Research and development of the polarized deuteron source for the Van de Graaff accelerator

Yu.A. Plis

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1 Introduction

Formally, the measurement of spin-dependent parameters allows imposing additional restrictions on the reaction mechanism and structure of the micro-object under study. As an example, the measurements of $\Delta\sigma_T$ and $\Delta\sigma_L$ are necessary to determine the imaginary part of nd forward elastic scattering amplitude [S. Ishikawa et al., in *Proc. of the 14th Int. Spin Physics Symp.*, Osaka, 2000, p. 724]. Also these measurements are important for the problem of 3-nucleon forces [H. Witala et al., *Phys. Lett.* B447 (1999) 216-220].

So we plan to send polarized deuterons to a tritium target for producing 14-MeV polarized neutrons which will be used with the frozen-spin polarized deuteron target for measuring $\Delta\sigma_T$ and $\Delta\sigma_L$ in the neutron-deuteron transmission experiment.

In the former experiments (Prague, Charles University), transversely polarized neutrons were produced as a secondary beam in the ^{3}H$(d,\vec{n})^4$He reaction with deuterons of energies up to 2.5 MeV. To achieve a monoenergetic collimated neutron beam, the associated particle method was used [I. Wilhelm et al., *Nucl. Instr. & Meth.* A317 (1992) 553].

The neutron beam with an energy of $\boldsymbol{E_n = 16.2}$ MeV was emitted at an angle $\boldsymbol{\theta_{lab} = 62.0^\circ}$. The value of neutron polarization amounted $\boldsymbol{P_n = -0.135 \pm 0.014}$.

To get longitudinal beam polarization in the $\boldsymbol{\Delta\sigma_L}$ experiment, the neutron spin was rotated with help of a permanent magnet of 0.5 T m.

The present experiment is a continuation in the Czech Technical University in Prague of the previous measurements of the same quantities in $\vec{n}\vec{p}$ scattering [J. Broz et al., *Z. Phys.* A35 (1996) 401; A359 (1997) 23].

Preliminary experiments showed that polarization and intensity of the neutron beam and also the deuteron polarization of the target are insufficient for achievement of necessary accuracy of the measurement of the cross-section difference [N.S. Borisov et al., Nucl. Instr. & Meth. A593 (2008) 177].

To improve the parameters of the neutron beam it is proposed now to use the reaction $^3\text{H}(\vec{d},\vec{n})^4\text{He}$ with polarized deuterons of an energy of 100-150 keV.

Also we plan to replace the current target material (propanediol) with a novel material with chemical doping by the radicals of the trityl family, which showed the deuteron polarization as high as 0.80 [S.T. Goertz et al., *Nucl. Instr. & Meth.* A526 (2004) 43].

The total cross-section difference $(\Delta\sigma_L)_d$ was measured at TUNL (North Carolina) [R.D. Foster et al., *Phys. Rev.* C73 (2006) 034002] for incident neutron energies of 5.0, 6.9 and 12.3 MeV.

The first proposal concerning the nuclear polarization via a pick-up of polarized ferromagnetic electrons was made by Zavoiskii in 1957 [E.K. Zavoiskii, *J. Exp. Theor. Phys.* 32 (1957) 408; English translation, *Sov. Phys. – JETP* 5 (1957) 338].

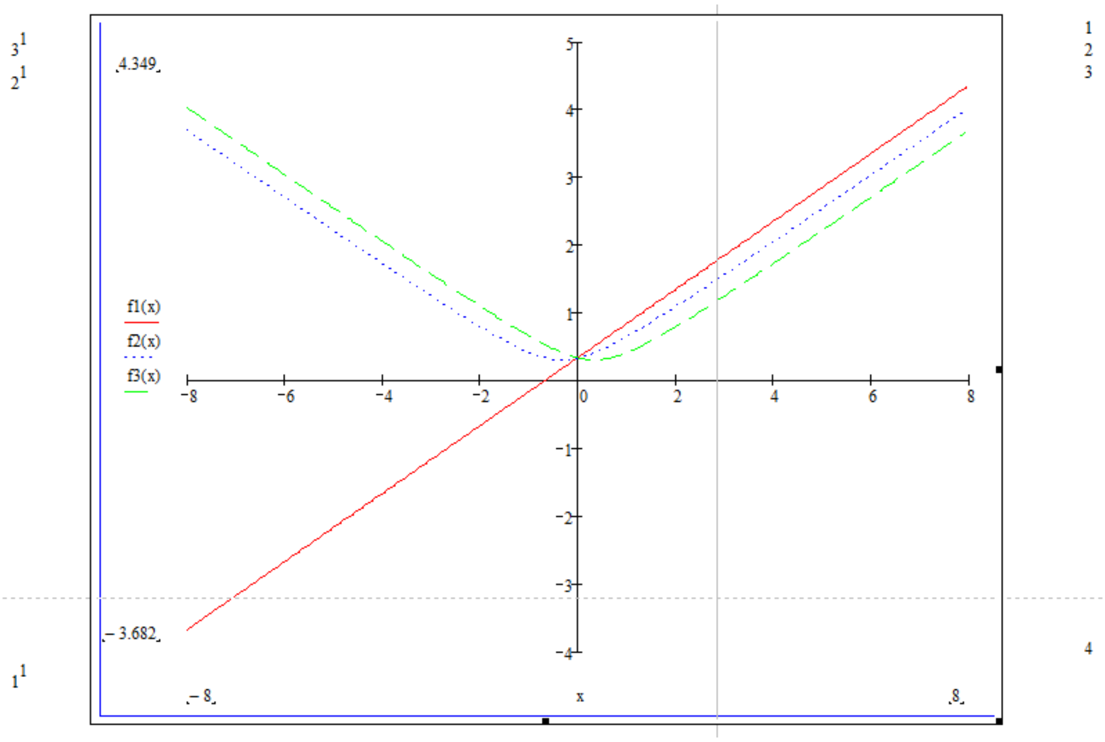


Figure 1: Breit-Rabi diagram of hyperfine components

The method proposes adiabatic transition of the atoms from a high magnetic field to a low magnetic field of an order 1 mT where the nuclei are polarized through the hyperfine interaction.

Here, we base on the results of the experiment of Kaminsky [M. Kaminsky, *Phys. Rev. Lett.* **23** (1969) 819; in *Proc. of 3rd Int. Symp. on Polarization Phenomena in Nuclear Reactions*, Madison, 1970, p. 803] on the production of nuclear polarized deuterium atoms by channeling of a low energy deuteron beam through a magnetized single-crystal nickel foil. In his setup a beam of D^+ with a half

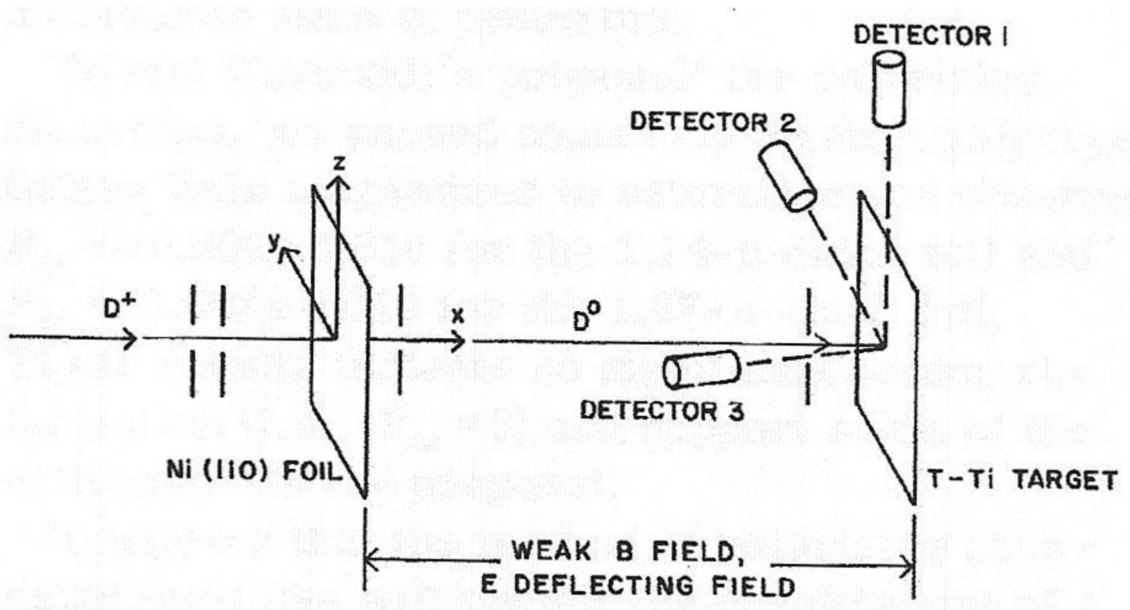


Figure 2: The scheme of Kaminsky' experiment.

angle of 0.01° was incident on a Ni(110) foil $\approx 2\mu$m thick within 0.1° of the [110] direction (the critical acceptance angle $(1.6 - 1.8)^\circ$).

He obtained 500 nA/cm^2 of channeled deuterium atoms with nuclear polarization $P_{zz} = -0.32 \pm 0.010$ (without a significant lattice damage for 25 h of operating time).

2 Another experiments

Feldman et al. [L.C. Feldman et al., *Radiation Effects* 13 (1972) 145] have made polarization measurements with an experimental arrangement very similar to that of Kaminsky.

Their data qualitatively agree with Kaminsky's ($P_{zz} = -0.14 \pm 0.06$). Also, as in Kaminsky's experiment, no effect is seen for polycrystalline foils.

Feldman et al. have studied the influence of surface oxide layers and the deleterious effects of radiation damage.

In addition, these authors attempted to observe an effect using thin polycrystalline foils of Fe.
No effect was seen, possibly because of the presence of thick (50-100 Å) surface oxide layers.

Electron field-emission experiments [W. Gleich et al., *Phys. Rev. Lett.* 27 (1971) 1066] on Ni have shown that electrons field-emitted along the [100], [110] and [137] directions have predominantly spin-up (along the magnetic field), but are spin-down along the [111].

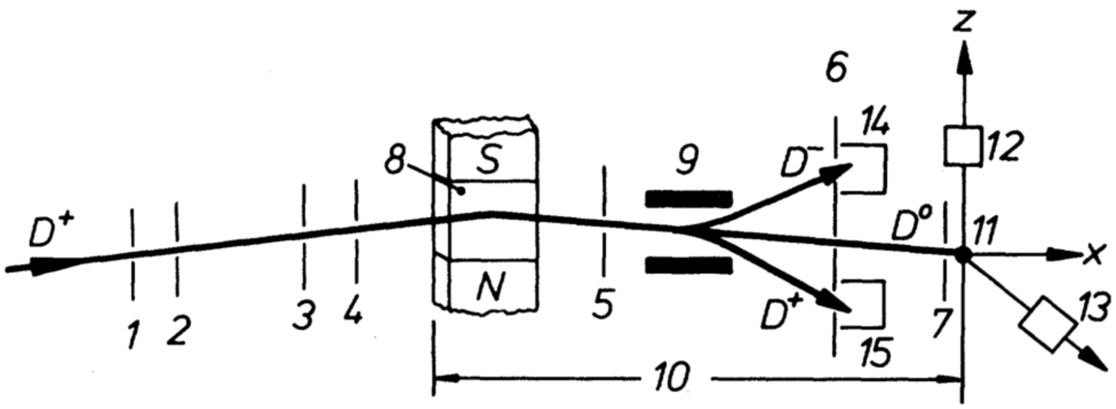


Figure 3: Scheme of the experimental setup of Rau and Sizman.

Rau and Sizmann [C. Rau, R. Sizmann, *Phys. Lett.* A43 (1973) 317] measured the polarization, also using the ^{3}H(d,n)^{4}He reaction, of the nuclei in neutral deuterium atoms created by electron capture during reflection of a 150-keV D^+ beam incident at glancing angles ($< 0.4°$) upon the surface (110) of magnetized Ni crystals.

The results show that the electron spin orientation is predominantly parallel to the magnetizing field for electrons in the (100), (110), and (111) surfaces and antiparallel in the (120) surface.

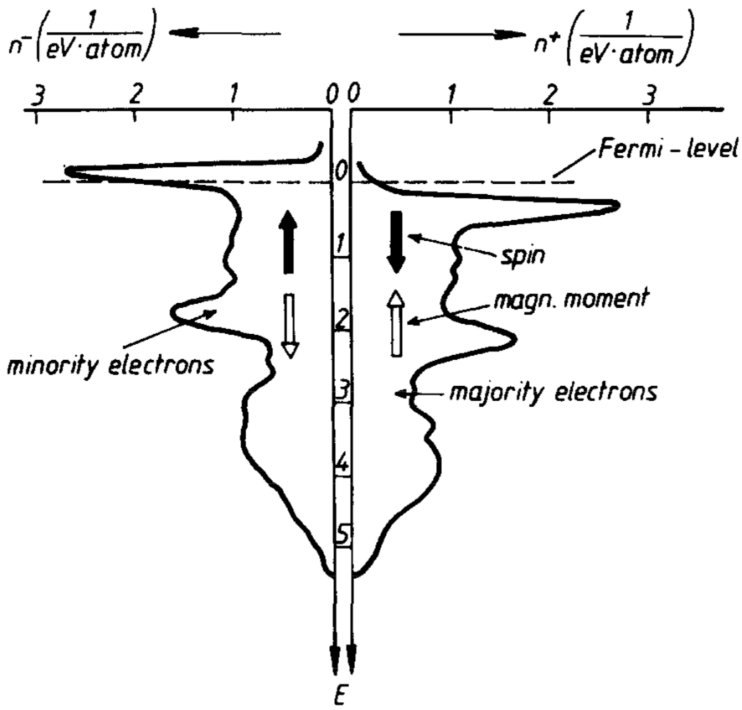


Figure 4: Spin-polarized total electron densities for Ni(110) as function of electron energy.

At the surface (110) the electron spin polarization $P_z = 0.96 \pm 0.03$ [C.Rau, *J. Magnetism and Magnetic Materials* **30** (1982) 141].

It was found that vacuum of 2×10^{-8} Torr was necessary in order to see polarization effects.

If the vacuum was allowed to deteriorate to 5×10^{-6} Torr, the polarization gradually vanishes, presumably, as a result of the build-up of thin layers of surface contaminants.

3 Theory

Ebel [M.E. Ebel, *Phys. Rev. Lett.* 24 (1970) 1395] tried to explain the high observed polarization by postulating that once a deuteron has captured a spin-up electron inside the crystal, the probability of its losing would be small since the spin-up 3d-band states are filled.

A captured spin-down electron, on the other hand, could readily be lost since the spin-down 3d-band states in the crystal are not filled.

This would give rise to a pumping of electrons from spin-down to spin-up atomic states of deuterium.

Brandt and Sizmann [W.Brandt, R. Sizmann, *Phys. Lett.* A37 (1971) 115], however, pointed out that there cannot exist stable bound electronic states in deuterium atoms passing through metals at these velocities.

They proposed instead that the electron capture takes place in the tail of the electron density distribution at the crystal surface where the density is low enough for bound states to be stable.

Thus the electron polarization in the neutral beam would be determined by the polarization of the electrons available at the surface.

Later, Kreussler and Sizmann [S. Kreussler, R. Sizmann, *Phys. Rev.* B26 (1982) 520] noted that at high energies (more than 250 keV/amu) neutralization take place chiefly in the bulk of a crystal and the surface effects are important at more lower energies.

The theory estimates approximately that the surface Fermi electrons for (110) plane have the polarization **+0.67** and totally electrons are only **−0.05** polarized [L. Hodges et al., *Phys.Rev.* 152 (1966) 505].

4 Experimental setup

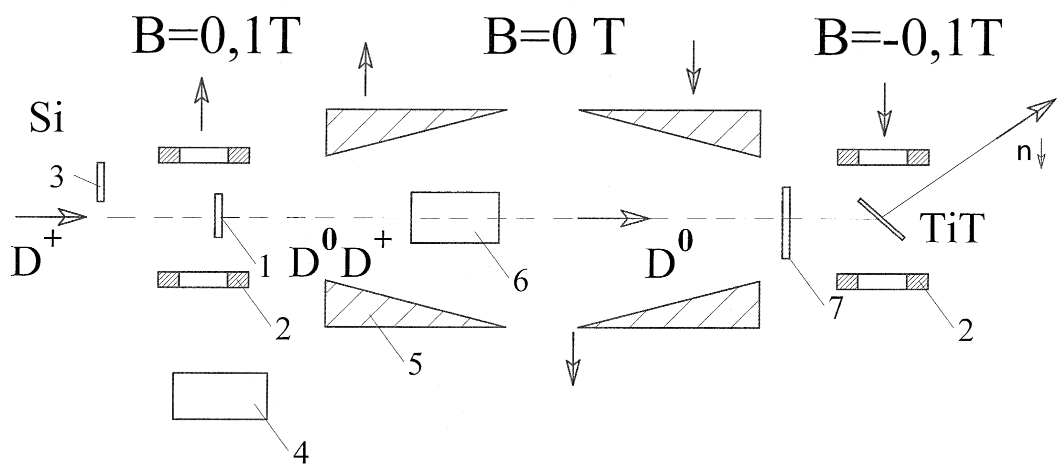


Figure 5: Scheme of the polarized deuteron source; 1 – a nickel foil, 2 – a permanent magnet (0.07 T), 3 – a solid state detector, 4 – a goniometer, 5 – polarizing permanent magnets (for Sona transitions), 6 – electrostatic plates, 7 – a target of a polarimeter.

The scheme of the experimental setup is shown in Fig.5. We propose to apply the Sona method, zero-field transitions with total transfer of the electron polarization to deuterons in the atomic beam [P.G. Sona, *Energia Nucleare* 14 (1967) 295]. We use the permanent magnets with changing distance between the poles.

The charged deuterons are deflected by magnetic and electric fields. The Ni single-crystal foil (110) with thickness 1.5-2 μm and the target of a polarimeter are placed in oppositely directed strong magnetic fields of an order of 0.1 T.

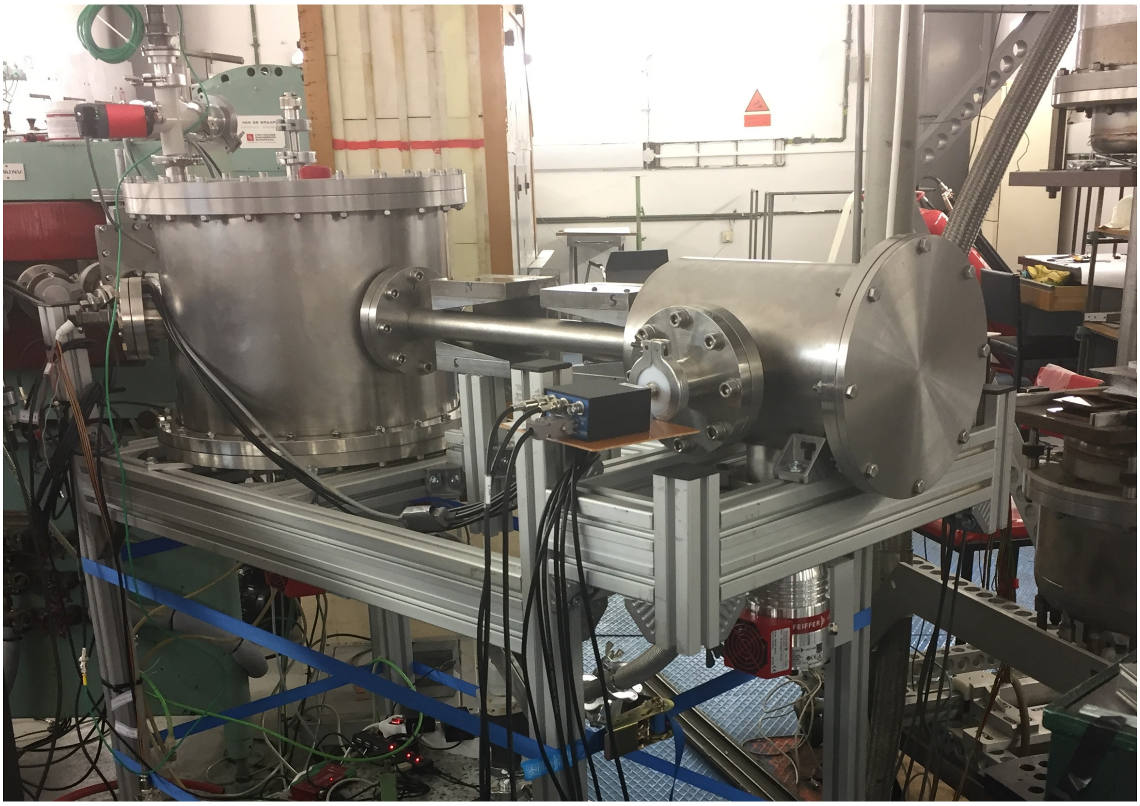


Figure 6: Photo of the experimental setup.

The magnetic field is directed vertically in the foil plane , so we must use Sona transitions with transversal magnetic fields. This is different from the usual configuration using axial magnetic fields.

The single-crystal nickel foils of thickness up to 2 μm are grown epitaxially on NaCl crystals cleaved to expose the (110) plane (produced by Princeton Scientific Corp.). The substrate was dissolved by water and the Ni-foils were floated on a Cu-support which was mounted in the goniometer.

According theory, the atomic beam being in a strong magnetic field should have vector polarization of deuterons up to the theoretical maximum $P_3 = 2/3$ and zero tensor polarization.

If we send this deuterium beam to a tritium target, the 14-MeV neutrons of the dt-reaction produced at the angle 90° (CM) have almost the same vector polarization as deuterons [G.G. Ohlsen, *Rep. Progr. Phys.* 35 (1972) 717].

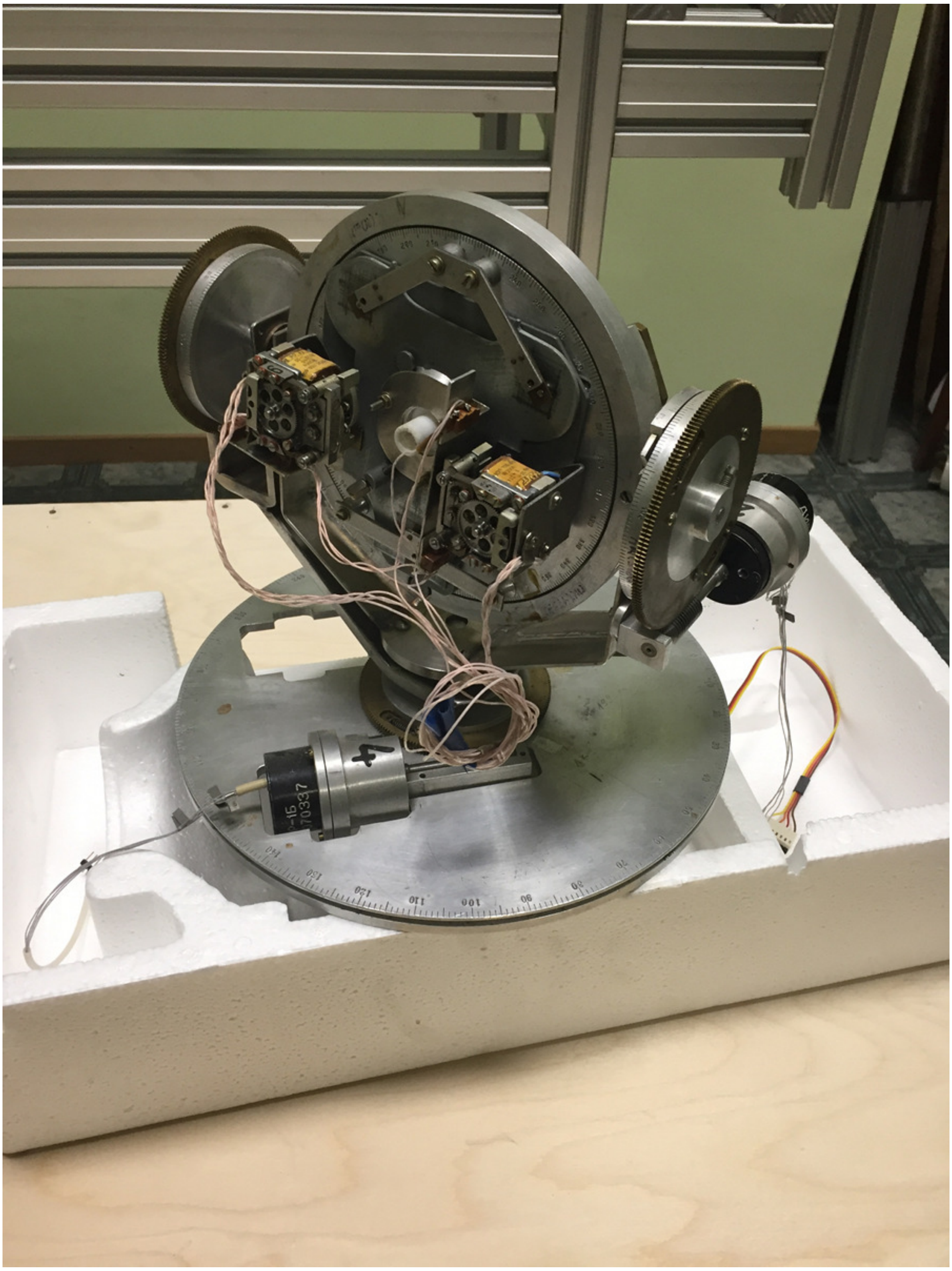


Figure 7: **The goniometer.**

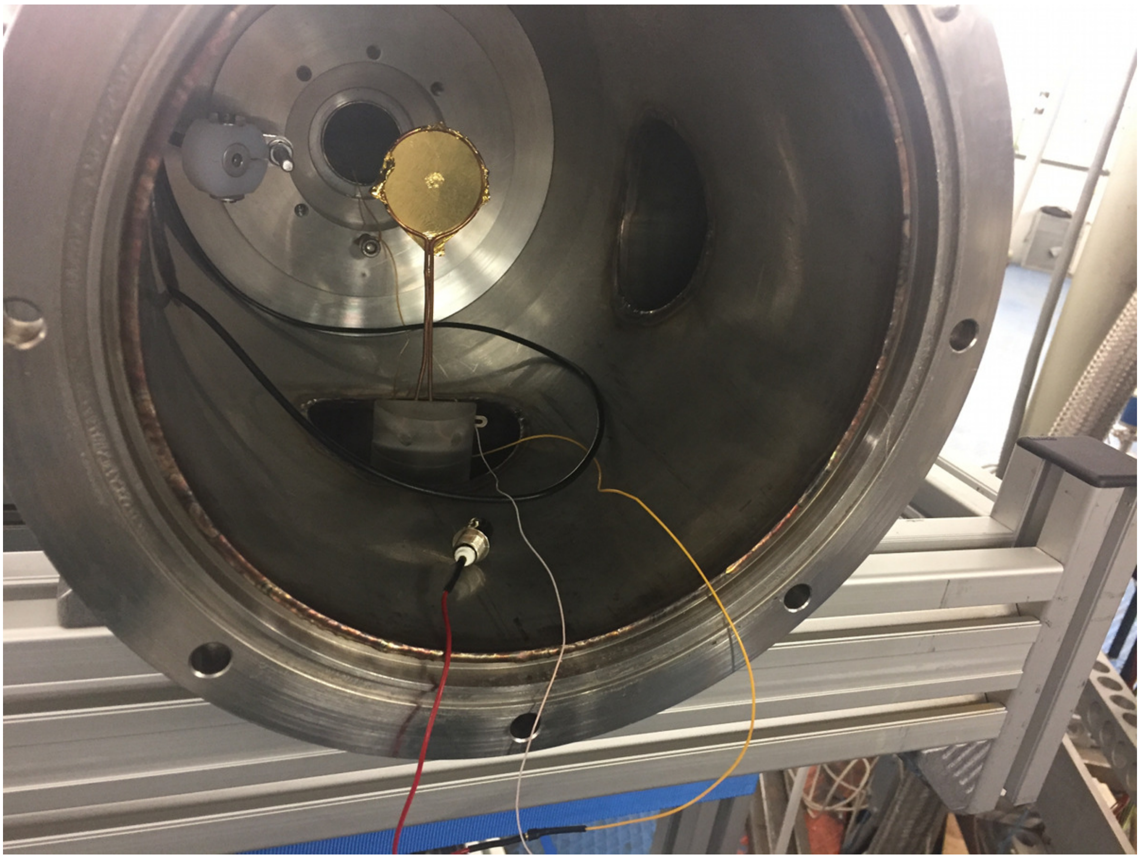


Figure 8: **The Au-foil used for beam adjustment.**

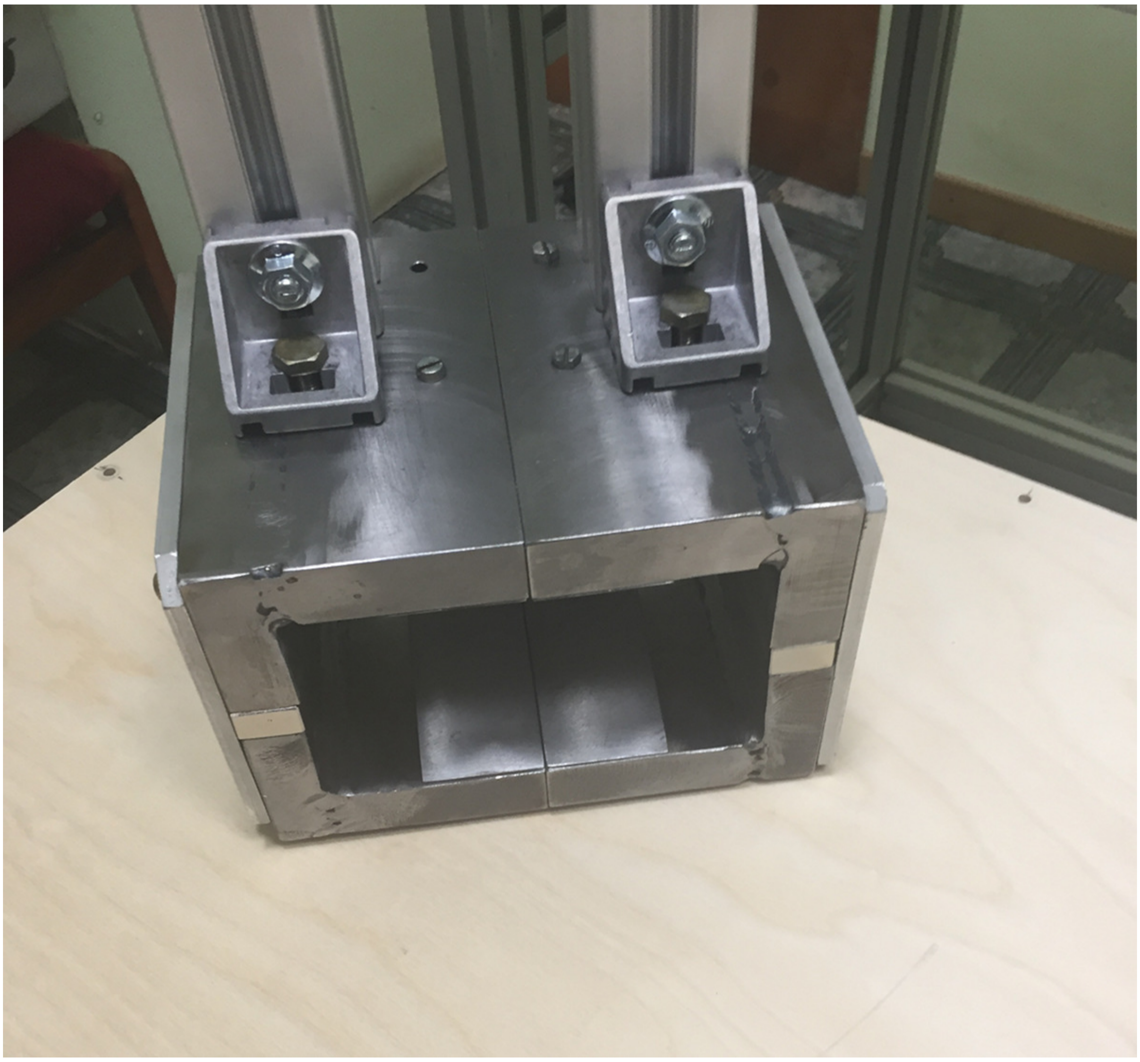


Figure 9: **Magnets for Sona transitions.**

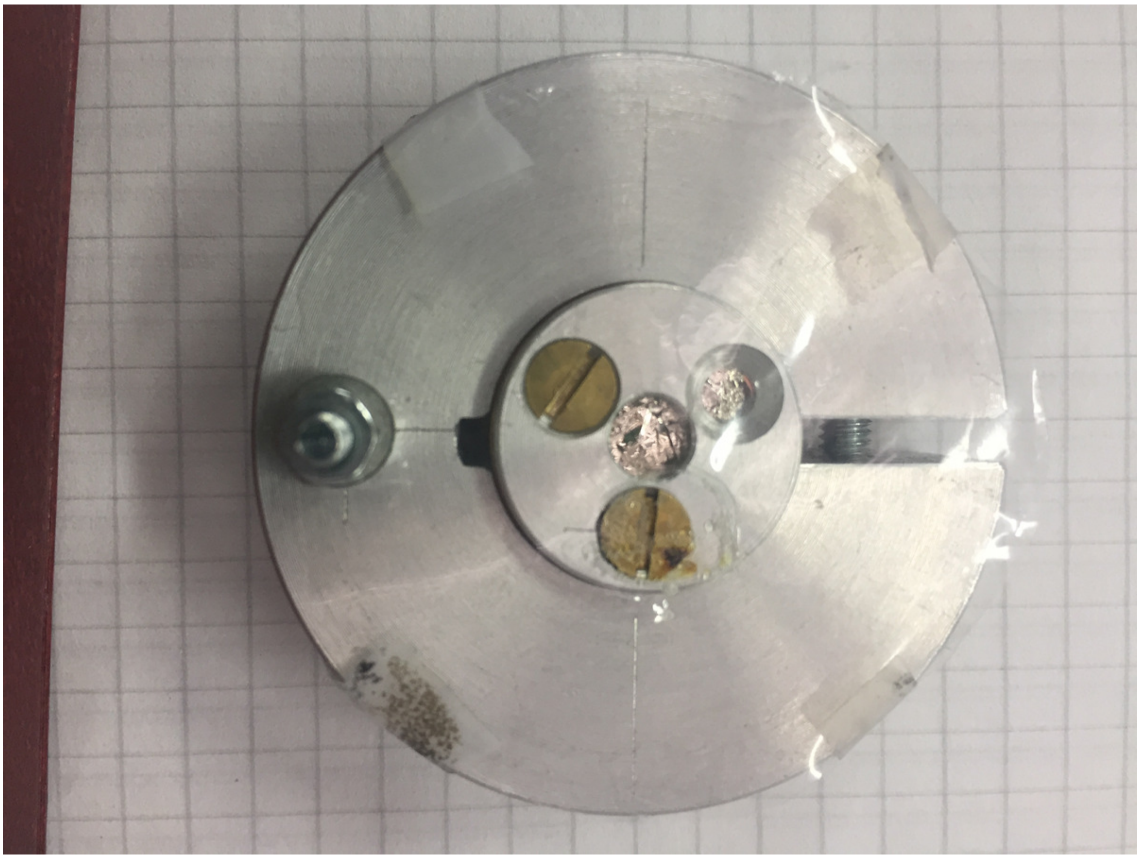


Figure 10: **The nickel foil after irradiation.**

5 Polarimeter

The deuteron vector polarization may be measured with the reaction d($\vec{d}, p$)t, [A.A. Naqvi, G. Clausnitzer, *Nucl. Instr. & Meth.* A324 (1993) 429].

The polarimeter target consisted of deuterated polyethylene with a thickness of about 2-3 μm backed on the Cu support. The protons with an energy of 2700 ke produced in the d($\vec{d}, p$)t reaction were detected by two surface barrier detectors, each having an effective area of 20 mm^2.

The detectors were placed symmetrically at $\pm 120^\circ$ with respect to the beam axis, the solid angle was equal $\approx$ 1 msr. In order to suppress the elastically scattered deuterons, ^3H and ^3He, each detector was masked with a 10 μm thick aluminum foil.

For deuteron with an energy of 400 keV the expected count is $6.25 \times 10^{12} \cdot 5 \times 10^{-27} \cdot 10^{-3} \cdot 10^{17} = 4$ sec.$^{-1}$ per 1 μA of the neutral deuterium atoms on the target. The range in CD_2 is 0.4 μm.

We tested the target TiT for measurement of tensor polarization.

For a vector polarized beam particle intensities detected by two detectors placed at right and left of the beam axis are proportional to the cross sections $\sigma_R(\theta)$ and $\sigma_L\theta)$, respectively,

$$\sigma_R(\theta) = \sigma_{0R}(\theta)\left[1 - \frac{3}{2}P_z A_y(\theta)\right]$$

and

$$\sigma_L(\theta) = \sigma_{0L}(\theta)\left[1 + \frac{3}{2}P_z A_y(\theta)\right].$$

Replacing the cross sections by the corresponding right and left detector intensities, N_R and N_L, with polarized and unpolarized beams we obtain

$$\frac{N_R(\theta)}{N_L(\theta)} \times \frac{N_{0L}(\theta)}{N_{0R}(\theta)} = \frac{1 - 3/2 P_z A_y(\theta)}{1 + 3/2 P_z A_y(\theta)}.$$

With

$$\kappa = \frac{N_R(\theta)}{N_L(\theta)} \times \frac{N_{0L}(\theta)}{N_{0R}(\theta)}, \;\; P_z = \frac{1 - \kappa}{3/2(\kappa + 1) A_y(\theta)}.$$

The statistical error is

$$\delta P_z^2 = \frac{16}{9(\kappa+1)^4 A_y^2}\delta\kappa^2 + \frac{P_z^2}{A_y^2}\delta A_y^2,$$

where

$$\delta\kappa = \kappa\sqrt{\frac{1}{N_R}+\frac{1}{N_L}+\frac{1}{N_{R0}}+\frac{1}{N_{L0}}}.$$

The typical value for $E_d = 425$ keV after the Ni foil 2 μm (initial $E_d = 800$ keV) and with the target of deuterated polyethelene 5 ± 5 mm are: $N_R = 152$, $N_L = 186$ for 3600 s, $N_{R0} = 1720$, $N_{L0} = 18$ for 1200 s. This gives $P_z = 0.14 \pm 0.15$.

If we include all the date, we get (preliminary) $P_z = 0.20 \pm 0.11$ with the magnet on the d-target.

According to the calculations, for the real magnetic field 0.08 T there is the rest tensor polarization of 0.1 after Sona transitions. So, we use the general formula

$$\sigma(\theta,\phi) = [1 + \frac{3}{2}\sin\beta\cos\phi P_z A_y(\theta) - \cos\beta\sin\beta\sin\phi P_{zz} A_{xz}(\theta)$$

$$-\frac{1}{4}\sin^2\beta\cos 2\phi P_{zz} A_{xx-yy}(\theta) + \frac{1}{4}(3\cos^2\beta - 1) P_{zz} A_{zz}(\theta)],$$

For $\beta = 90^\circ$ and $\phi = 0^\circ$

$$\sigma_L(\theta) = \sigma_{0L}(\theta)\left[1 + \frac{3}{2}P_z A_y(\theta) - \frac{1}{4}P_{zz} A_{xx-yy}(\theta) - \frac{1}{4}P_{zz} A_{zz}(\theta)\right]$$

and for $\phi = 180^\circ$

$$\sigma_R(\theta) = \sigma_{0R}(\theta)\left[1 - \frac{3}{2}P_z A_y(\theta) - \frac{1}{4}P_{zz} A_{xx-yy}(\theta) - \frac{1}{4}P_{zz} A_{zz}(\theta)\right].$$

According to Ad'yasevich [B.P. Ad'yasevich et al., *Sov. J. Nucl. Phys.* 33 (1981) 313] at 300 keV $A_{zz} = A_{xx-yy} \approx 0$, at 400 keV $A_{zz} = -A_{xx-yy} = -0.1$ and in this energy range additional terms can be neglected.

The tensor polarization was estimated with TiT target by measuring the angular distribution of α-particles emitted in the reaction ^{3}H(d,n)^{4}He [A. Galonsky et al., *Phys. Rev. Lett.* 2 (1959) 349]. The cross section depends of the cm angle between the spin and the particle direction:

$$\sigma(\theta) = \sigma_0 \left[1 - \frac{1}{4}(3\cos^2\theta - 1)P_{zz}\right].$$

We use two Si detectors at the angles $\theta = 90^\circ$ and $\theta = 20^\circ$. In the result, (preliminary) $P_{zz} = -0.10 \pm 0.05$ at the deuteron energy of 250 keV (575 keV before the Ni foil) for the foil thickness 1.5 μm.

We did not use the effect of channeling. It seems that channeling is not important, the essential is the electron polarization at the surface, which is depended from the surface index. The measured value of the tensor polarization corresponds to the electron polarization sign on the surface (110).

6 Adiabaticity

The polarized deuterium atoms enter a region where the value $B_z = B_0(1 - 2x/L)$ is decreasing in value, and if this decrease is slow enough (adiabatic), each state follows the corresponding energy line.

Ionization in a low field at $x = L/2$ gives ideally the deuteron vector polarization $P_z = 1/3$ and tensor polarization $P_{zz} = -1/3$.

If we ionize atoms in a strong magnetic field, vector polarization $P_z = 2/3$ and tensor polarization $P_{zz} = 0$.

To estimate the depolarization we have to take into account the finite beam dimension, and therefore the presence of the transverse component $B_x = (dB_z/dx)z$.

A particle off-axis never "sees" a field going exactly to zero, but a field which in a "short" but finite time changes continuously its direction by $180°$, taking its minimum value when the field is normal to the beam direction.

We begin from the Schredinger equation

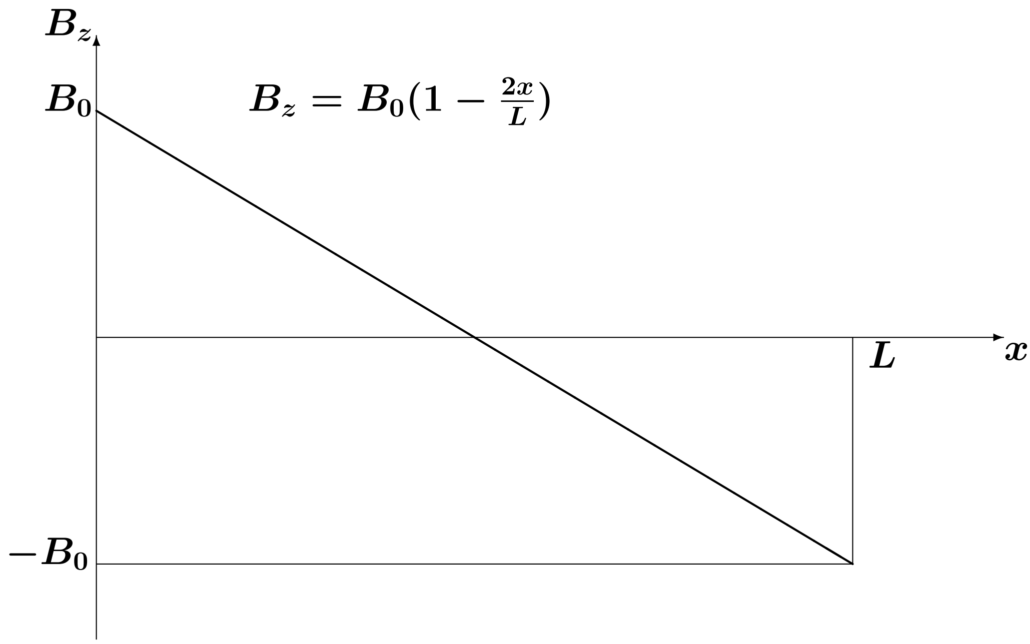
$$i\hbar\frac{d\psi(t)}{dt} = \hat{H}(t)\psi(t) = [-\mu_J\hat{\vec{\sigma}}_J\vec{B}(t) - \mu_d\hat{\vec{S}}_d\vec{B}(t) + \frac{1}{3}\Delta W\hat{\vec{\sigma}}_J\hat{\vec{S}}_d]\psi(t),$$

or for movement on the axis x,

$$\frac{d\psi(x)}{dx} = -\frac{i}{\hbar v}\hat{H}(x)\psi(x) = -\frac{i}{\hbar v}[-\mu_J\hat{\vec{\sigma}}_J\vec{B}(x) - \mu_d\hat{\vec{S}}_d\vec{B}(x) + \frac{1}{3}\Delta W\hat{\vec{\sigma}}_J\hat{\vec{S}}_d]\psi(x),$$

where $v = \sqrt{2E_d/m_d}$, for $E_d = 100$ keV, $v = 3\cdot 10^6$ m/s,

$$\psi(x) = C_1(x)\varphi_e^+\varphi_d^+ + C_2(x)\varphi_e^+\varphi_d^0 + C_3(x)\varphi_e^+\varphi_d^- + C_4(x)\varphi_e^-\varphi_d^+ + C_5(x)\varphi_e^-\varphi_d^0 + C_6(x)\varphi_e^-\varphi_d^-.$$



$$B_z(x) = B_0(1-\frac{2x}{L}),\ dB_x/dz = dB_z/dx,$$

$$B_x = z_1 dB_z/dx = -\frac{2B_0}{L}z_1,\ z_1 = z_0 + \alpha x,\ B_y = 0.$$

B (T)	z (mm)	v (m/s)	L (m)	B(L/2)	C	P_3	P_{33}
0.066	1.5×10^{-3}	$4.2{\times}10^6$	0.5	zero	C1	0.999	0.998
					C2	0.939	0.823
					C3	0.00908	-1.710
					avr	**0.649**	**0.0371**
	2.5				C1	0.996	0.989
					C2	0.849	0.577
					C3	0.0331	-1.274
					avr	**0.626**	**0.0971**
0.085	1.5	$4.2{\times}10^6$	0.5	zero	C1	0.999	0.997
					C2	0.924	0.777
					C3	0.00209	-1.634
					avr	**0.642**	**0.0468**
	2.5				C1	0.994	0.983
					C2	0.822	0.496
					C3	0.0226	-1.118
					avr	**0.613**	**0.120**

Table 1: **Zero transition**

B (T)	z (mm)	v (m/s)	L (m)	C	P_3	P_{33}
0.066	**1.5**	4.2×10^6	**0.5**	**avr**	**0.649**	**0.0371**
	2.5				**0.626**	**0.0971**
0.085	**1.5**	4.2×10^6			**0.642**	**0.0468**
	2.5				**0.613**	**0.120**
0.085	**1.5**	3×10^6			**0.637**	**0.0658**

Table 2: **Zero transition**

B (T)	z (mm)	v (m/s)	L (m)	B(L/2) (mT)	C	P_3	P_{33}
0.085	1.5	4.2×10^6	0.5	1	C1	0.998	0.993
					C2	0.295	-1.102
					C3	-0.437	-0.674
					avr	**0.285**	**-0.261**
	2.5				C1	0.993	0.980
					C2	0.290	-1.096
					C3	-0.436	-0.657
					avr	**0.282**	**-0.258**
0.2	2.5	4.2×10^6	0.5	1	C1	0.987	0.962
					C2	0.234	-1.233
					C3	-0.426	-0.665
					avr	**0.265**	**-0.312**

Table 3: **Transition to the field 0.001 T**

The angular velocity of the magnetic field rotation ω_B, as seen by a particle travelling with the velocity v and at the distance z from the central plane follows from the equation

$$\coth\theta = \frac{B_x}{B_z}, \quad \frac{1}{\sin^2\theta}\frac{d\theta}{dx} = \frac{1}{z}, \quad \frac{d\theta}{dx} = \frac{1}{z}\frac{B_z^2}{B_x^2 + B_z^2}.$$

Generally,

$$\omega_B(x) = \frac{d\theta}{dx}v = \frac{4zv}{L^2[(1-2x/L)^2 + 4z^2/L^2]}.$$

In zero crossing point ($B_x = 0$), the angular velocity of the rotation of the field ω_B is

$$\omega_B(L/2) = \frac{v}{z}.$$

At $x = 0$ the velocity of the magnetic field rotation is

$$\omega_B(0) = \frac{4zv}{L^2(1 + 4z^2/L^2)}.$$

The angular velocity of the spin precession ω_P is

$$\omega_P(x) = \frac{1}{\hbar}\left[\frac{\Delta W}{2} - \mu_e B(x) - \frac{\mu_d B(x)}{2} - \frac{\Delta W}{2}\sqrt{1 + \frac{2}{3}X(x) + X(x)^2}\right],$$

where

$$B(x) = \sqrt{B_x(x)^2 + B_z^2} = B_0\sqrt{\left(1 - \frac{2x}{L}\right)^2 + \frac{4z_1^2}{L^2}}, \quad X(x) = \frac{B(x)}{B_c}.$$

The angular velocity of the precession at zero crossing is

$$\omega_P(L/2) = \frac{2\mu_e}{3\hbar}B(L/2) = \frac{2\mu_e}{3\hbar}B_z = \frac{2\mu_e}{3\hbar}\frac{2B_0 z}{L}.$$

At $B_0 \gg B_c = 14.6$ mT,

$$\omega_P(0) = \frac{1}{\hbar}\left[\frac{\Delta W}{2} - \mu_d B_0\right],$$

$\Delta W = 21.69 \times 10^{-26}$ J, $\mu_d = 0.433 \times 10^{-26}$ J T.

For $B_0 = 7 \times 10^{-2}$ T, $z = 2$ mm, $L = 0.4$ m and the atom velocity $v = 4 \times 10^6$ m/s
$\omega_B(L/2) = 2 \times 10^9$ rad/s, and $\omega_P(L/2) = 3.9 \times 10^7$ rad/s.

Thus, the velocity of precession in the zero transition region is much slower than the velocity of field rotation, i.e. the spin does not follow the field.

At $x = 0$ the velocity of the magnetic field rotation is $\omega_B(0) = 2 \times 10^5$ rad/s, and the angular velocity of precession is $\omega_p(0) = 6.109 \times 10^8$ rad/s.

Here we have adiabatic transition. Note that two velocities are equal 1.355×10^8 rad/s at $x = 0.19258$ m (at $z = 2$ mm).

7 Conclusion

The final aim is to produce a 14-MeV polarized neutron beam with polarization up to 2/3 for measuring the neutron-deuteron total cross section differences $\Delta\sigma_L(nd)$ and $\Delta\sigma_T(nd)$.

To increase the accuracy of the measurements we modernize all the system.

The deuteron polarization in the polarized target can be increased from present 0.4 up to 0.8 by use trityl radical as a dopant to the target material.

To improve the parameters of the neutron beam it is proposed to use the reaction ^{3}H$(\vec{d},\vec{n})^4$He with polarized deuterons of an energy 100-150 keV.

For nonchanneled beam, the preliminary value of the vector polarization for strong magnetic field at the target is (preliminary) $P_z = 0.20 \pm 0.11$. The vector polarization was measured with deuterated polyethelene target.

The measurements of tensor polarization were carried out with TiT target, (preliminary) $P_{zz} = -0.10 \pm 0.05$ for weak field at the target. It is close to Feldman's result $P_{zz} = -0.14 \pm 0.06$.

8 Acknowledgments

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