A PROPOSAL OF POLARIZED $^3He^{++}$ ION SOURCE FOR NUCLOTRON-M

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The goal is to make a source of polarized ^{3}He^{++} ions (helions) on a base of the source of polarized deuterons for NUCLOTRON-M.

The RF dissociator is fed with unpolarized helium-3 gas for production of ^{3}He atoms in the metastable 2^3S_1 state.

Ionization to ^{3}He^{++} and accumulation of the polarized helions will be carried out by the electron beam ion source (EBIS) in a reflex mode.

Magnetic moment of helion $\mu_h = -2.127\mu_N$.
Magnetic moment of neutron $\mu_n = -1.913\mu_N$.

Earlier, the Laval group (Slobodrian et al., Nucl. Instr. & Meth. 220 (1984) 582**) polarized ^{3}He atoms in the metastable state 2^3S_1 (a lifetime of 7860 s) with electron spin $J = 1$ and then ionized them to $^3He^+$ in an electron impact ionizer.**

The subsequent ionization to $^3He^{++}$ was effected by stripping in the base of the Van de Graaf accelerator at 7.5 MV.

The cold cathode discharge source of metastable atoms with an average velocity of 2.5×10^5 cm/s produced a flux of 6×10^{15} atoms/s sterad.

Stern-Gerlach separation with a sextupole magnet and an RF transition in a weak magnetic field were used for nuclear polarization of the metastable atoms.

The ionization potential of metastable atoms is quite low, 4.6 eV compared to 24.6 eV for atoms in the ground state.

Slobodrian operated the ionizer in a mode that discriminates between metastables and ground state atoms, producing thus $^3He^+$ from the nuclear polarized metastable atoms.

The angular momentum of a ^{3}He(2S) atom is the vector sum $\vec{F} = \vec{J} + \vec{I}$, where $\vec{J}$ and $\vec{I}$ correspond to the electronic ($J = 1$) and nuclear ($I = 1/2$) angular momenta, respectively.

The wave functions of the hyperfine states are

$$\psi(F = 1/2, m_F = +1/2) = \sqrt{2/3}\phi_J(+1)\phi_I(-1/2) - \sqrt{1/3}\phi_J(0)\phi_I(+1/2) \ \ \rightarrow \phi_J(+1)\phi_I(-1/2), \quad (1)$$

$$\psi(F = 3/2, m_F = +3/2) = \phi_J(+1)\phi_I(+1/2), \quad (2)$$

$$\psi(F = 1/2, m_F = -1/2) = -\sqrt{2/3}\phi_J(-1)\phi_I(+1/2) + \sqrt{1/3}\phi_J(0)\phi_I(-1/2) \ \rightarrow \phi_J(0)\phi_I(-1/2), \quad (3)$$

$$\psi(F = 3/2, m_F = +1/2) = \sqrt{2/3}\phi_J(0)\phi_I(+1/2) + \sqrt{1/3}\phi_J(+1)\phi_I(-1/2) \ \ \rightarrow \phi_J(0)\phi_I(+1/2), \quad (4)$$

$$\psi(F = 3/2, m_F = -1/2) = \sqrt{2/3}\phi_J(0)\phi_I(-1/2) + \sqrt{1/3}\phi_J(-1)\phi_I(+1/2) \ \ \rightarrow \phi_J(-1)\phi_I(+1/2) \quad (5)$$

$$\psi(F = 3/2, m_F = -3/2) = \phi_J(-1)\phi_I(-1/2). \quad (6)$$

The Breit-Rabi diagram of the six Zeeman hyperfine components of this metastable state is shown at Fig. 1, where the numbers correspond to those of equations (1) – (6).

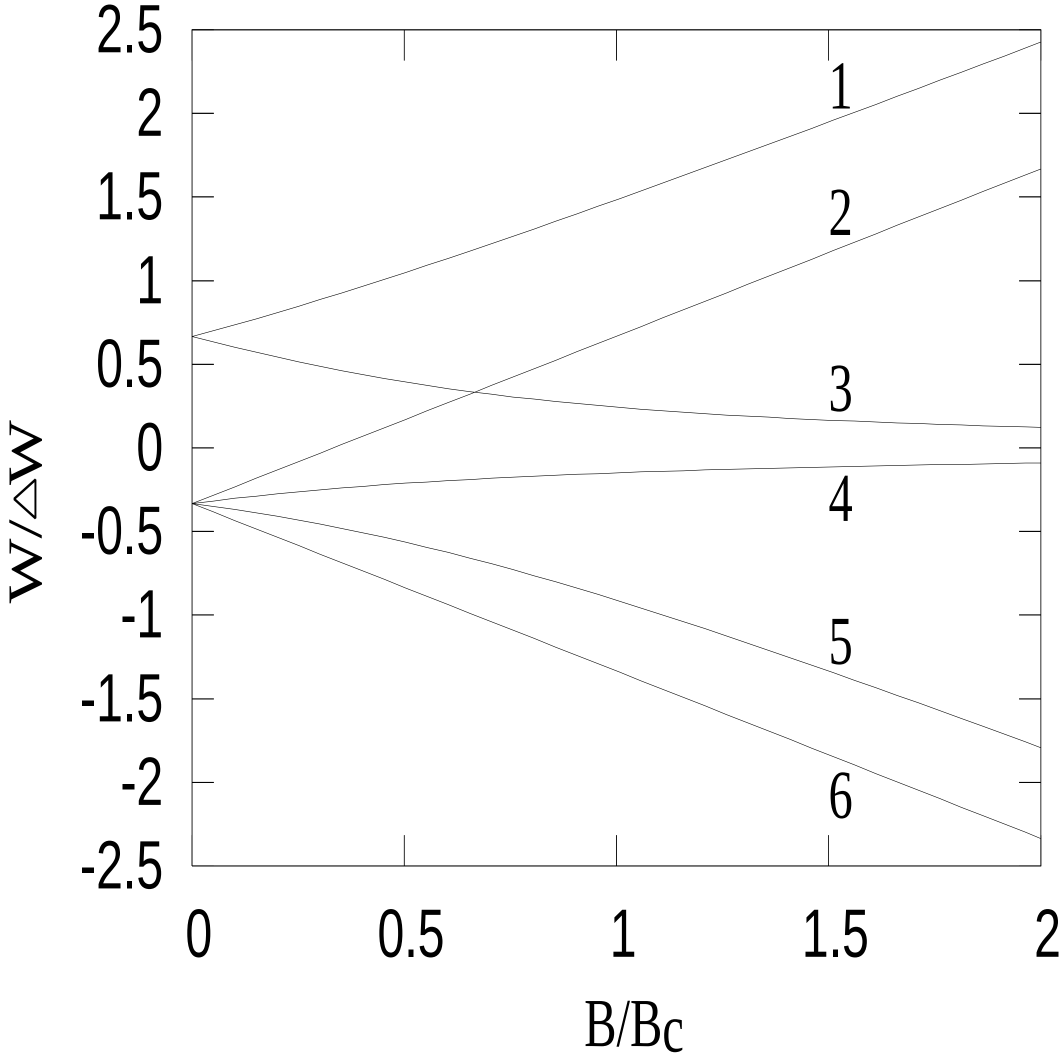

Figure 1: **Scheme of helion substates showing the hyperfine structure and Zeeman splitting**

The Hamiltonian for ^{3}He(2S) atoms

$$\hat{H} = -\mu_J \vec{B}\vec{J} - \mu_I \vec{B}\vec{\sigma}_I - \frac{1}{4}\Delta W \vec{J}\vec{\sigma}_I,$$

where $\Delta W/h = 6.7397$ GHz is the hyperfine splitting at zero magnetic field, $\mu_J \approx -2\mu_B = -28.0250$ GHz/T and $\mu_I = -2.1275\mu_N = -1.6217 \times 10^{-2}$ GHz/T.

The energies of the hyperfine states are

$$W_1 = \frac{\Delta W}{6} - \mu_J \frac{B}{2} + \frac{\Delta W}{2}\sqrt{1 + \frac{2}{3}x + x^2},$$
$$W_2 = -\frac{\Delta W}{3} - \mu_J B - \mu_I B,$$
$$W_3 = \frac{\Delta W}{6} + \mu_J \frac{B}{2} + \frac{\Delta W}{2}\sqrt{1 - \frac{2}{3}x + x^2},$$
$$W_4 = \frac{\Delta W}{6} - \mu_J \frac{B}{2} - \frac{\Delta W}{2}\sqrt{1 + \frac{2}{3}x + x^2},$$
$$W_5 = \frac{\Delta W}{6} + \mu_J \frac{B}{2} - \frac{\Delta W}{2}\sqrt{1 - \frac{2}{3}x + x^2},$$
$$W_6 = -\frac{\Delta W}{3} + \mu_J B + \mu_I B,$$

where

$$x = \frac{B}{B_c}, \quad B_c = \frac{\Delta W}{-\mu_J + 2\mu_I} = 0.2407 \text{ T}.$$

The SATURNE group (Beauvais et al. In Proc. Int. Symp. "Dubna-Deuteron-93", Dubna, 1994, p. 278) reported the preliminary results of tests made with an use of the dissociator of the HYPERION polarized ion source fed with unpolarized ^{3}He gas.

The parameters of this polarized ion source are as follows:

The dissociator is made of a Pyrex tube with a 2.2 mm diameter nozzle cooled to 80-100 K. Gas flows only during 3 ms each cycle. Peak RF power is 6 kW at 19 MHz.

The ionizer with a reflex electron beam yielded mostly ^{3}He$^+$ ions.

They produced a pulsed beam current 50 μA of 1 ms duration.

The difference between the sextupole magnet "on" and sextupole "off" was 10 μA.

Accordingly to (Ichikawa and Teil, J. Phys. D13 (1980) 1243) the metastable atom density in the dissociator is $\simeq 10^{12}$ atoms/cm^3, see Fig. 2.

For a nozzle of 2.2 mm diameter and an atom velocity of 2.5×10^5 cm/s, the metastable flux would be $\simeq 7\times10^{14}$ atoms/s sterad.

If the ionization efficiency of metastables to ^{3}He$^+$ is $\simeq$ 10 %, we may estimate the metastable atom density $\simeq 10^{14}$ atoms/cm^3.

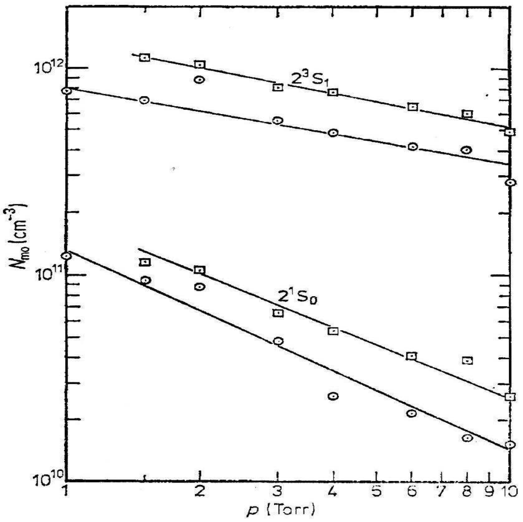

Figure 5. Experimental values of He (2^1S_0 and 2^3S_1) metastable atom densities with varying gas pressure for two different values of electron density. The maximum error of the data in the measurement is within $\pm 20\%$. ⊡, $N_{eo} = 10^{11}$ cm^{-3}; ⊙, $N_{eo} = 3 \times 10^{10}$ cm^{-3}.

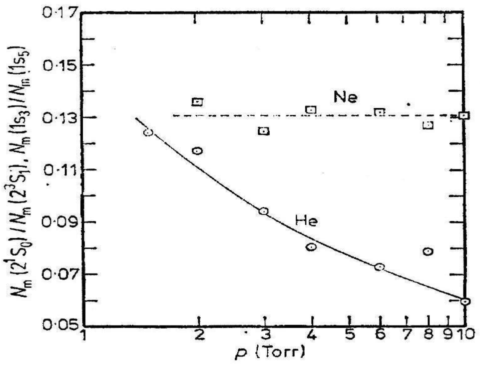

Figure 6. Variation of metastable atom density ratio with varying gas pressure at a fixed electron density. $N_{eo} = 10^{11}$ cm^{-3}.

Figure 2: **Experimental values of He metastable atom densities.**

The atomic beam source of the polarized deuteron source for NUCLOTRON-M has the following parameters:

Dissociator: pulsed RF of 2 kW peak at 35 MHz for 1 ms duration at 4 Hz. Gas flow is 7.4×10^{17} molecules/pulse. Nozzle of 2.2 mm diameter, skimmer of 4 mm diameter.

The sextupole triplet consists of permanent magnets. The forth sextupole is an electromagnet. Pole tip magnetic fields are from 1.66 T to 1.1 T.

The sextupole focuses the atomic beam into an ionizer positioned at a distance of 120 cm.

For polarized ^{3}He atomic beam, we need only one transition unit in a weak field that should be placed after all the sextupole magnets.

The trajectories of the ^{3}He(2S) atoms in the different hyperfine substates are presented at Figs. 3–4.

It is seen that the beam with a velocity of 2500 m/s could not be focused. The cooling of the atomic beam is necessary.

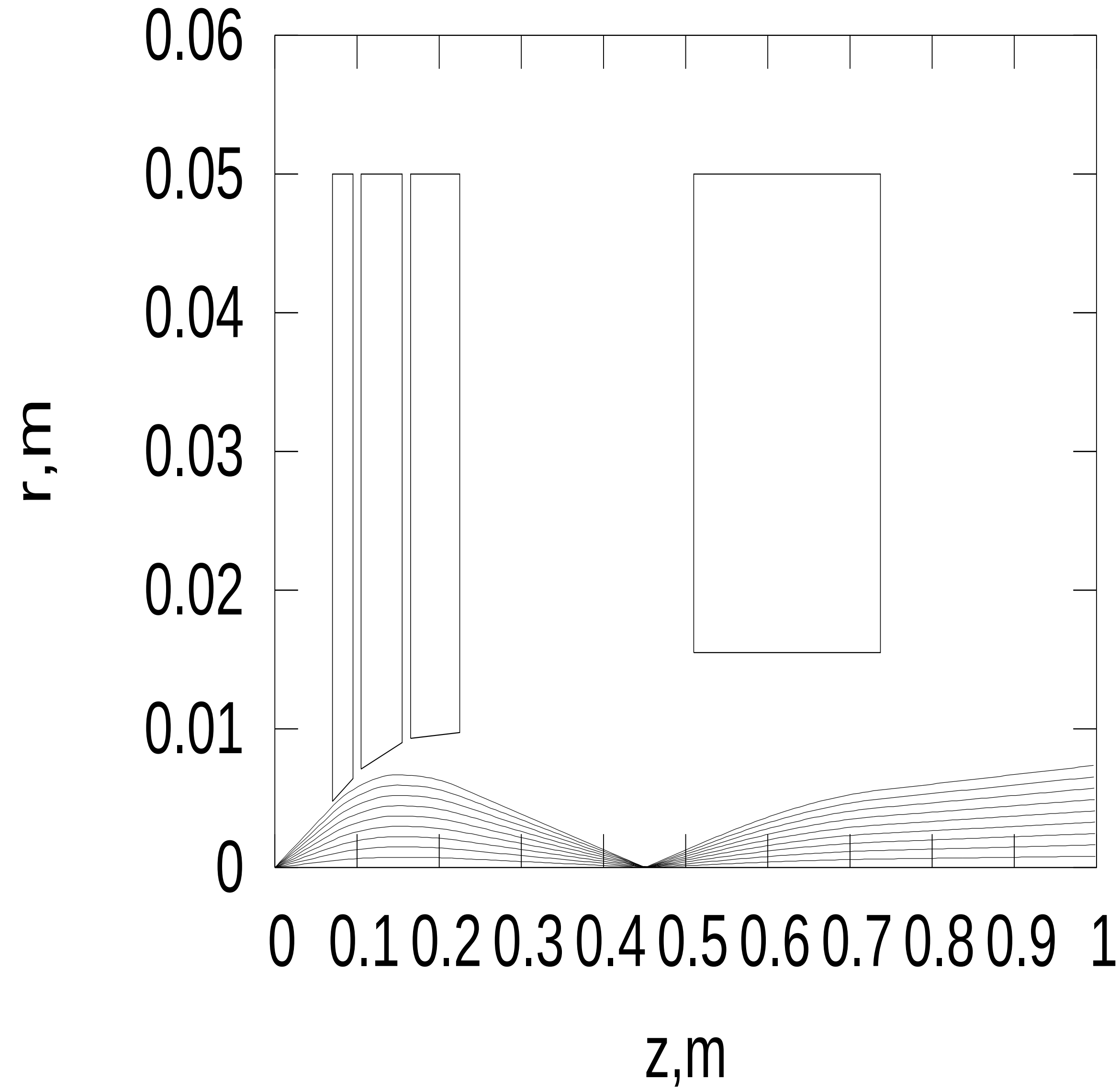

Figure 3: **Trajectories of the atoms in the substate $F = 3/2$, $m_F = +3/2$, $v = 1200$ m/s**

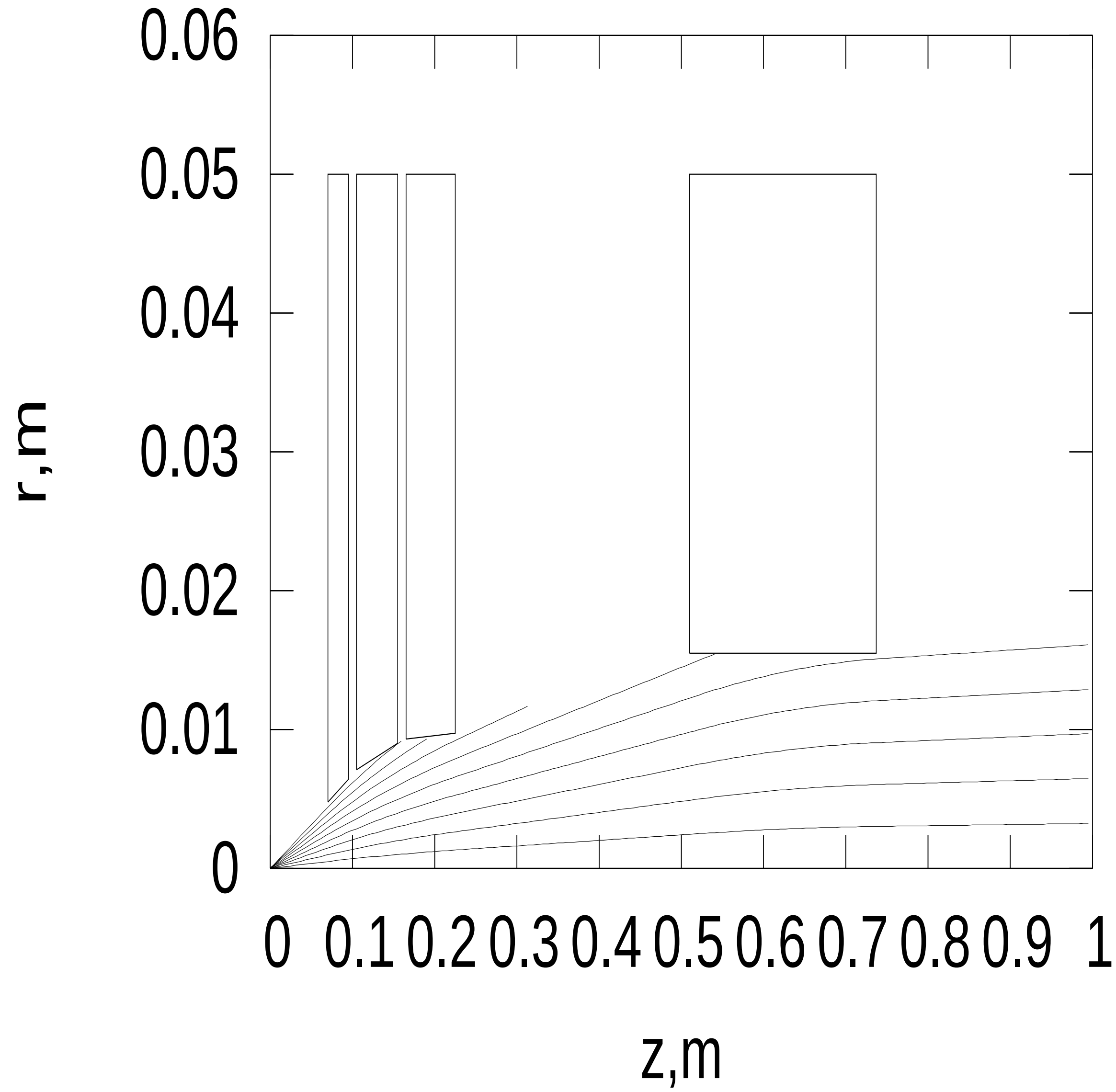

Figure 4: **Trajectories of the atoms in the substate $F = 3/2$, $m_F = +3/2$, $v = 2500$ m/s**

An evident way for producing polarized helions is to repeat the results of the Laval group and inject the nuclear polarized $^3He^+$ ions into the electron beam ion source for subsequent ionization.

But for a pulsed regime there is a possibility to ionize metastable atoms directly up to $^3He^{++}$ in an ion trap of the EBIS with 8 μs pulse extraction.

The ion trap is produced by space charge of oscillating electrons in a drift tube region (radial confinement) and potential barriers on the boundary drift tubes (axial confinement).

An electron cloud is confined in the radial direction by a solenoid magnetic field up to 5 T.

This high field is also needed to exclude ^3He nuclear depolarization in the ionizer.

For metastables, the cross section of ionization at an electron energy of 10 keV $\sigma_i^*(0 \to 1) \approx 7.3 \times 10^{-18}$ cm^2, much more than for atoms in the ground state ($\sigma_i(0 \to 1) \approx 2 \times 10^{-18}$ cm^2).

The electron beam density for the metastable atom ionization to $^3He^+$ at the length of the ionizer 100 cm with a velocity of 1.2×10^5 cm/s is 26 A/cm^2.

The cross section $\sigma_i(1 \to 2) \approx 4.3 \times 10^{-19}$ cm^2. Then, for the electron density 26 A/cm^2 the confinement time for ionization to helions will be 14 ms.

With the electron beam diameter of 5 mm the effective electron current is 5 A.

In comparison with production of highly charged ions the given mode has a number of advantages:

1. There is no time of ionization, as much as possible charge of ions entered into the trap will be extracted therefore.

2. It is not required the division of the place of ion input with the volume of the trap. Input in all the volume will lead to increase in the accumulated charge as the working length of the trap increases.

3. It is possible to enter ^{3}He into the trap at the raised pressure that will lead to increase of the ion charge in the trap.

4. Earlier Donets et al. (Rev. Sci. Instr. 71 (2000) 887) realized a pulsed extraction of ions from a trap for 7 μs with a current of 1 mA, that corresponds to 4×10^{10} charges. At work with helium, it is really to receive the intensity 2-3 times higher.

Here the projected ionizer parameters:

- electron energy – 10–20 keV,
- effective current ≈ 5 A,
- ion trap length – 1 m,
- helion intensity $\approx 2 \times 10^{11}$ ions/pulse.

The experiments (Fimushkin et al., Czech. J. Phys. 51 (2001) A319) (Fig. 5) with the ionizer of the polarized deuteron source POLARIS show the feasibility to store in the ion trap up to 4×10^{11} charges.

The chief elements of the future ionizer are: a 5 T superconducting magnet, electronic optical system, 20 keV modulator, 8 μs system of fast extraction and remote control system.

At the exit of the ionizer we have to install a deflecting magnet to separate $^3He^{++}$ from $^3He^{+}$ ions. For helions G-factor equals -4.183963, so, to get transversal spin polarization we need to deflect the beam to $21.5°$. Then a solenoid will rotate spin to vertical direction, up or down.

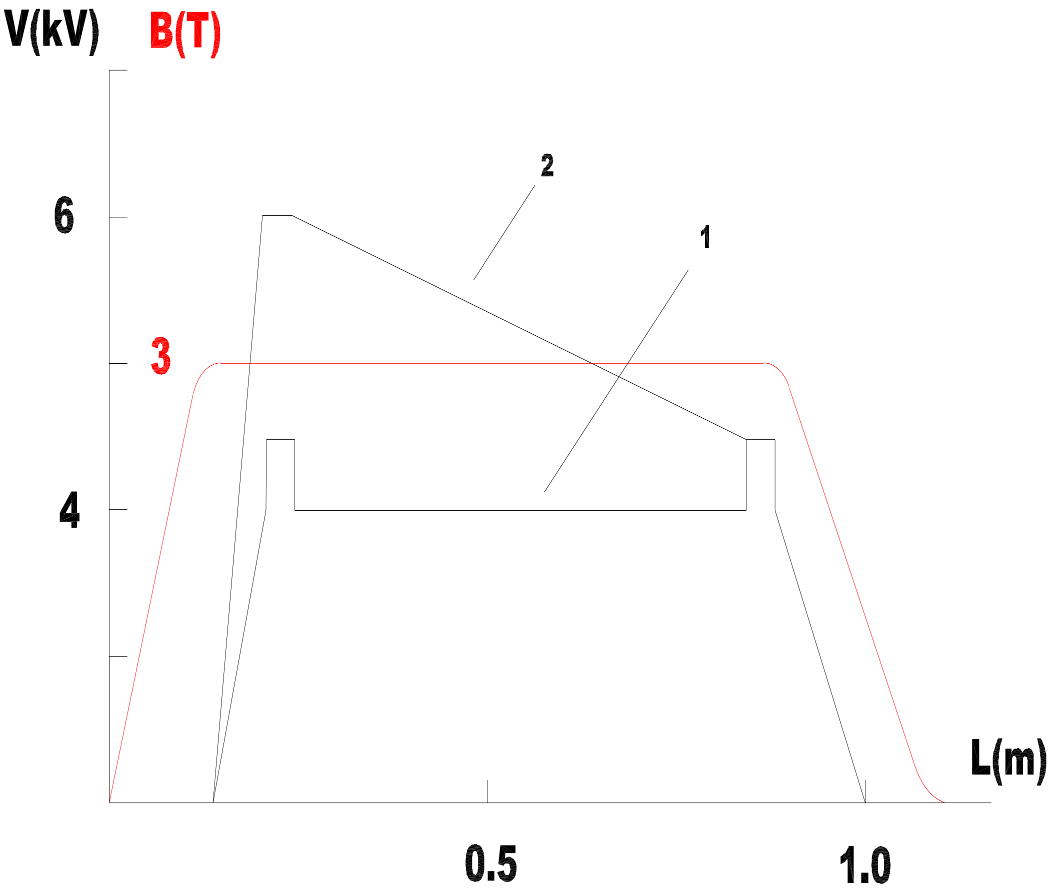

Figure 5: **The distributions of magnetic field and voltage on the drift tubes at accumulation (1) and extraction(2) of the helions.**

The time between metastability exchange collisions is $\tau = 1/\sigma v N$, where σ is the cross section for the metastability exchange, v is the velocity of metastables and N is the density of ground state atoms.

With $v = 2.5 \times 10^5$ cm/sec and $\sigma = 4 \times 10^{-16}$ cm^2 (Colegrove et al., Phys. Rev. 132 (1963) 2561) the condition for $\tau \gg T_{acc}$, where T_{acc} is the time of accumulation

$$\sigma v N \ll T_{acc}^{-1} \ \text{ or } \ N \ll 10^{10} T_{acc}^{-1},$$

or $p \ll 2.7 \times 10^{-7}/T_{acc}$ Torr.

For $T_{acc} = 10^{-2}$ s it is necessary that $p \ll 2.7 \times 10^{-5}$ Torr.

The dangerous process is the symmetric resonant charge transfer expressed by

$$^3\mathrm{He}^{++} + ^3\mathrm{He} \rightarrow ^3\mathrm{He} + ^3\mathrm{He}^{++}.$$

The cross section of this process is estimated to be $\simeq 7 \times 10^{-16}$ cm^2, even more than the cross section for metastability exchange.

Then it is demanded that the background pressure of ^{3}He be

$$p \ll 10^{-6} \text{ Torr}.$$

Let a metastable flux be 6×10^{15} atoms/s sterad.

If we assume that the flux of atoms in the ground state is $\simeq 10^2$ times more than the metastable flux, the pressure of the ground state atoms in the ionizer at the distance of 120 cm from the nozzle is $\simeq 10^{-8}$ Torr.

Hamiltonian for $^3He^+$ ions

$$\hat{H} = -\mu_J \vec{B}\vec{\sigma}_J - \mu_I \vec{B}\vec{\sigma}_I - \frac{1}{4}\Delta W \vec{\sigma}_J \vec{\sigma}_I.$$

$\mu_J \approx -\mu_B$, $\Delta W/h = 8.6437$ GHz.

The wave functions of the hyperfine states:

$\psi(\mathrm{F}=1, \mathrm{m}=1) = \phi_e^+ \phi_I^+$,

$\psi(1,0) = \sin\beta\phi_e^+\phi_I^- + \cos\beta\phi_e^-\phi_I^+$,

$\psi(1,-1) = \phi_e^-\phi_I^-$,

$\psi(0,0) = -\cos\beta\phi_e^+\phi_I^- + \sin\beta\phi_e^-\phi_I^+$,

where

$$\sin\beta = \frac{1}{\sqrt{2}}\left(1 - \frac{y}{\sqrt{1+y^2}}\right)^{1/2},$$

$$\cos\beta = \frac{1}{\sqrt{2}}\left(1 + \frac{y}{\sqrt{1+y^2}}\right)^{1/2},$$

$$y = \frac{B}{B_c}, \quad B_c = \frac{\Delta W}{-2\mu_J + 2\mu_I} = 0.3087 \text{ T}.$$

Zeeman effect:

$$W(1,1) = -\frac{\Delta W}{4} - \mu_J B - \mu_I B,$$

$$W(1,0) = \frac{\Delta W}{4} - \frac{\Delta W}{2}\sqrt{1+y^2},$$

$$W(1,-1) = -\frac{\Delta W}{4} + \mu_J B + \mu_I B,$$

$$W(0,0) = \frac{\Delta W}{4} + \frac{\Delta W}{2}\sqrt{1+y^2}.$$

The adiabatic transition in a weak magnetic field ($m_F \to -m_F$) transforms components 1-2 into 3-6. This produces nuclear polarization $P \approx -1$ in a strong magnetic field $B > B_c$, ($B \approx 3B_c \approx$ 1 T).

In the magnetic field the wave function of hyperfine substate 3 of a ^{3}He(2S) atom is

$$\psi(F = 1/2, m_F = -1/2) \to \cos\alpha\phi_J(0)\phi_I(-1/2) \\ +\sin\alpha\phi_J(-1)\phi_I(+1/2),$$

where

$$\tan\alpha = \frac{2\sqrt{2}}{3}\frac{1}{\frac{1}{3} - x - \sqrt{1 - \frac{2}{3}x + x^2}}$$

For $x = 1$, $\alpha = -0.5176$, $\cos\alpha = 0.8808$, $\cos^2\alpha = 0.7887$ and $\sin\alpha = -0.4597$, $\sin^2\alpha = 0.2113$.

In a strong magnetic field

$$\psi(F = 1/2, m_F = -1/2) \to \phi_J(0)\phi_I(-1/2). \qquad (7)$$

Substate 6 $\psi(F = 3/2, m_F = -3/2) = \phi_J(-1)\phi_I(-1/2)$ does not change.

The helion polarization at ionization in a strong magnetic field B will be

$$P = \frac{1}{2} + \frac{1}{2}\sin^2\alpha\left(\frac{1}{1+y^2} - 1\right) + \frac{1}{2}\cos^2\alpha\left(1 - \frac{0.5}{1+y^2}\right),$$

where $y = B/B_c(^3\mathrm{He}^+)$.

In Slobodrian' scheme, with ionization ^{3}He$^+$ to ^{3}He^{++} in a weak field ($y \approx 0$)

$$P = \frac{1}{2} + \frac{1}{4}\cos^2\alpha \approx 0.7 \ \text{ for } \ x = 1.$$

When an atom or ion has an electron spin, the nuclear depolarization can be influenced by hyperfine interaction.

Under an external field B, the primary nuclear polarization of the ^{3}He atom is reduced in the intermediate $^3He^+$ ion by a factor α:

$$\alpha = 1 - \frac{1}{2(1 + y^2)},$$

where $y = B/B_c$, with $B_c = 0.3087$ T for $^3He^+$ ions. For $B = 1$ T, $\alpha = 0.956$.

There are many different processes that may produce depolarization, but it seems that they are unessential as the experience of SATURNE group (Courtois et al., Rev. Sci. Instrum. 63 (1992) 2815) shows. They ionized $^6Li^+$ polarized ions to bare nuclei $^6Li^{3+}$ in the 5 T field EBIS without depolarization during accumulation for 3 ms and extraction.

Conclusion

We have discussed the possibility of the creation of the polarized helion source for NUCLOTRON-M.

It seems possible to provide a polarized beam with polarization larger than 80% and helion intensity $\approx 2 \times 10^{11}$ ions/pulse of 8 μsec.

The depolarizing effects in the polarized ion source are expected to be low.

For acceleration at the NUCLOTRON it is necessary to provide the conditions for low depolarization.

The installation of the polarized helion source at the accelerator complex of JINR, Dubna, will allow to extend the program of spin physics experiments.