] M. Tanaka et al. , Nucl. Instr. & Meth. **A302** (1991) 460.

[4] T. Ohshima et al., Phys. Lett. **B279** (1992) 163.

[5] M. Tanaka et al., Hyperfine Interactions **74** (1992) 205.

[6] M. Tanaka et al., Hyperfine Interactions **78** (1993) 251.

[7] M. Tanaka et al., Phys. Rev. **A50** (1994) 1184.

[8] M. Tanaka et al., Phys. Rev. **A52** (1995) 392.

[9] T. Yamagata et al., Nucl. Instr. Meth. **A402** (1998) 199.

[10] M. Tanaka, Nucl. Instr. Meth. **A402** (1998) 492.

[11] T. Takeuchi et al., Rev. Sci. Instr. **69** (1998) 412.

[12] M. Tanaka et al., Phys. Rev **A60** (1999) R3354.

[13] Y. Arimoto et al, Eur. Phys. J. **D8** (2000) 305.

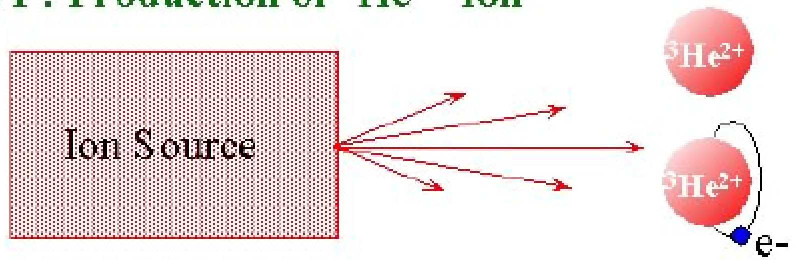
[14] Y. Arimoto et al., Nucl. Instr. Meth. B173 (2001) 370.

[15] K. Yonehara et al., Nucl. Instr. Meth. B184 (2001) 391

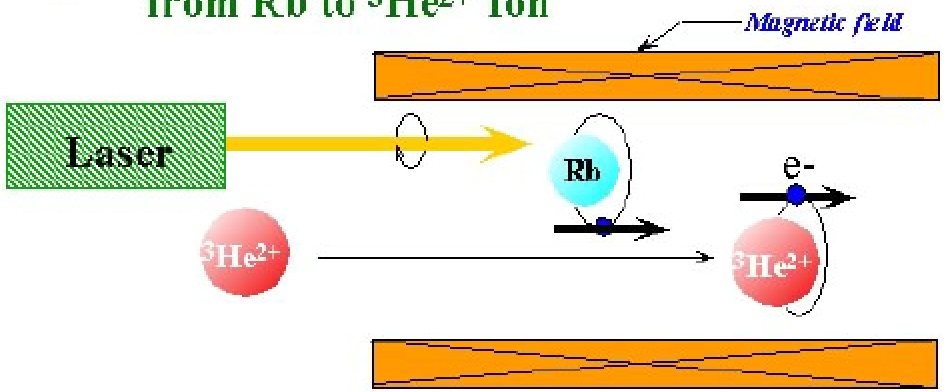
[16] Y. Arimoto et al. Phys. Rev. A64 (2001) 062714-1.

Principle of OPPIS applied for Polarization of ^3He

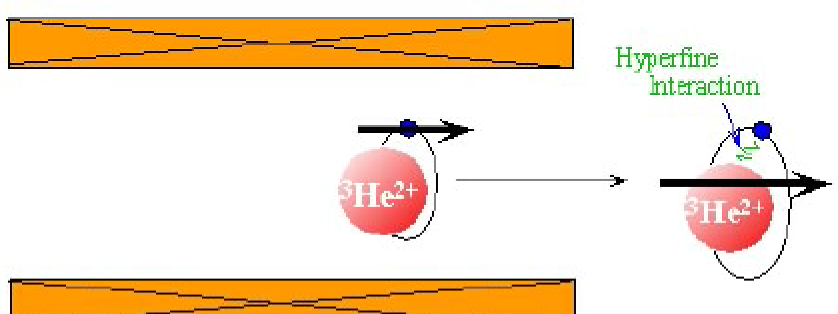
Step I : Production of $^3He^{2+}$ Ion

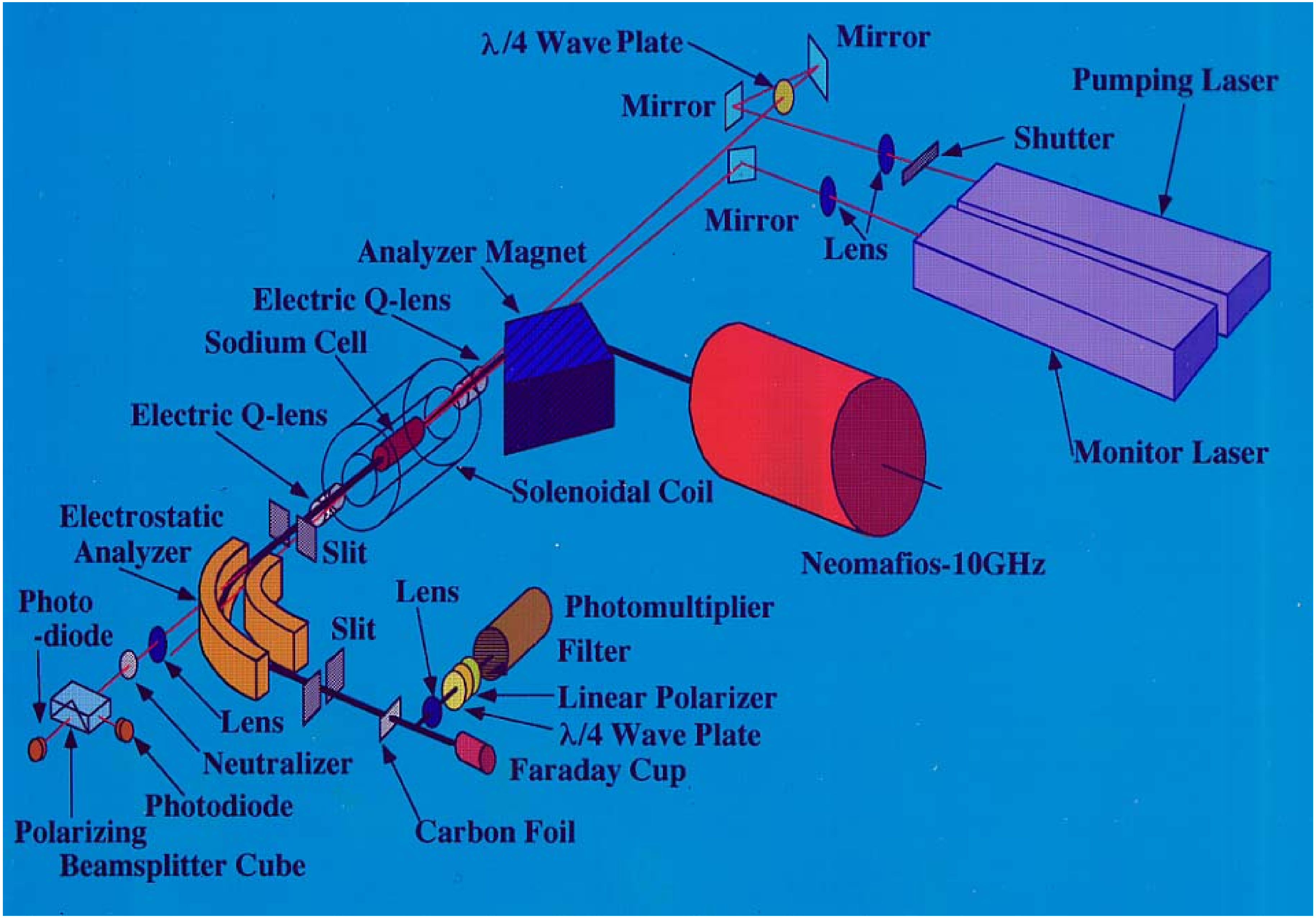


Step II : Polarized Electron transfer from Rb to $^3He^{2+}$ Ion

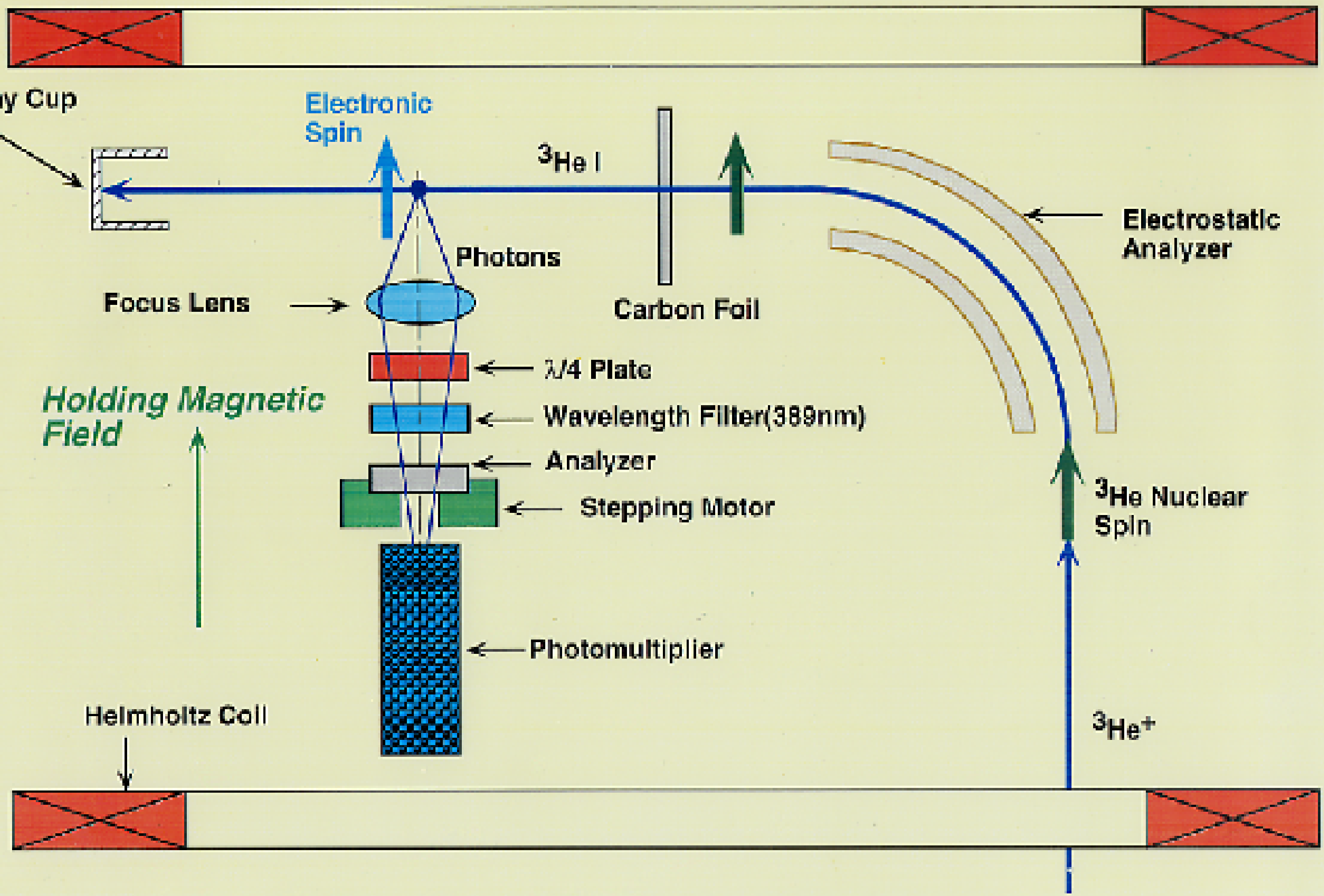


Step III : Conversion of Electron Polarization to Nuclear Polarization

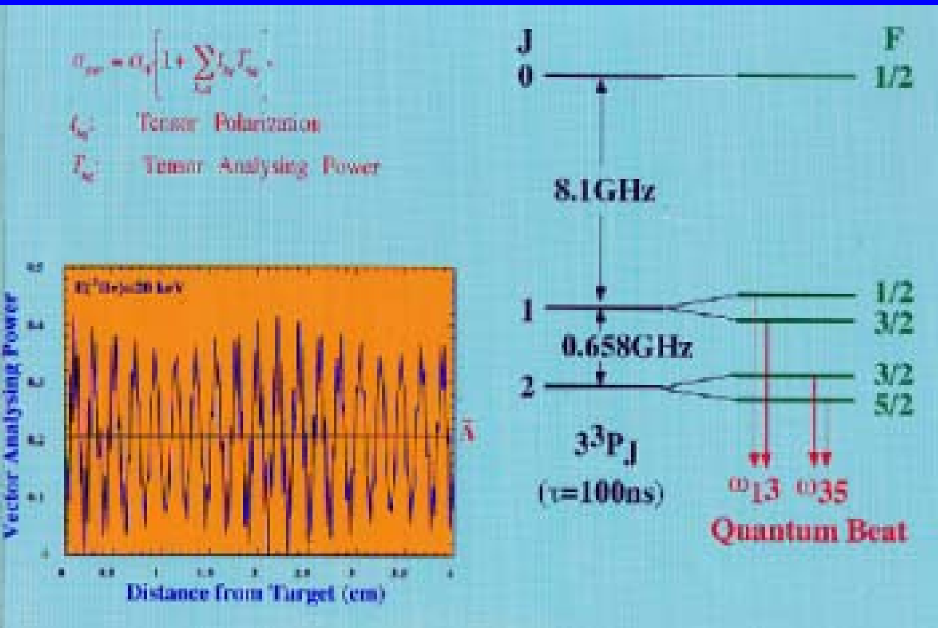




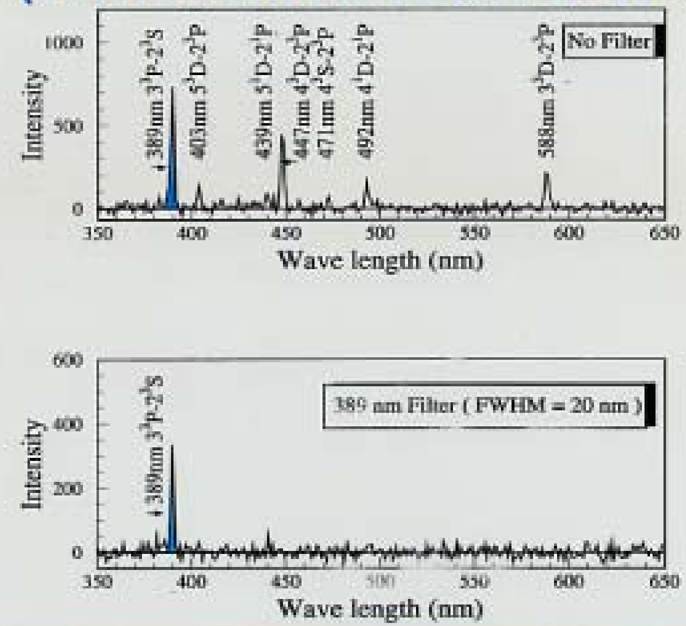
λ/4 Wave Plate
Mirror
Mirror
Pumping Laser
Shutter
Mirror
Lens
Analyzer Magnet
Electric Q-lens
Sodium Cell
Electric Q-lens
Solenoidal Coil
Monitor Laser
Electrostatic
Analyzer
Slit
Neomafios-10GHz
Photo
-diode
Lens
Photomultiplier
Slit
Filter
Lens
Linear Polarizer
λ/4 Wave Plate
Neutralizer
Faraday Cup
Photodiode
Polarizing
Beamsplitter Cube
Carbon Foil



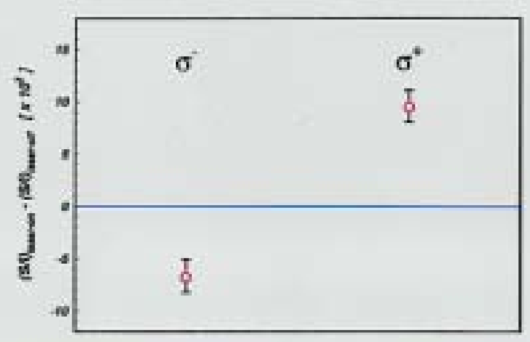
Schematic view of the Polarimeter

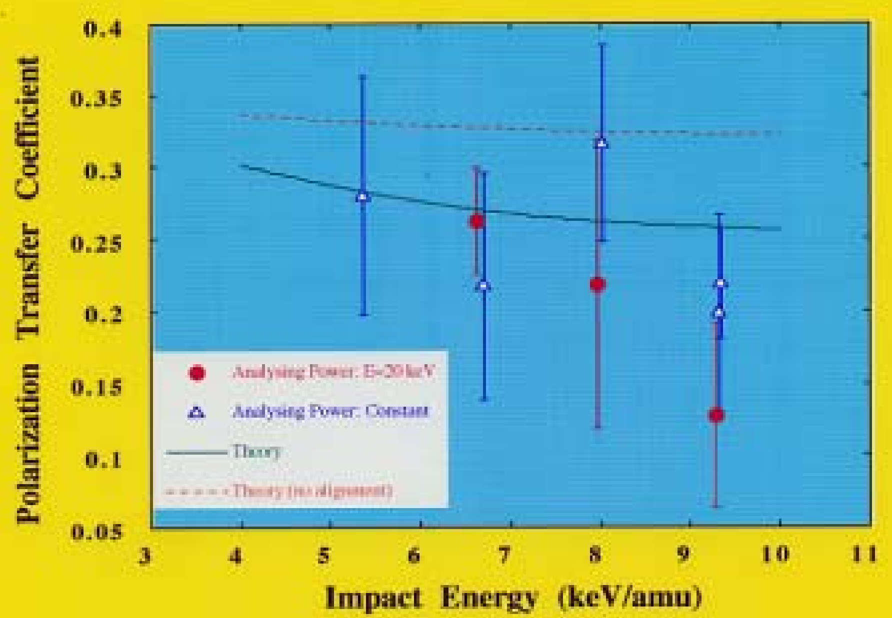


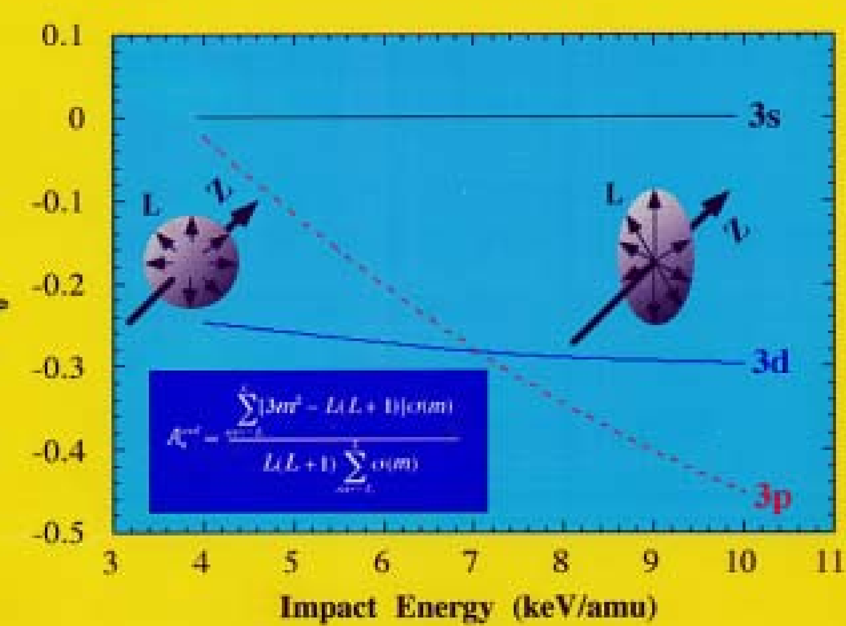
Photon Spectrum of He I (He II Incident on Carbon Foil)



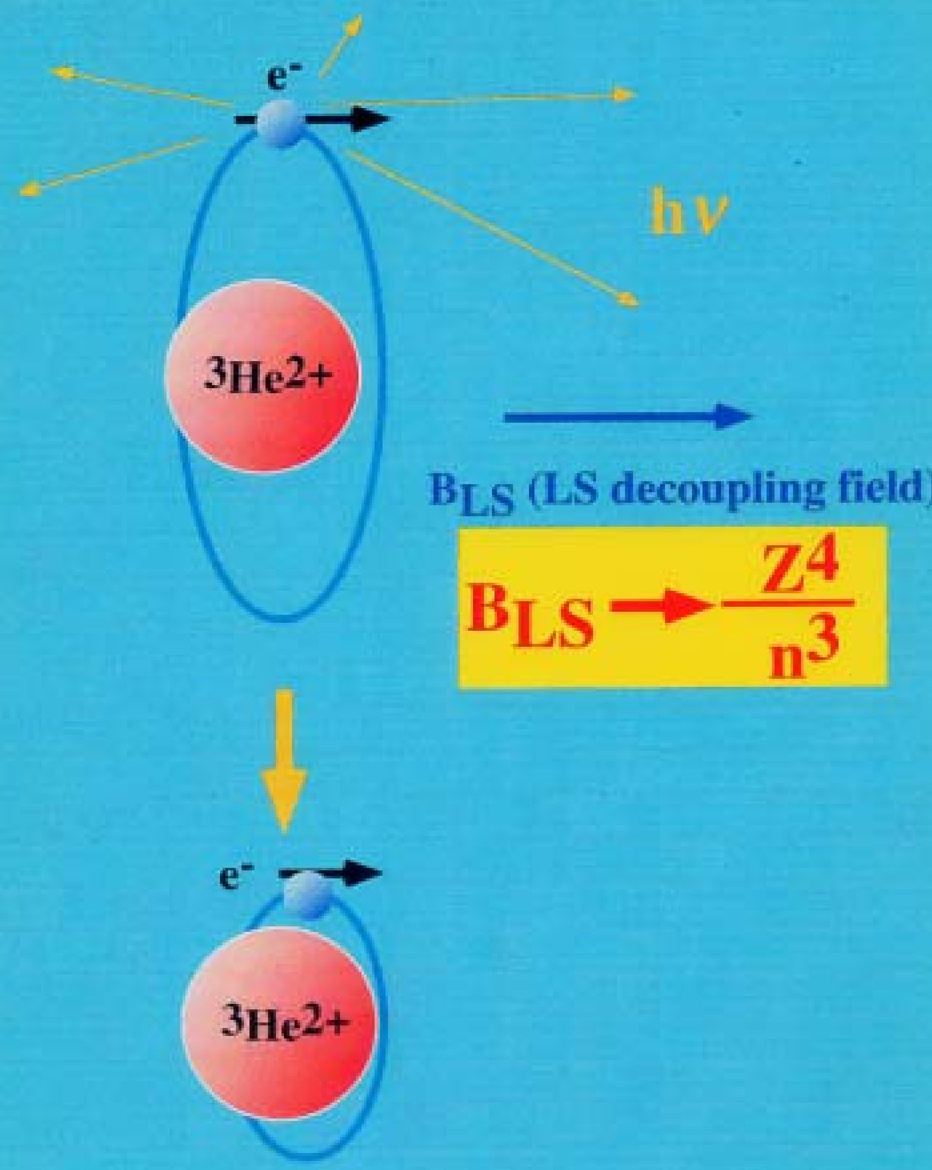
Observed Circular Polarization



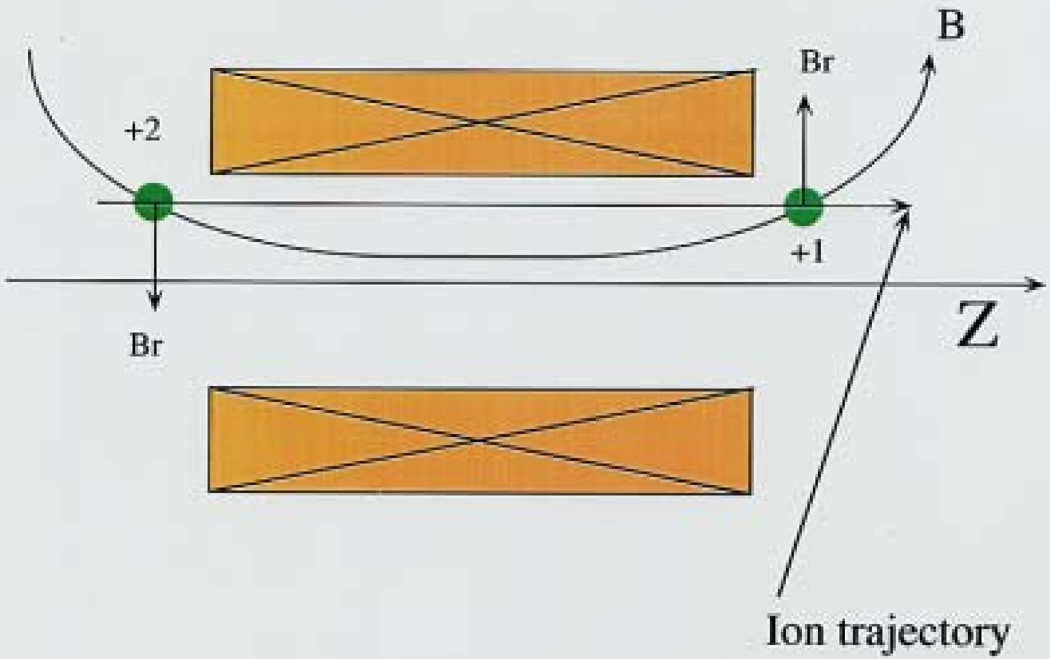

Polarization Transfer Coefficient
Impact Energy (keV/amu)
Analysing Power: Constant
Theory
Theory (no alignment)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
3
4
5
6
7
8
9
10
11


A_0^{col}
Impact Energy (keV/amu)
3s
3d
3p
L
Z
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
3
4
5
6
7
8
9
10
11

Origin of Depolarization



Transversal Emittance growth due to the fringing field



Failure of OPPIS

In contrast with the success of the proton OPPIS, the ^3He OPPIS was unsuccessful in the following points:

1) Large depolarization
   due to insufficient LS decoupling field,

2) Emittance growth
   due to charge changing collision in the magnetic field.

We must look for

an avenue to an innovative method how to produce ^{3}He beam with

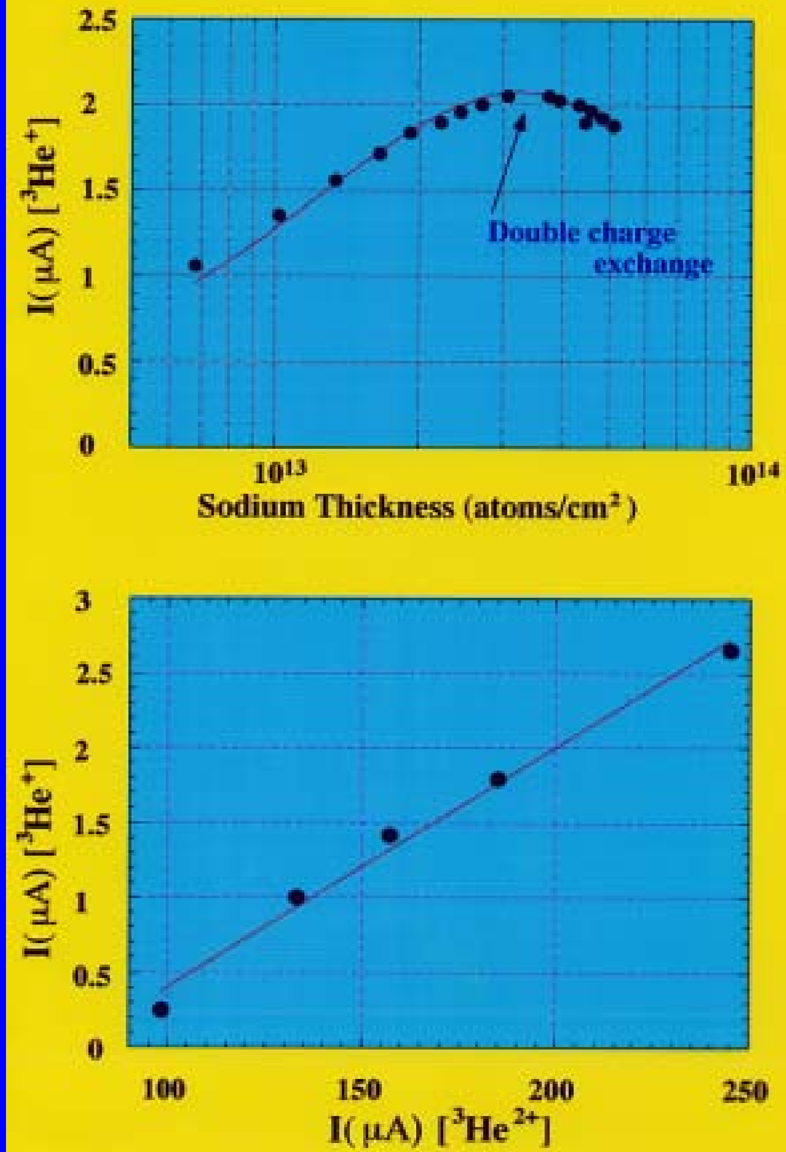
1) fully polarized,
2) no sizable beam emittance growth

This is a second step of our development.

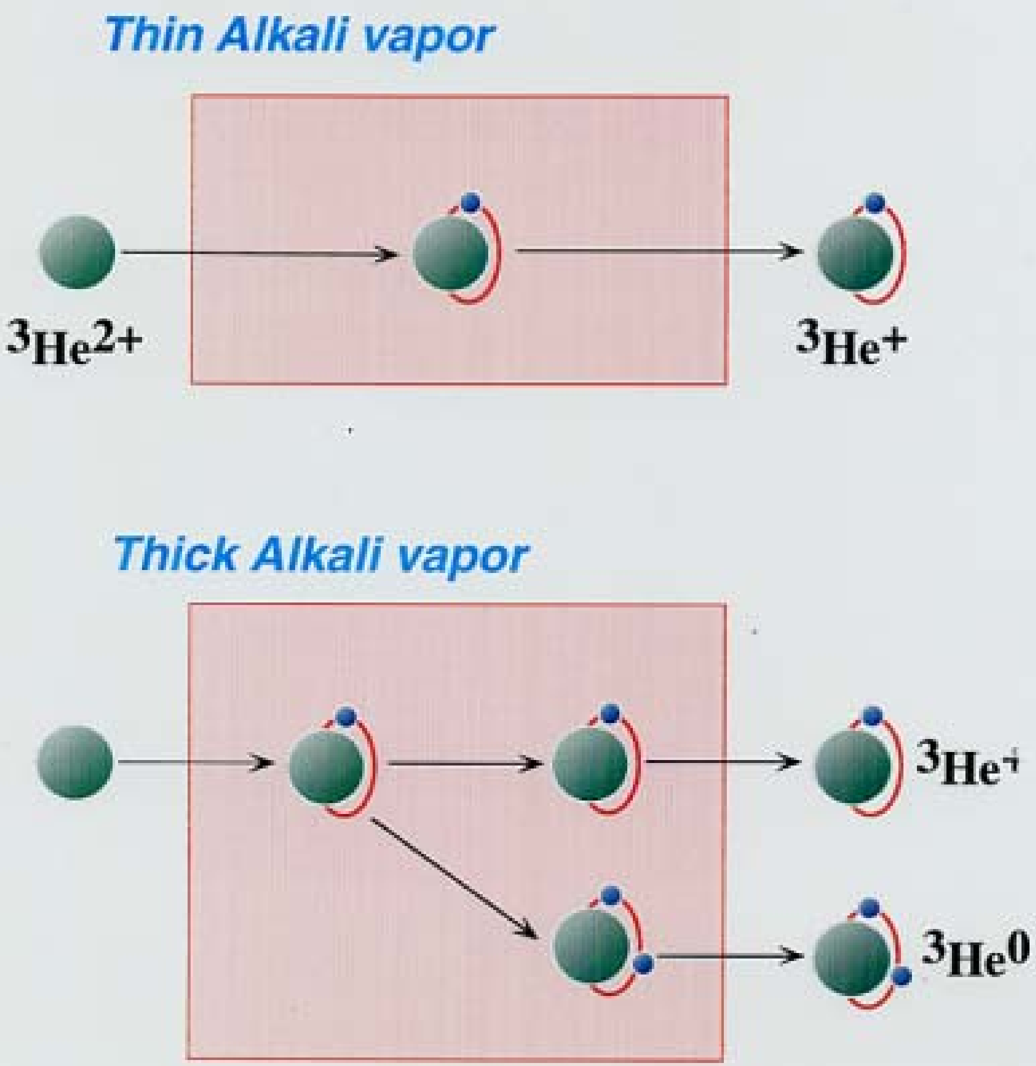
EPPIS

(Electron Pumping Polarized Ion Source)

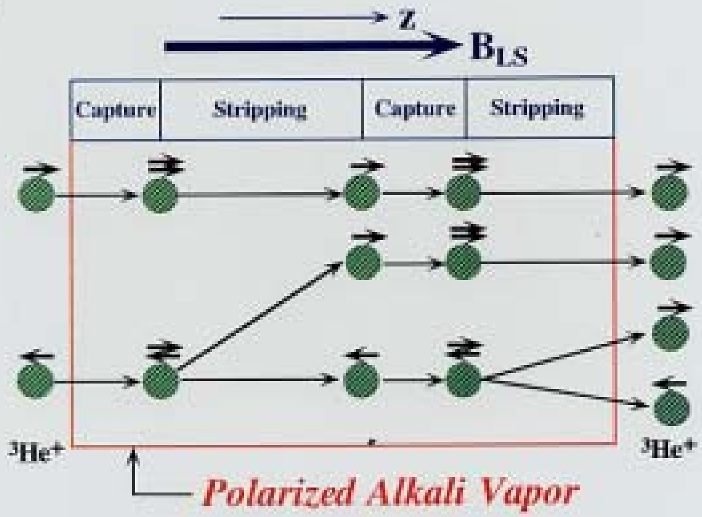
Charge Exchange Collisions



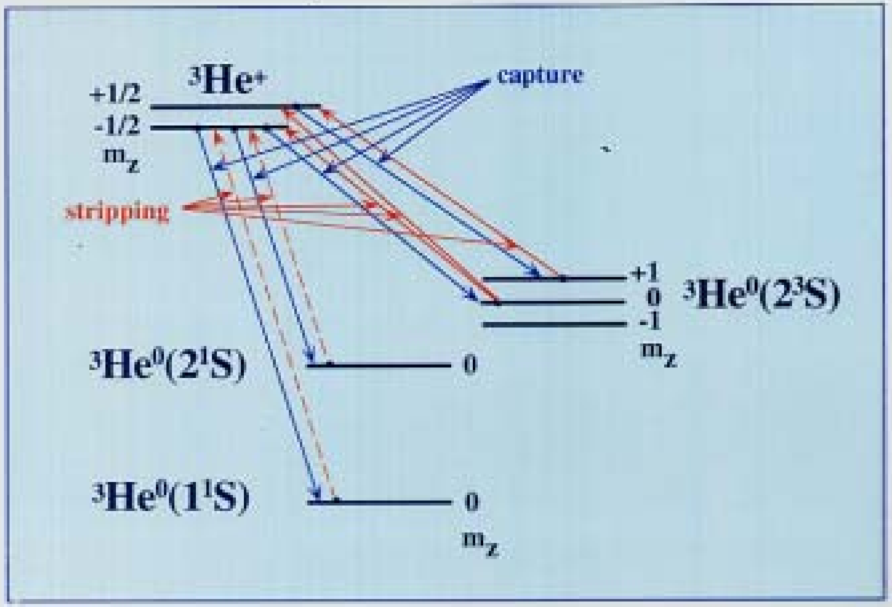
To understand the strange phenomenon

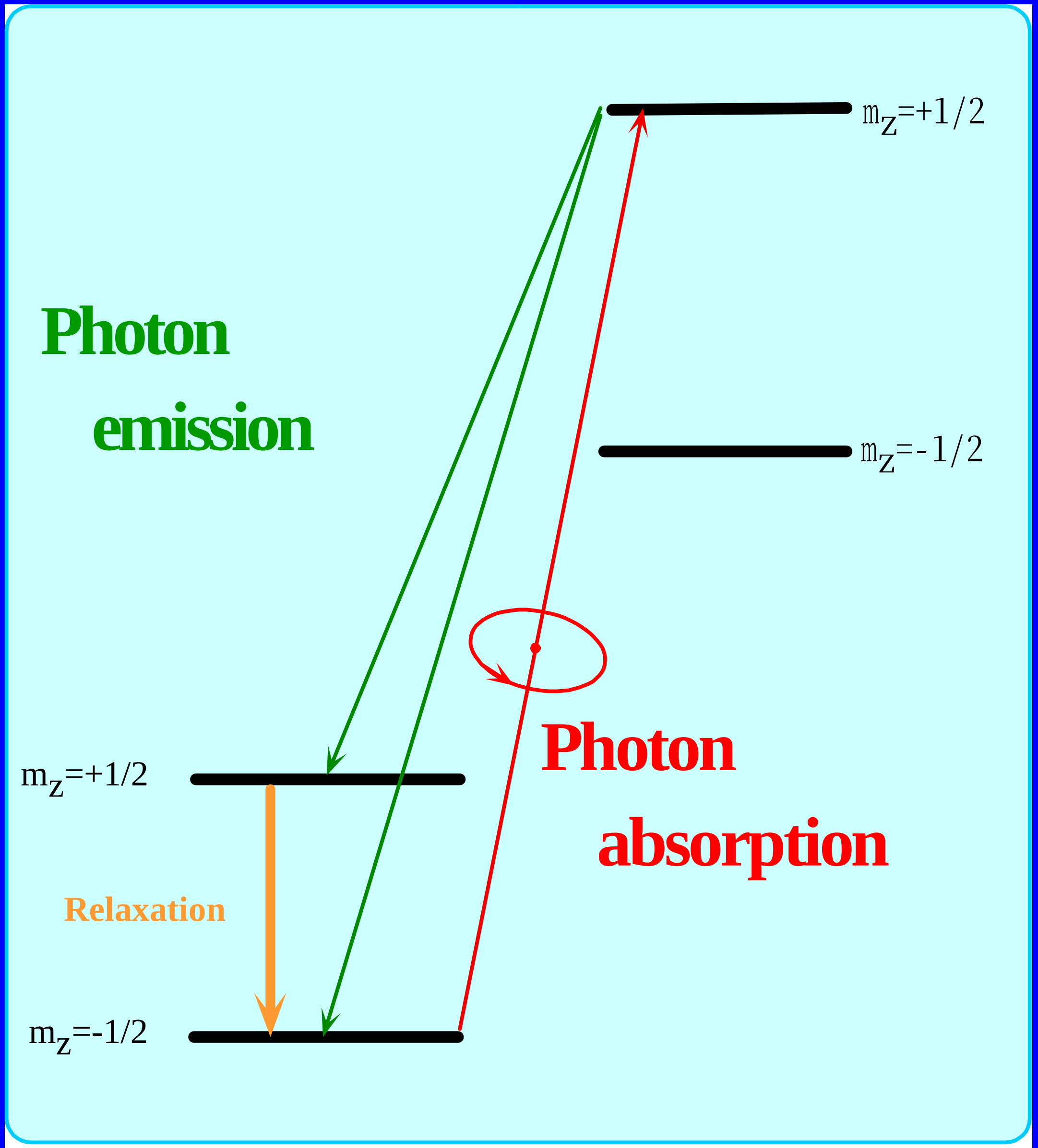


a)


z
B$_{LS}$
Capture
Stripping
Capture
Stripping
$^3He^+$
$^3He^+$
Polarized Alkali Vapor

b)


$^3He^+$
+1/2
-1/2
m_z
capture
stripping
+1
0
-1
m_z
$^3He^0(2^3S)$
$^3He^0(2^1S)$
0
$^3He^0(1^1S)$
0
m_z



Optical Pumping

Characteristic of EPPIS

1) Generalized concept of the optical pumping

Open up a new field as a powerful tool for the nuclear spectroscopy for which the pumping laser light is not available.

2) No need for powerful ion source which provides $^3He^{2+}$ ions

3) No beam emittance growth

because of no charge changing collisions

Prerequisite conditions imposed for EPPIS

1) Production of highly polarized dense alkali vapor homogenously distributed throughout the Rb cell.

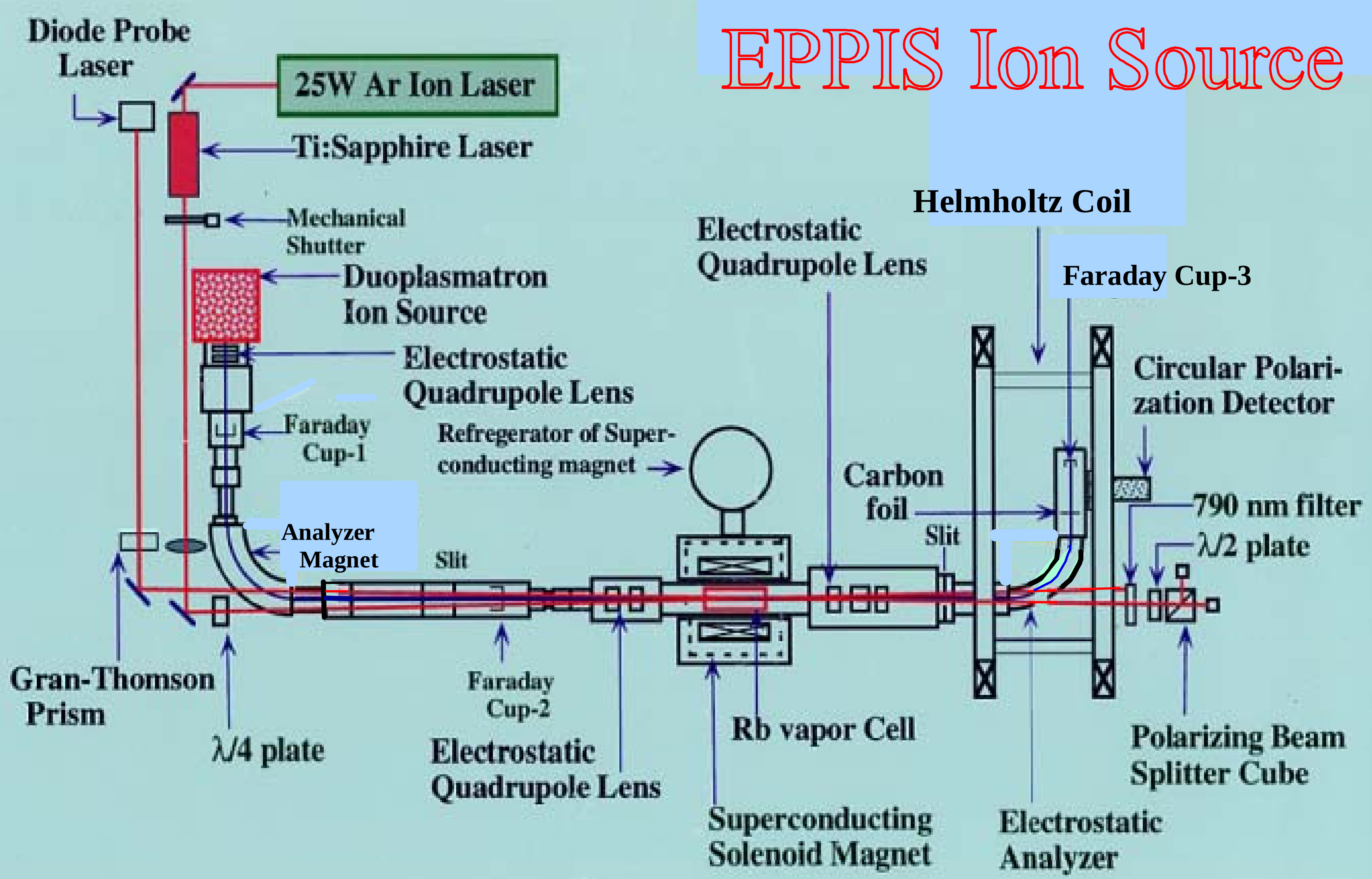
An areal polarization distribution was investigated by the time differential measurement.

2) Evaluation of the Spin-exchange cross section.

This term helps the EPPIS create an additional polarization.

→ SEPIS (Spin-exchange)

EPPIS Ion Source



Electron Pumping Rate Equation

Rb polarization = +1

$$\frac{d}{dx}H = Rb_+ H$$

$$\frac{d}{dx}\begin{pmatrix} H^+_{1/2} \\ H^+_{-1/2} \\ H_{t1} \\ H_{t0} \\ H_{t-1} \\ H_{s0} \end{pmatrix} = \left(\begin{array}{cc|ccc|c} -\sigma_{1t} & \sigma_{SEI} & \sigma_{t1} & \frac{\sigma_{t1}}{2} & 0 & \frac{\sigma_{s1}}{2} \\ 0 & -\sigma_{1t}-\sigma_{SEI} & 0 & \frac{\sigma_{t1}}{2} & \sigma_{t1} & \frac{\sigma_{s1}}{2} \\ \hline \kappa_+\sigma_{1t} & \frac{\kappa_-\sigma_{1t}}{2} & -\sigma_{t1} & \sigma_{SEA} & 0 & 0 \\ \frac{\kappa_-\sigma_{1t}}{2} & \frac{\kappa_+\sigma_{1t}}{2} & 0 & -\sigma_{t1}-\sigma_{SEA} & \sigma_{SEA} & 0 \\ 0 & \frac{\kappa_-\sigma_{1t}}{2} & 0 & 0 & -\sigma_{t1}-\sigma_{SEA} & 0 \\ \hline \frac{\kappa_-\sigma_{1s}}{2} & \frac{\kappa_+\sigma_{1s}}{2} & 0 & 0 & 0 & -\sigma_{s1} \end{array}\right)\begin{pmatrix} H^+_{1/2} \\ H^+_{-1/2} \\ H_{t1} \\ H_{t0} \\ H_{t-1} \\ H_{s0} \end{pmatrix}$$

Rb polarization = P_{Rb}

$$\frac{d}{dx}H = (\epsilon_+ Rb_+ + \epsilon_- Rb_-)H$$

$$Rb_- = T Rb_+ T^T, \quad T = \left(\begin{array}{cc|ccc|c} 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & 0 & 1 \end{array}\right), \quad \begin{cases} \epsilon_+ = \frac{1+P_{Rb}}{2} \\ \epsilon_- = \frac{1-P_{Rb}}{2} \end{cases}, \quad \begin{cases} \kappa_+ = \frac{1+P_{LS}}{2} \\ \kappa_- = \frac{1-P_{LS}}{2} \end{cases},$$

$\sigma_{1t} = \sigma_{11} + \sigma_{1s}$

x : vapor thickness of Alkali atom

P_{Rb} : Rb Polarization

$H^+_{1/2}, H^+_{-1/2}$: $^3He^+$ intensity for the $m_s = \frac{1}{2}, m_s = -\frac{1}{2}$ levels

H_{t1}, H_{t0}, H_{t-1} : ^3He 2^3S intensity for the $m_s = 1, 0, -1$ levels

H_{s0} : ^3He 2^1S intensity

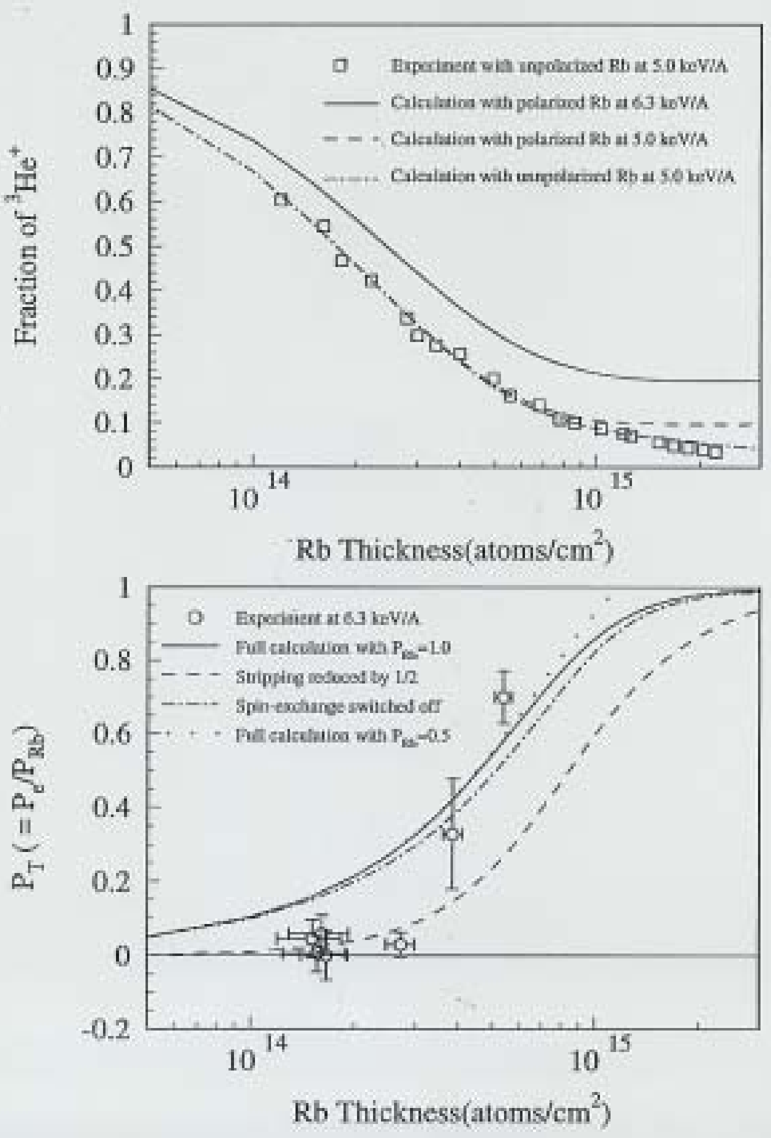
σ_{21} : Capture cross section from the doubly to singly charged state

σ_{1t}, σ_{t1} : Capture cross section from the singly charged state to the $2\,^3S$ level and vice versa

σ_{1s}, σ_{s1} : Capture cross section from the singly charged state to the 2^1S level and vice versa

$\sigma_{SEI}, \sigma_{SEA}$: Spin-exchange cross section for an ion and atom

σ_{ts}, σ_{st} : Cross section from the triplet to singlet and vice versa



Experiment with unpolarized Rb at 5.0 keV/A
Calculation with polarized Rb at 6.3 keV/A
Calculation with polarized Rb at 5.0 keV/A
Calculation with unpolarized Rb at 5.0 keV/A
Fraction of $^3He^+$
Rb Thickness(atoms/cm^2)
Experiment at 6.3 keV/A
Full calculation with P_{Rb}=1.0
Stripping reduced by 1/2
Spin-exchange switched off
Full calculation with P_{Rb}=0.5
P_T (= P_e/P_{Rb})
Rb Thickness(atoms/cm^2)

Results obtained for EPPIS

1) ^{3}He nuclear polarization ~7 %
   (Rb polarization ~20%)

2) $^3He^+$ beam intensity ~ 2 μA
   (Primary beam ~ 100 μA)

Problems associated with EPPIS using high density polarized Rb vapor

Smallness of the nuclear polariation attainable is caused by

1) Small Rb polarization due to
   - a) Absorption of pumping laser
   - b) Radiation trapping effect

2) Non uniform distribution of the Rb vapor in the Rb vapor cell due to
   - a) Effusion
   - b) Polarization sheath formed by radiation trapping

How to overcome above difficulties

1) Development of high Rb polarization

2) Spin-exchange polarized ion source (SEPIS) which uses a highly polarized Rb vapor with a low density.

A way to obtain highly polarized Rb vapor homogeneously distributed in the cell

An areal uniformity of the Rb polarization depends on the relaxation mechanism occuring in the vapor cell.
For this purpose, the Rb relaxation times were measured by observing the polarization time-differentially with chopped laser lights.

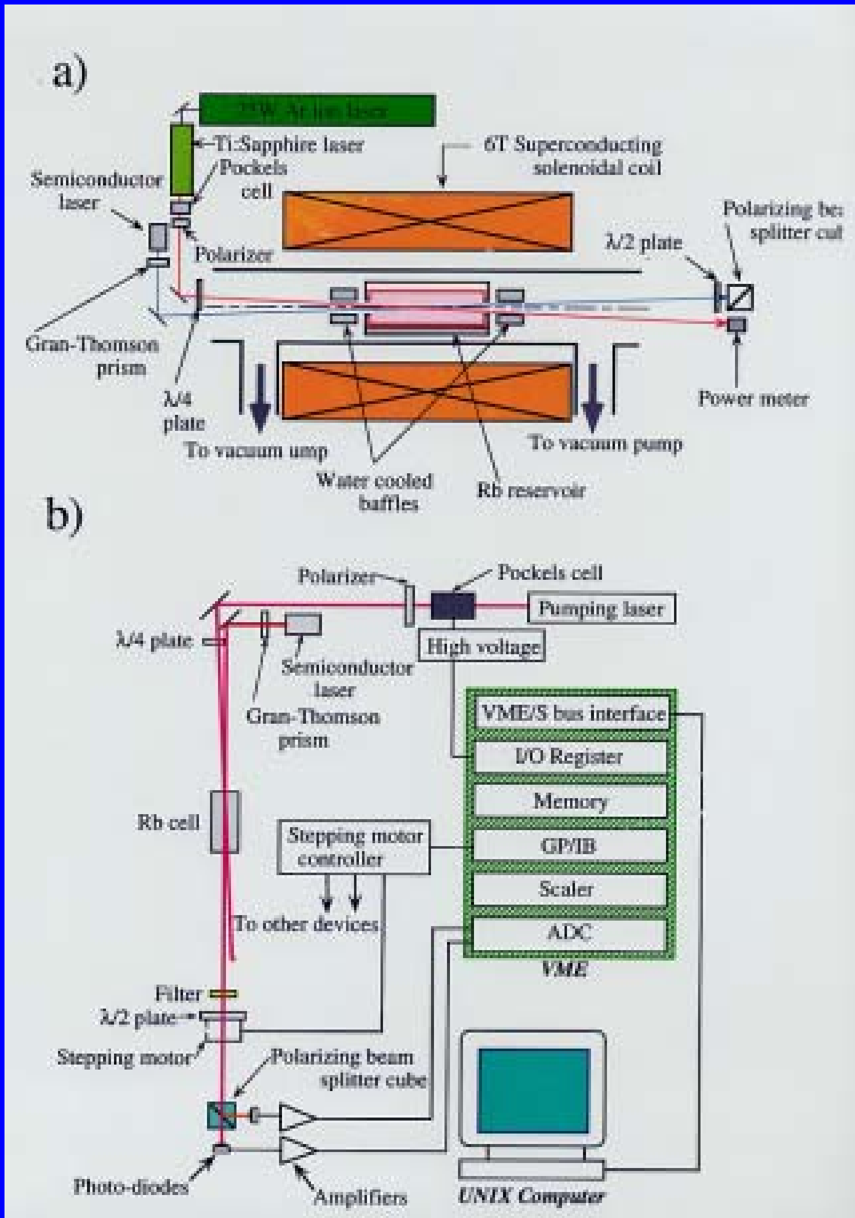
Changing parameters:

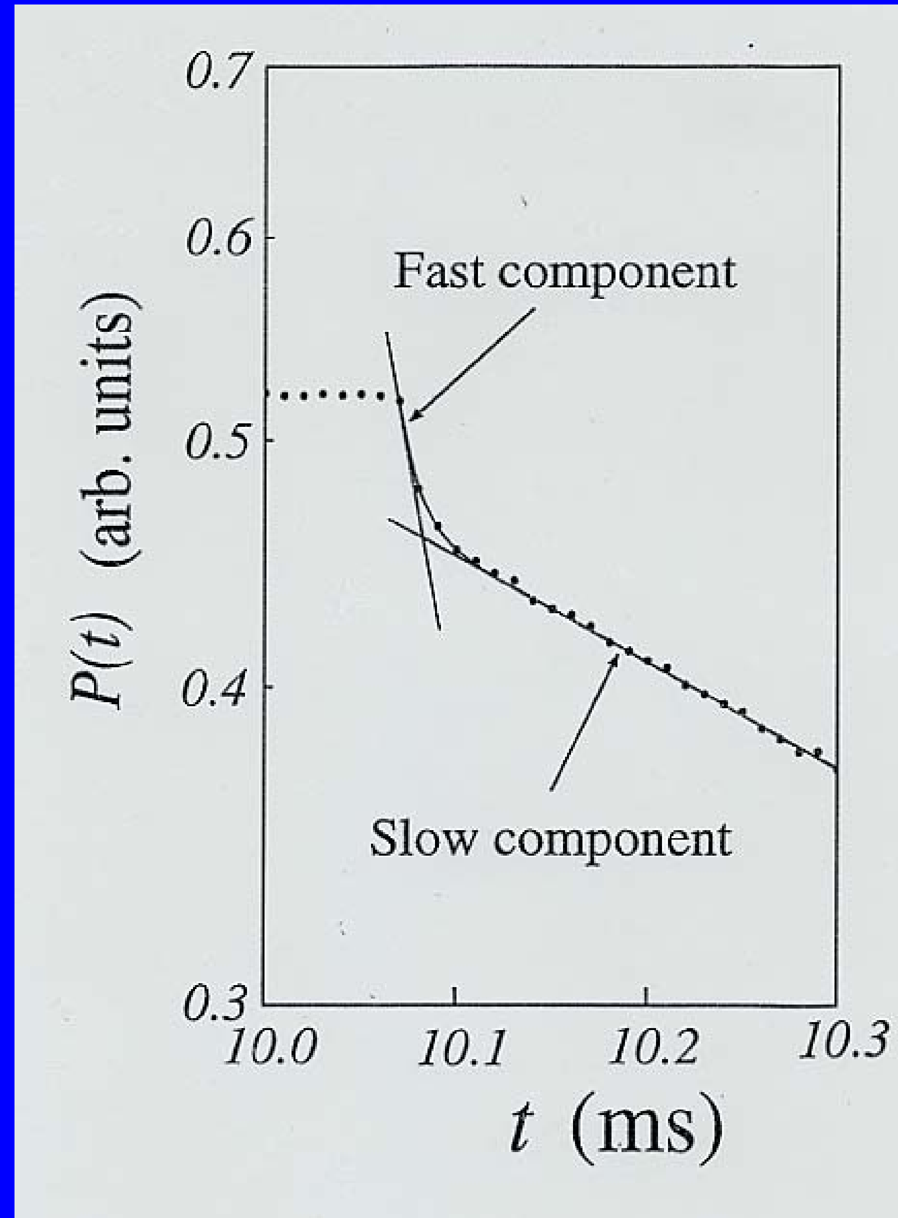
1) the external magnetic field
2) the cell temperature
3) the pumping laser frequency

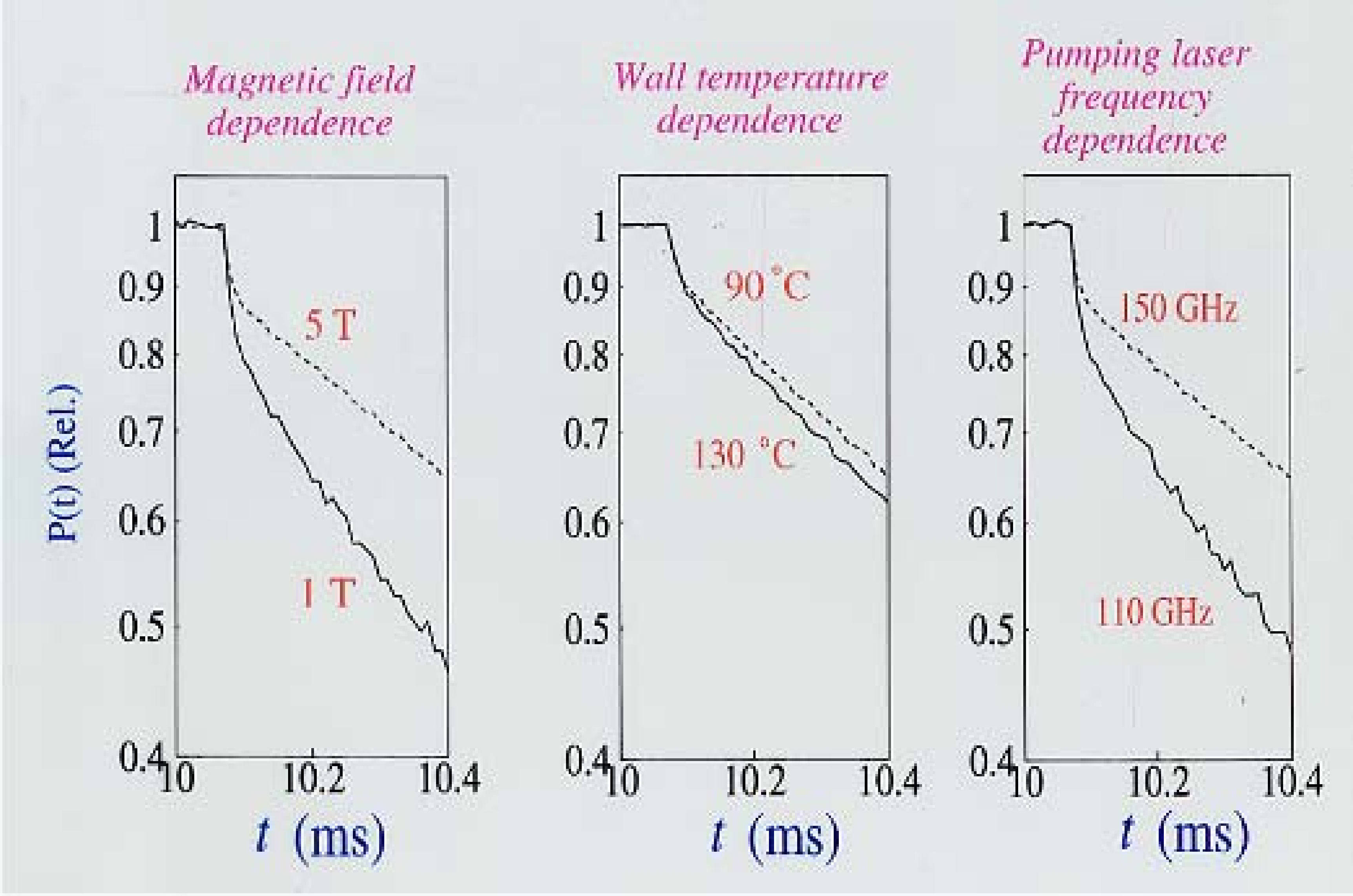
A simple model and Monte Carlo simulation were compared with the observed quantities to discuss the relaxation mechanisms.
As a result, the relaxation mechanism is found to mainly be determined by

1) Wall relaxation
2) Effusion
3) Radiation trapping

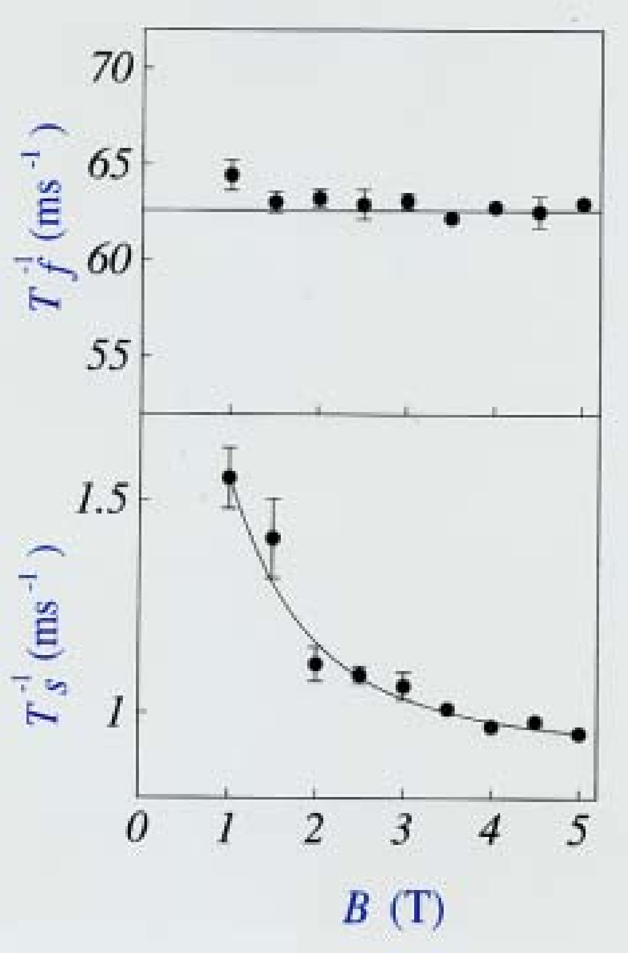
This finally gave insight into how to realize uniform distribution of the Rb polarization.

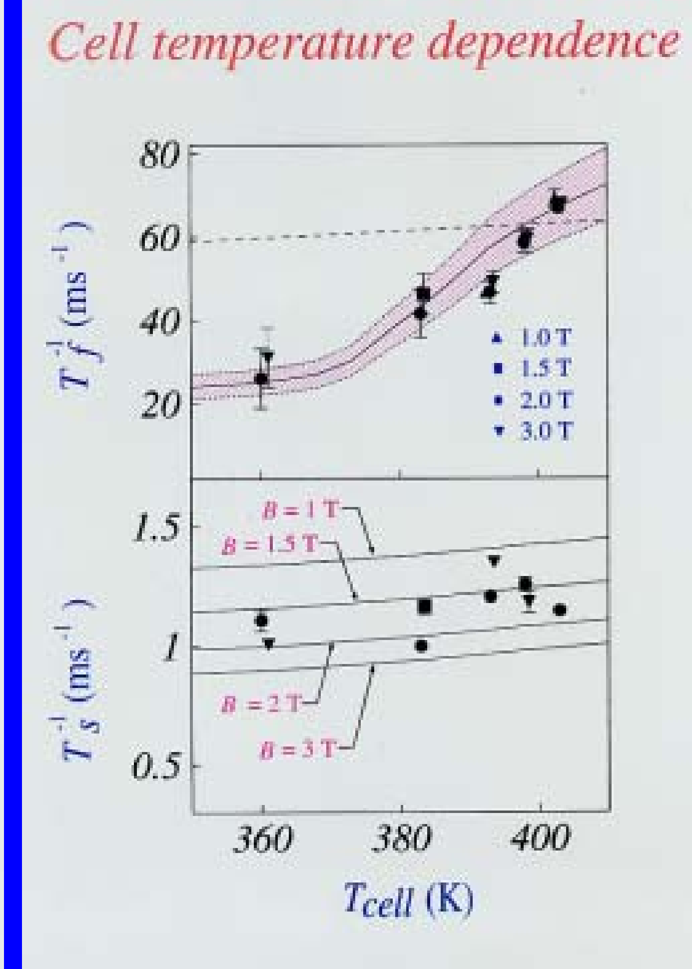

a)
Ti:Sapphire laser
6T Superconducting
solenoidal coil
Semiconductor
laser
Pockels
cell
Polarizer
Polarizing be
splitter cu
λ/2 plate
Gran-Thomson
prism
λ/4
plate
Power meter
To vacuum ump
To vacuum pump
Water cooled
baffles
Rb reservoir
b)
Polarizer
Pockels cell
Pumping laser
λ/4 plate
High voltage
Semiconductor
laser
Gran-Thomson
prism
VME/S bus interface
I/O Register
Memory
Rb cell
Stepping motor
controller
GP/IB
Scaler
To other devices
ADC
VME
Filter
λ/2 plate
Stepping motor
Polarizing beam
splitter cube
Photo-diodes
Amplifiers
UNIX Computer

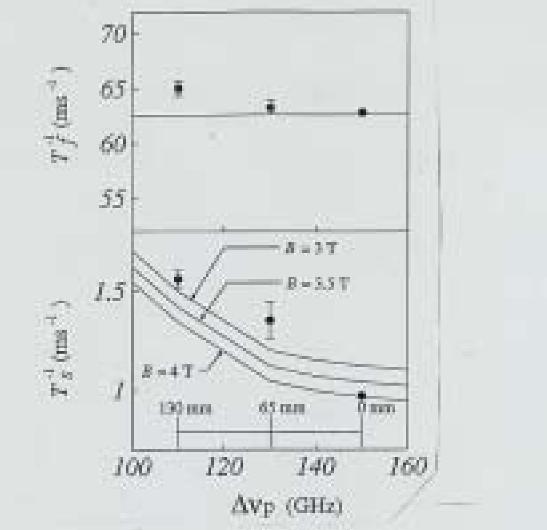

Fast component
Slow component
P(t) (arb. units)
t (ms)
0.7
0.6
0.5
0.4
0.3
10.0
10.1
10.2
10.3

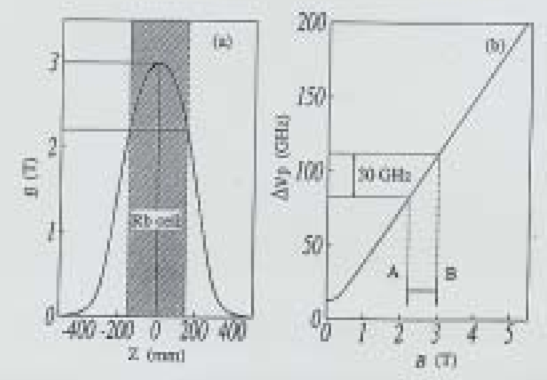

Magnetic field dependence
Wall temperature dependence
Pumping laser frequency dependence
P(t) (Rel.)
1
0.9
0.8
0.7
0.6
0.5
0.4
10
10.2
10.4
t (ms)
5 T
1 T
90 °C
130 °C
150 GHz
110 GHz

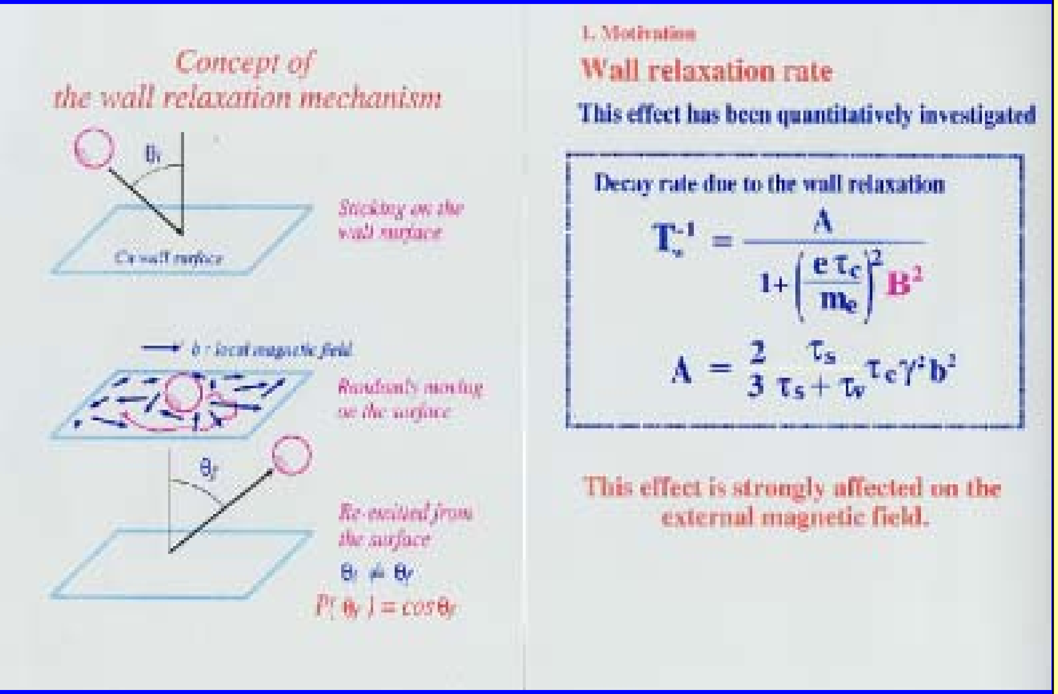
B, T_{cell}, and ν_{laser} dependences of decay constants for fast and slow components



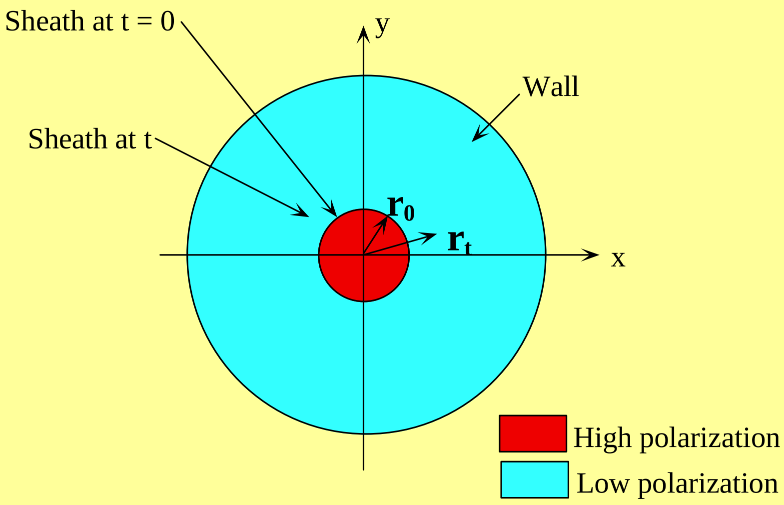








Temperature dependence of the fast component



Polarization nonuniformity is induced by the Radiation Trapping Effect

$r_t = r_0 + vt$ (v is a velocity of Rb atom)

$$P_t r_t^2 = P_0 r_0^2$$

$$P_t = P_0 \frac{r_0^2}{(r_0 + vt)^2}$$

$$T_f^{-1} = \sqrt{\frac{2k}{\pi M}} \frac{1}{\sqrt{e} - 1} \frac{\sqrt{T_{cell}}}{r_0\,(T_{cell})}$$

Beam emittance growth really suppressed in the EPPIS?

To investigate this point, behavior of ^{3}He ions colliding with polarized/unpolarized Rb gas under a strong magnetic field has been studied by means of the Monte Carlo simulation method.

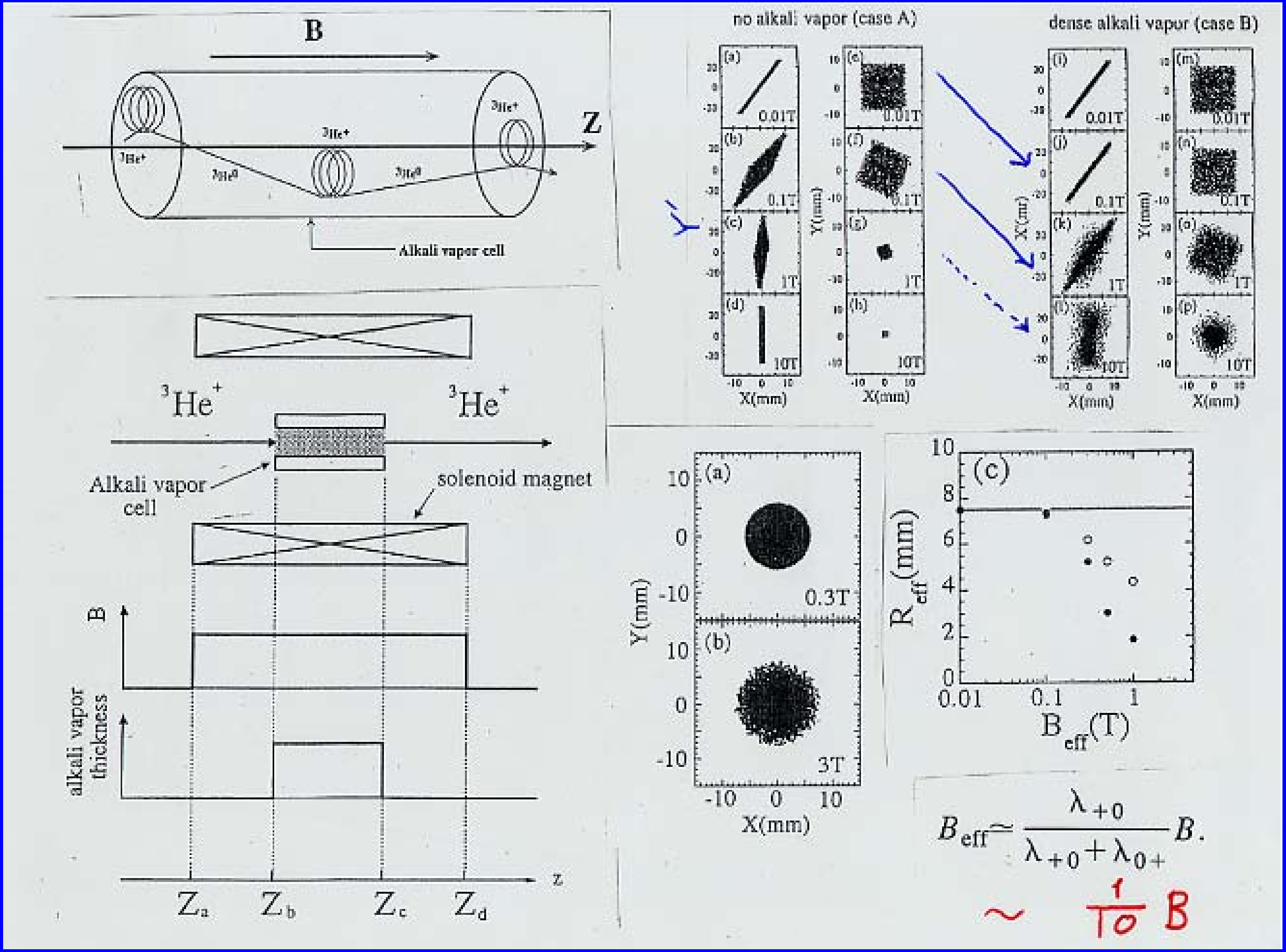
- **Study with unpolarized gas:**

  A new concept of effective magnetic field

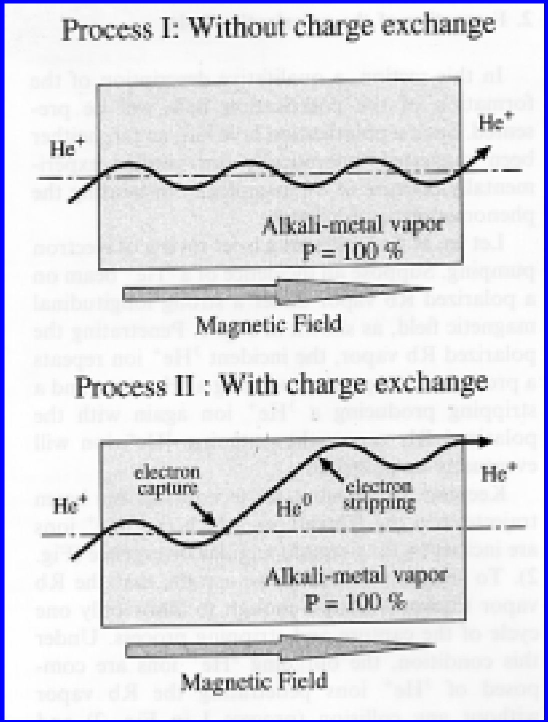
- **Study with polarized gas:**

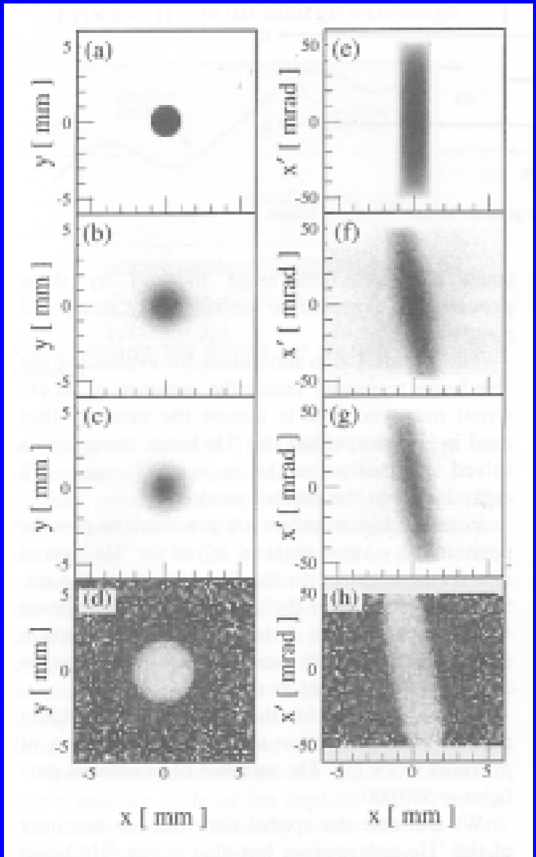
  A new concept of polarization hole.

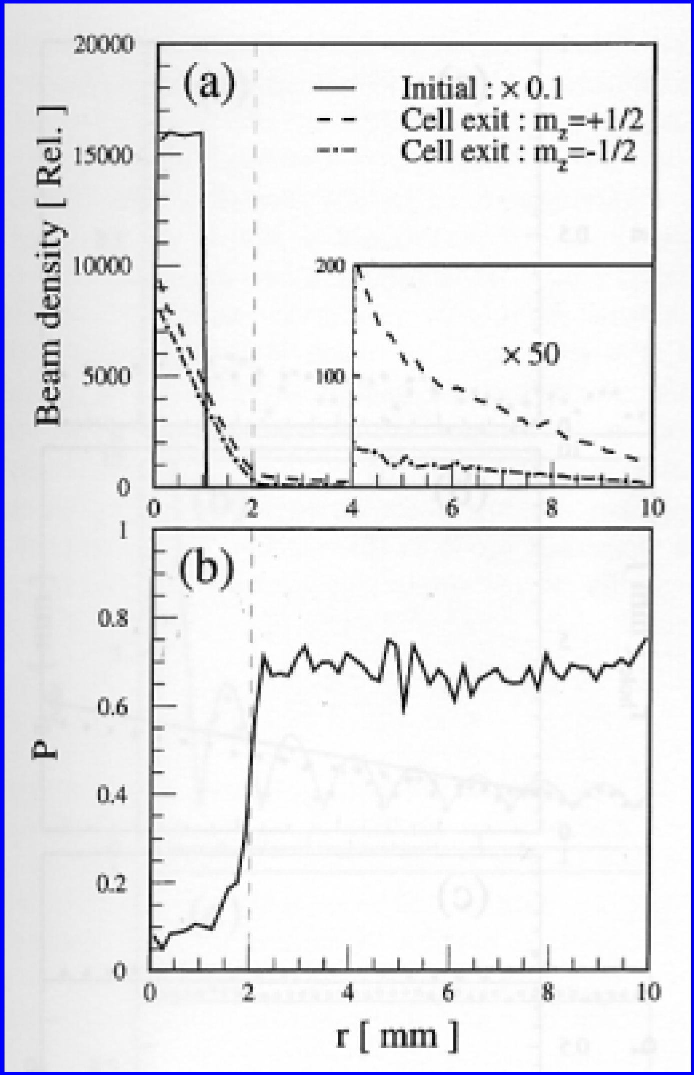
Unpolarized beam



Polarized Rb gas





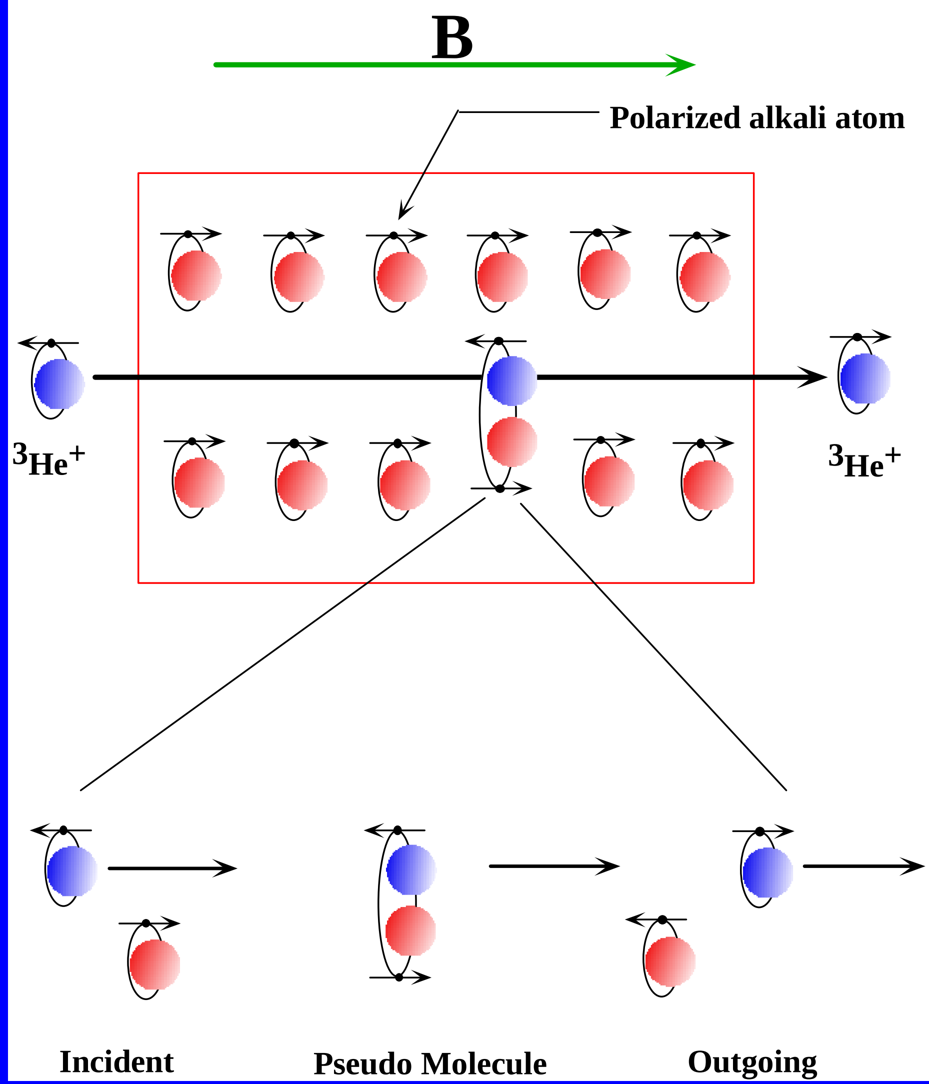


SEPIS ^{3}He Ion Source

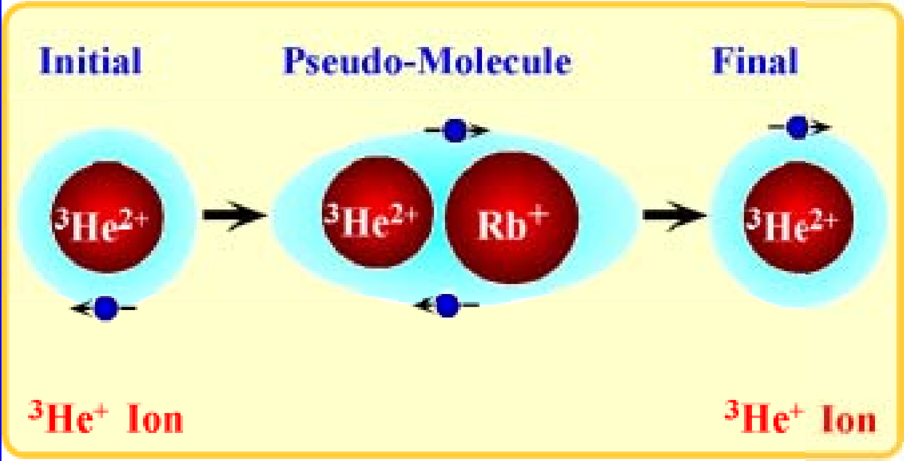
(Spin-exchange polarized ion source)

This ion source was invented to overcome the difficulities in EPPIS

Principle of SEPIS



Spin-exchange process between $^3He^+$ and Rb

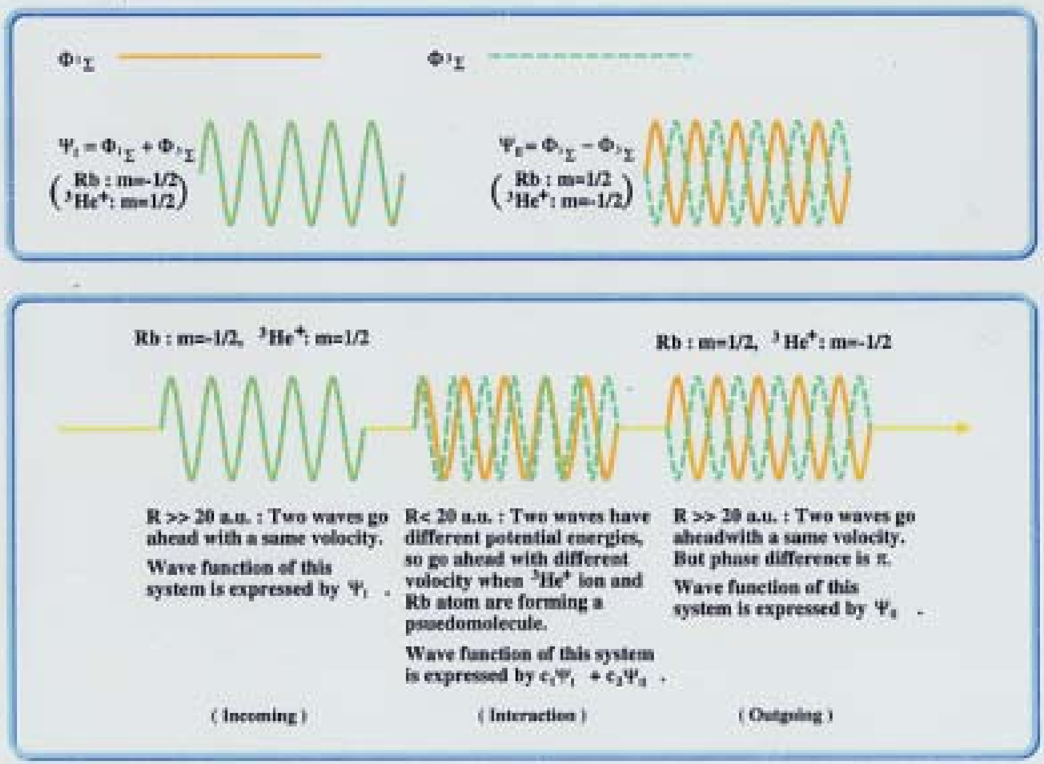


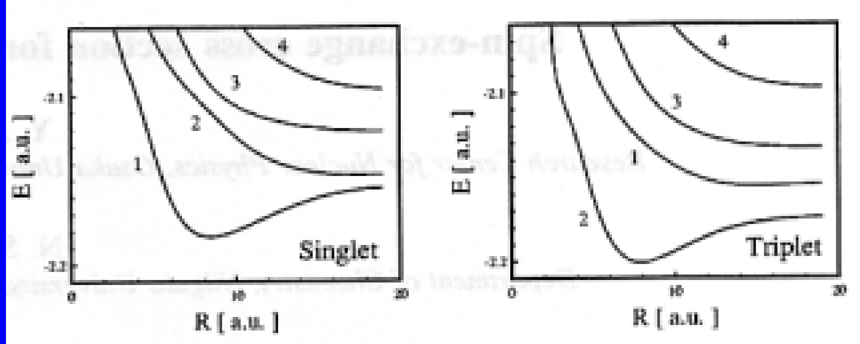
Estimation of the spin-exchange cross section

1) Formation of the pseudo-molecule

2) The semiclassical impact parameter method
   - Transitions: Quantum mechanics
   - Ion trajectories: Classical orbits

Quantum Mechanical Principle of electron spin-exchange





$$\Phi_{^1\Sigma} = \frac{1}{2}\{\alpha(1)\beta(2) - \beta(1)\alpha(2)\} \times \{\phi_{Rb}(1)\phi_{He}(2) + \phi_{He}(1)\phi_{Rb}(2)\}, \quad (A2)$$

$$\Phi_{^3\Sigma} = \frac{1}{2}\{\alpha(1)\beta(2) + \beta(1)\alpha(2)\} \times \{\phi_{Rb}(1)\phi_{He}(2) - \phi_{He}(1)\phi_{Rb}(2)\}, \quad (A3)$$

$$\Psi_I = \frac{1}{\sqrt{2}}\begin{vmatrix} \alpha(1)\phi_{Rb}(1) & \beta(1)\phi_{He}(1) \\ \alpha(2)\phi_{Rb}(2) & \beta(2)\phi_{He}(2) \end{vmatrix} \quad (A4)$$

$$= \frac{1}{\sqrt{2}}\{\alpha(1)\phi_{Rb}(1)\beta(2)\phi_{He}(2) - \alpha(2)\phi_{Rb}(2)\beta(1)\phi_{He}(1)\}, \quad (A5)$$

$$\Psi_{II} = \frac{1}{\sqrt{2}}\begin{vmatrix} \beta(1)\phi_{Rb}(1) & \alpha(1)\phi_{He}(1) \\ \beta(2)\phi_{Rb}(2) & \alpha(2)\phi_{He}(2) \end{vmatrix} \quad (A6)$$

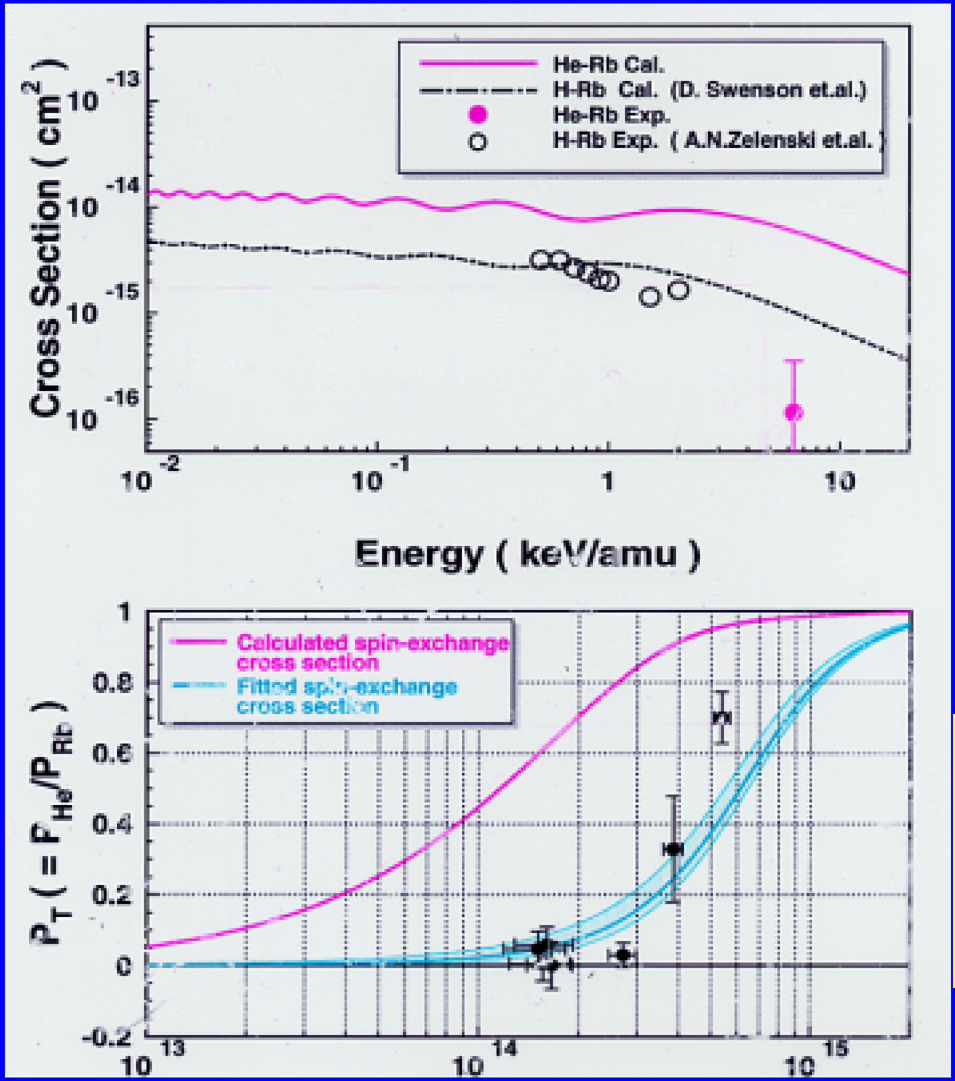
$$= \frac{1}{\sqrt{2}}\{\beta(1)\phi_{Rb}(1)\alpha(2)\phi_{He}(2) - \beta(2)\phi_{Rb}(2)\alpha(1)\phi_{He}(1)\}. \quad (A7)$$

$$\begin{pmatrix} \Psi_I(t) \\ \Psi_{II}(t) \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} E(t,V_s) & 0 \\ 0 & E(t,V_t) \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \Psi_I \\ \Psi_{II} \end{pmatrix}$$

$$= \begin{pmatrix} E(t,V_s)\cos^2\theta + E(t,V_t)\sin^2\theta & [-E(t,V_s)+E(t,V_t)]\sin\theta\cos\theta \\ [-E(t,V_s)+E(t,V_t)]\sin\theta\cos\theta & E(t,V_s)\cos^2\theta + E(t,V_t)\sin^2\theta \end{pmatrix} \begin{pmatrix} \Psi_I \\ \Psi_{II} \end{pmatrix}$$

$$= U\begin{pmatrix} \Psi_I \\ \Psi_{II} \end{pmatrix}.$$

Spin-exchange cross sections for He-Rb and H-Rb systems



Thickness (atoms/cm^2)

Theory : Semiclassical Impact Parameter Method

$$\sigma_{se} = 5.9 \times 10^{-15}\ \text{cm}^2$$

Experimental Results :

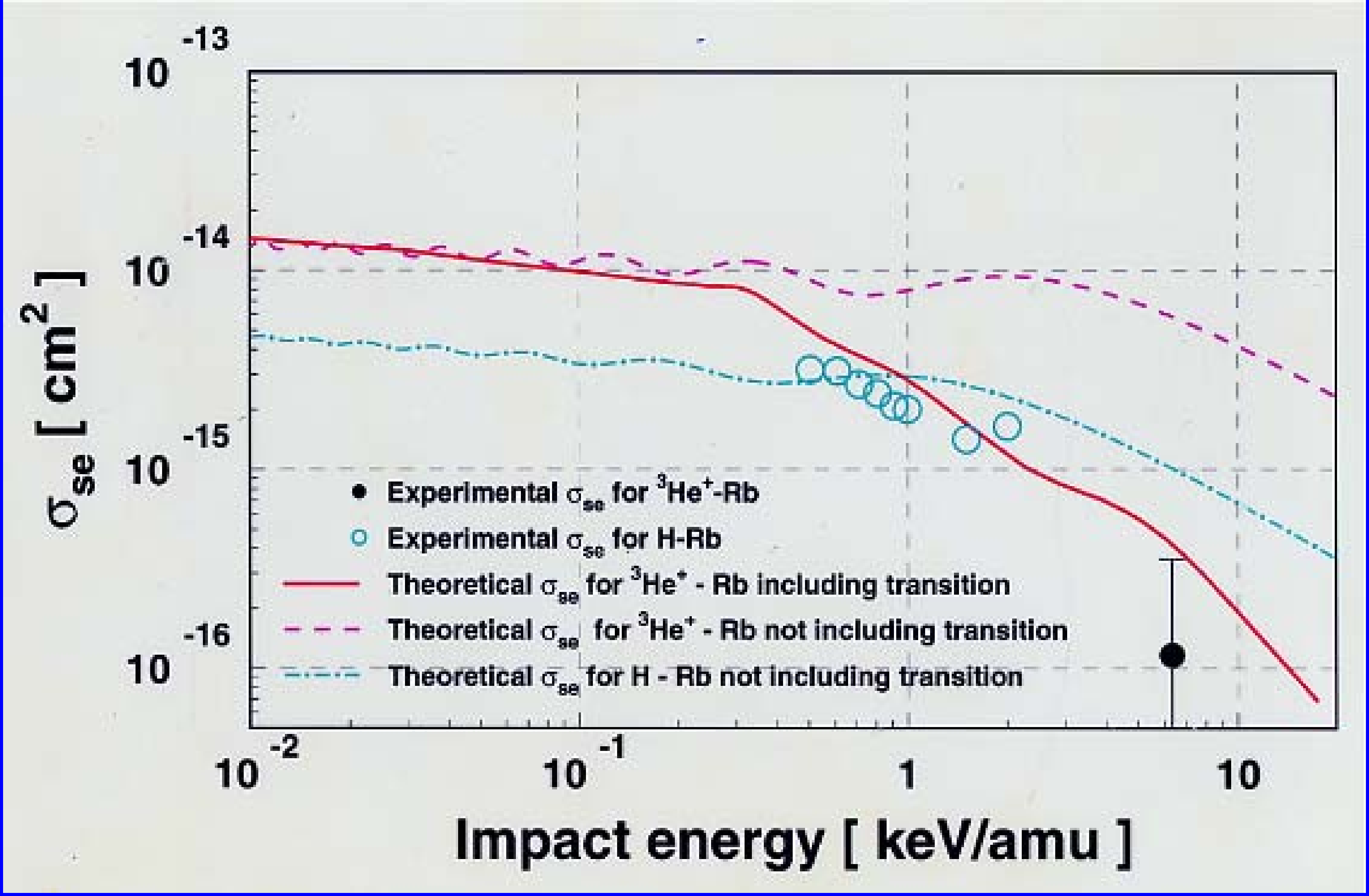
$$\sigma_{se} = 0.12^{+0.3}_{-0.2} \times 10^{-15}\ \text{cm}^2$$

A simple model could not reproduce the smallness of the spin exchange cross sections.

What is the origin of this failure?

Improvement of the theory is desired.

State	Symmetry	Asymptotic limit
1	$^{1,3}\Sigma$	$\rightarrow {}^3\mathrm{He}^+(1s\ ^2S) + \mathrm{Rb}(5s\ ^2S)$
2	$^{1,3}\Sigma$	$\rightarrow {}^3\mathrm{He}(1s2s\ ^{1,3}S) + \mathrm{Rb}^+$
3	$^{1,3}\Sigma$	$\rightarrow {}^3\mathrm{He}(1s2p\ ^{1,3}P) + \mathrm{Rb}^+$
4	$^{1,3}\Sigma$	$\rightarrow {}^3\mathrm{He}^+(1s\ ^2S) + \mathrm{Rb}(5p\ ^2P)$



10 -13
10 -14
10 -15
10 -16
σse [cm2]
10 -2
10 -1
1
10
Impact energy [keV/amu]
Experimental σse for 3He+-Rb
Experimental σse for H-Rb
Theoretical σse for 3He+ - Rb including transition
Theoretical σse for 3He+ - Rb not including transition
Theoretical σse for H - Rb not including transition

Observed anomaly of the spin-exchange cross sections was qualitatively reproduced by taking the target excitations and target ionizations.

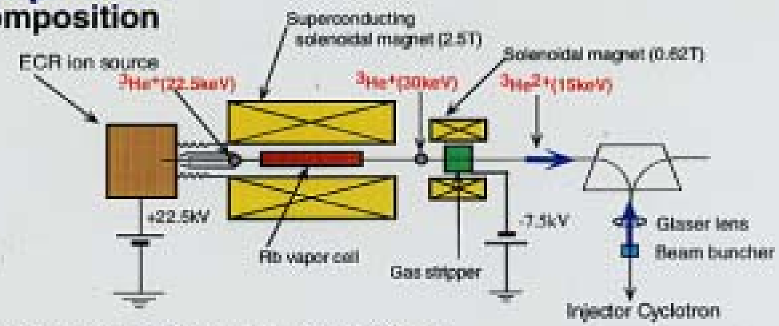
A more important aspect is that the spin-exchange cross sections at a low energy region are two orders of magnitude larger than that at a high energy region.

This is practically important particularly in designing the polarized ^{3}He ion source.

Expected Performance for the polarized ^3He ion source based on electron pumping

I. First phase

a) Composition



b) Beam current and Polarization

$I_{inj}(^3He^{2+}) \sim I_{ECR} \times 0.36 \times 7 \cdot 10^{-3} = 4mA \times 0.36 \times 7 \cdot 10^{-3} = 10\mu A$

$I_{target}(^3He^{2+}) \sim I_{inj}(^3He^{2+})/1000 = 10\mu A/1000 = 10nA$

Polarization ~ 0.3

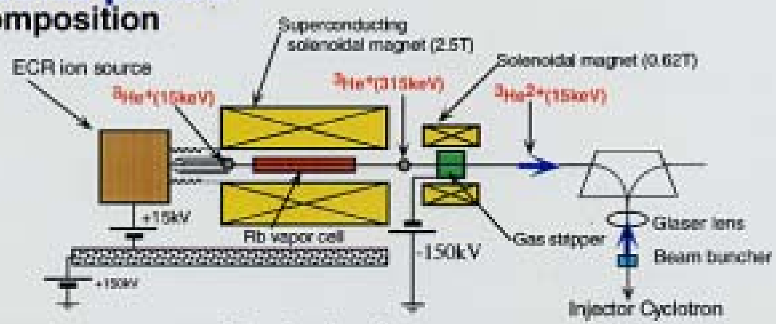
assuming that a Rb vapor thickness is 5×10^{14} atoms/cm^2 and P_{Rb} is 0.6.

c) Beam emittance

$\eta_{inj} \sim \sqrt{\eta_{ECR}^2 + \eta_{Rb}^2 + \eta_{SONA}^2} \sim \sqrt{(50\pi)^2 + (100\pi)^2 + (179\pi)^2} \sim 211\pi$ mm · mr

II. Second phase

a) Composition



b) Beam current and Polarization

$I_{inj}(^3He^{2+}) \sim I_{ECR} \times 0.2 \times 3 \cdot 10^{-1} = 4mA \times 0.2 \times 3 \cdot 10^{-1} = 240\mu A$

$I_{target}(^3He^{2+}) \sim I_{inj}(^3He^{2+})/1000 = 240\mu A/1000 = 240nA$

Polarization ~ 0.63

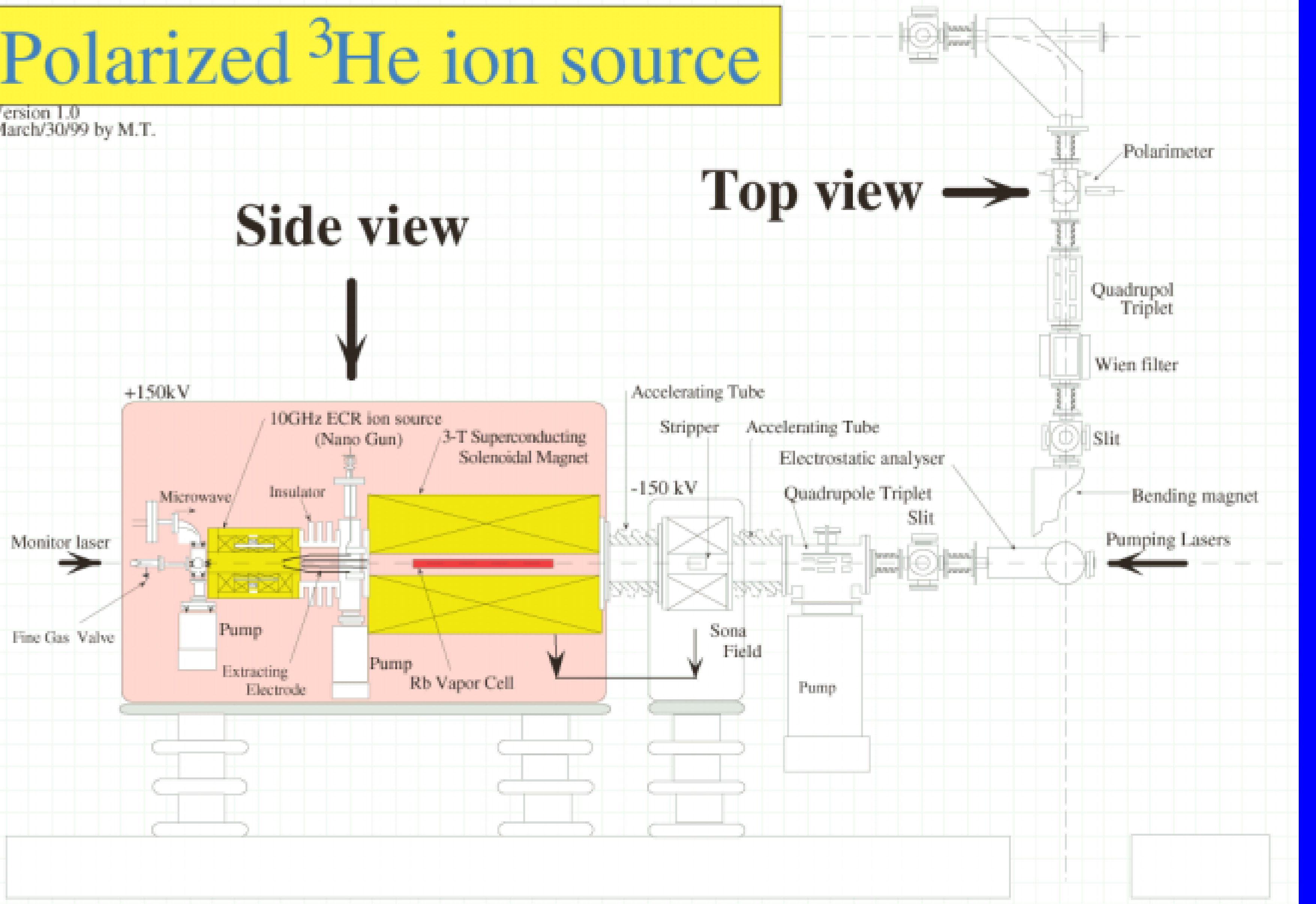
assuming that a Rb vapor thickness is 7×10^{14} atoms/cm^2 and P_{Rb} is 0.85.

c) Beam emittance

$\eta_{inj} \sim \sqrt{\eta_{ECR}^2 + \eta_{Rb}^2 + \eta_{SONA}^2} \sim \sqrt{(50\pi)^2 + (100\pi)^2 + (179\pi)^2} \sim 211\pi$ mm · mr

Polarized ^{3}He ion source

Version 1.0
March/30/99 by M.T.



Summary and future direction

We have developed a polarized ^{3}He ion source.

The OPPIS offers a very convenient method to simply polarize nuclei as far as we don't say an amount of the polarization degree. Let me show, for example, the polarization of ^{14}N recently observed by Shimoda.

The EPPIS is an extended concept of the optical pumping invented by Prof. Kastler. We hope in future there would be versatile applications in the field of science.

Further technical progress is needed for its full performance particularly in realizing high alkali polarization uniformly distributed.

The SEPIS is one of the most convenient methods to produce a fully polarized ^{3}He beam without further development.

Another important aspect imposed for the polarized ion sources is a beam intensity.

In fact, Ramsey said that

Intensity is everything.

For this purpose, we have examined carefully beam emittances and theoretically predicted a strange effect named polarization hole which will be useful in future.

Roma non uno die aedifficata est.

Beam emittance growth really suppressed in the EPPIS?

For this purpose, Behavior of ^{3}He ions colliding with polarized/unpolarized gas under a strong magnetic field has not well bee investigated by means of the Monte Carlo simulation method.

1. Study with unpolarized gas:

   Come up to concept of
   effective magnetic field

2. Study with polarized gas:

   Come up to concept of
   polarization hole

How to realize highly polarized Rb vapor uniformly distributed

An areal uniformity of the Rb polarization depends on the relaxation mechanism occuring in the vapor cell.
For this purpose, the Rb relaxation times were measured by observing the polarization time-differentially with chopped laser lights.

Changing parameters:

1) the external magnetic field
2) the cell temperature
3) the pumping laser frequency

A simple model and Monte Carlo simulation were compared with the observed quantities to discuss the relaxation mechanisms.
As a result, the relaxation mechanism is found to mainly be determined by

1) Wall relaxation
2) Effusion
3) Radiation trapping

This finally gave insight into how to realize uniform distribution of the Rb polarization.