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RESEARCH AND DEVELOPMENT OF THE POLARIZED DEUTERON SOURCE FOR THE VAN DE GRAAFF ACCELERATOR

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Исследование и разработка источника поляризованных дейтронов
для ускорителя Ван де Граафа

Предпринята попытка создать источник поляризованных дейтронов для ускорителя Ван де Граафа Чешского технического университета в Праге на основе эксперимента Каминского по каналированию дейтронов через монокристалл никеля. Описана установка, содержащая постоянные магниты с поперечным магнитным полем для увеличения поляризации дейтронов с использованием метода Сона (переход магнитного поля через ноль). Измерения тензорной поляризации были проведены на титан-тритиевой мишени. В результате $P_{zz} = -0{,}12 \pm 0{,}04$ для слабого поля на мишени без использования эффекта каналирования. Конечной целью является получение поляризованных нейтронов с энергией 14 МэВ, которые будут использованы вместе с дейтронной поляризованной мишенью с замороженным спином для измерения асимметрий $\Delta\sigma_T$ и $\Delta\sigma_L$ в nd-эксперименте с трансмиссией нейтронов.

Работа выполнена в Лаборатории ядерных проблем им. В. П. Джелепова ОИЯИ.

Plis Yu. A. et al. E13-2018-69

Research and Development of the Polarized Deuteron Source for the
Van de Graaff Accelerator

An attempt is made to develop a polarized deuteron source suited for the Van de Graaff accelerator of the Czech Technical University in Prague. We relied on Kaminsky's experiment on channeling deuterons through a Ni single crystal. The setup is described which contains permanent magnets with a transverse magnetic field to increase the deuteron polarization using the Sona method (zero transition). The measurements of tensor polarization were carried out with TiT target. The result is $P_{zz} = -0.12 \pm 0.04$ for a weak field at the target without channeling. The ultimate aim is to produce 14-MeV polarized neutrons which will be used jointly with the frozen-spin polarized deuteron target for measurement of $\Delta\sigma_T$ and $\Delta\sigma_L$ asymmetries in the nd-transmission experiment.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

INTRODUCTION

Formally, measurement of spin-dependent parameters allows imposing additional constraints on the reaction mechanism and the structure of the micro-object under study. For example, measurements of $\Delta\sigma_T$ and $\Delta\sigma_L$ are necessary to determine the imaginary part of the nd forward elastic scattering amplitude [1]. These measurements are important for the problem of 3-nucleon forces [2].

The total cross-section difference $(\Delta\sigma_L)_d$ was measured at TUNL (North Carolina) [3] for the incident neutron energies of 5.0, 6.9 and 12.3 MeV.

In the previous experiments on np-scattering (Charles University, Prague) [4,5], transversely polarized neutrons were produced as a secondary beam in the $\mathrm{T}(d, n)^4\mathrm{He}$ reaction with deuterons with energies up to 2.5 MeV [6]. The neutron beam with an energy $E_n = 16.2$ MeV was emitted at an angle $\theta_{\mathrm{lab}} = 62.0°$. The neutron polarization was $P_n = -0.135 \pm 0.014$. To get longitudinal beam polarization in the $(\Delta\sigma_L)_p$ experiment, the neutron spin was rotated with the help of a permanent magnet of 0.5 T m. The associated particle method was used in the experiments.

The planned experiments are a continuation, in the Czech Technical University in Prague, of the previous measurements of the same quantities in np-scattering.

Preliminary experiments showed that the polarization and intensity of the neutron beam and also the deuteron polarization of the target are insufficient for achieving the necessary accuracy of the measurement of the cross-section difference [7]. To improve the parameters of the neutron beam, it is proposed to use the reaction $\mathrm{T}(d, n)^4\mathrm{He}$ with polarized deuterons with an energy of 100–150 keV. Also, we plan to replace the current target material (propanediol) with a novel material chemically doped with the trityl family radicals, which showed the deuteron polarization as high as $P_d = 0.80$ [8].

As to the polarized beam, the first proposal concerning the nuclear polarization via a pick-up of polarized ferromagnetic electrons was made by Zavoiskii in 1957 [9]. The method proposes adiabatic transition of atoms from a high magnetic field to a low magnetic field on the order of 1 mT where nuclei are polarized through the hyperfine interaction.

Here we rely on the results of the experiment by Kaminsky [10] on the production of nuclear polarized deuterium atoms by channeling a low-energy deuteron beam through a magnetized single-crystal nickel foil.

In Kaminsky's setup a beam of deuterons with a half angle of $0.01°$ was incident on a Ni(110) foil ≈ 2 μm thick within $0.1°$ of the [110] direction (the critical acceptance angle $1.6°$–$1.8°$). This is a hyperchanneling regime. He obtained 500 nA/cm^2 of channeled deuterium atoms with an energy of 100–200 keV with nuclear polarization $P_{zz} = -0.32 \pm 0.010$ (without a significant lattice damage for 25 h of operating time). To test Zavoiskii's proposal, the author passed deuterons through magnetized polycrystalline foils and observed no significant tensor polarization (i.e., $P_{zz} \approx 0$).

Feldman et al. [11] also made polarization measurements with an experimental arrangement very similar to that of Kaminsky. Their data qualitatively agree with Kaminsky's data ($P_{zz} = -0.14 \pm 0.06$). Also, as in Kaminsky's experiment, no effect was seen for polycrystalline foils. 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 fairly thick (50–100 Å) surface oxide layers.

Quite a different electron field-emission experiment [12] on Ni showed that electrons emitted along the [100], [110] and [137] directions had predominantly spin-up (along the magnetic field), but when emitted along the [111] directiom they had a spin-down.

Rau and Sizmann [13], who also used the ^{3}H$(d, n)^4$He reaction, measured polarization of nuclei in neutral deuterium atoms created by electron capture during reflection of a 150-keV D$^+$ beam incident at glancing angles ($< 0.4°$) on the surface 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. In the (110) surface the electron polarization is $P = 96\%$ [14]. This explains the high polarization in Kaminsky's experiment.

On the other hand, there is evidence for polarization of $1s$ electrons ($P_{1s} = 0.10 \pm 0.03$) attached to F ions as they emerge from magnetized polycrystalline Fe layers [15].

It was found that a vacuum of $2 \cdot 10^{-8}$ Torr was necessary in order to see polarization effects. If the vacuum was allowed to deteriorate to $5 \cdot 10^{-6}$ Torr, the polarization gradually vanishes, presumably as a result of the build-up of thin layers of surface contaminants.

1. THEORY

Ebel [16] 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 this electron 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 [17], however, pointed out that stable bound electronic states could not exist in deuterium atoms passing through metals at these velocities. They proposed instead that the electron capture took place in the tail of the electron density distribution at the crystal surface where the density was low enough for bound states to be stable.

Later, Kreussler and Sizmann [18] discussed that at high energies (more than 250 keV/amu) neutralization took place chiefly in the bulk of the crystal and the surface effects were important at lower energies.

Kaminsky did not measure the polarization of nonchanneled atoms. We may suppose that the channeling is not essential, and the electron polarization in the neutral beam is determined by the polarization of the electrons at the surface.

2. EXPERIMENTAL SETUP

The scheme of the experimental setup is shown in Fig. 1. We propose to apply the Sona method, zero-field transitions with total transfer of the electron polarization to deuterons in the atomic beam [19]. We use two permanent magnets (2×20 cm) with a changing distance between the poles ($B_{\max} = 0.07$ T). The charged deuterons are deflected by the magnetic and electric fields. The Ni foil and the target of a polarimeter are placed in oppositely directed magnetic fields.

The magnetic field is directed along the foil plane (vertically), and we must use Sona transitions with vertical magnetic fields. This is different from the standard configuration.

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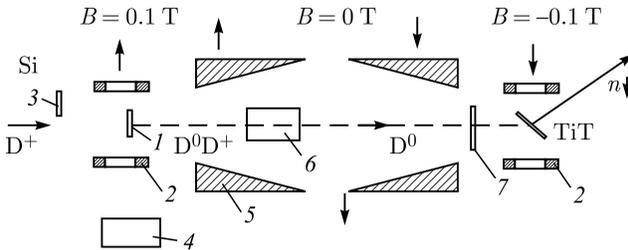
Fig. 1. Scheme of the polarized deuteron source: *1* — nickel foil, *2* — permanent magnet (0.07 T), *3* — solid state detector, *4* — a goniometer, *5* — polarizing permanent magnets (for the Sona transitions), *6* — electrostatic plates, *7* — the target of a polarimeter

3
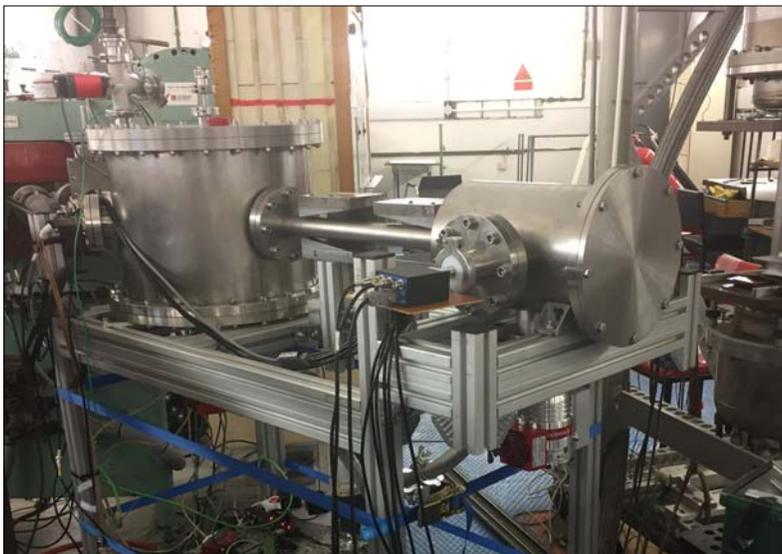
Fig. 2. The experimental setup
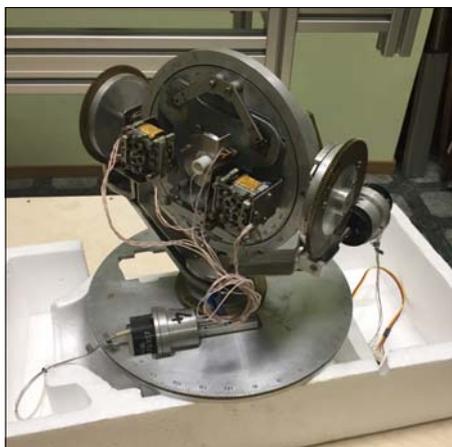
Fig. 3. Goniometer

entific Corp.). The substrate was dissolved by water and the Ni foils were floated on the Cu disc mounted on the goniometer.

Vacuum of better than 10^{-4} Pa was used.

The atomic beam in a strong magnetic field has vector polarization of deuterons up to the theoretical limit $P_3 = 2/3$ and zero tensor polarization.

Fig. 4. Au foil

Fig. 5. Magnets

If we pass the deuterium beam to a tritium target, 14-MeV neutrons of the dt-reaction produced at an angle of $90°$ (center of mass) have almost the same vector polarization as the deuterons [20].

3. POLARIMETRY

The deuteron vector polarization may be measured using the reaction D(d, p)T [21]. The polarimeter target consisted of deuterated polyethylene with a thickness of about 2–3 μm on a Cu support. The protons produced in this reaction were detected by two surface barrier detectors, each having an effective area of 20 mm^2.

The detectors were placed symmetrically at $\pm120°$ with respect to the beam axis, and the solid angle was ≈ 1 msr. In order to suppress the elastically scattered deuterons, ^{3}H and ^{3}He, each detector was masked with a 10-μm-thick aluminum foil. For deuteron with an energy of 400 keV the expected count rate is 4 s^{-1} per 1 μA of neutral deuterium atoms on the target. The range in CD$_2$ is 0.4 μm.

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

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

and

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

where $A_y(\theta)$ is the Cartesian analyzing power for the reaction.

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Replacing the cross sections by the corresponding right and left detector intensities, N_R and N_L, for polarized beam and N_{0R}, N_{0L} for unpolarized beam, we obtain

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

Designating

$$\kappa = \frac{N_R(\theta)}{N_L(\theta)} \times \frac{N_{0L}(\theta)}{N_{0R}(\theta)}, \tag{4}$$

one obtains

$$P_z = \frac{1 - \kappa}{3/2(\kappa + 1) A_y(\theta)}. \tag{5}$$

The statistical error is

$$\delta P_z^2 = \frac{16}{9(\kappa + 1)^4 A_y^2} \delta \kappa^2 + \frac{P_z^2}{A_y^2} \delta A_y^2, \tag{6}$$

where

$$\delta \kappa = \kappa \sqrt{\frac{1}{N_R} + \frac{1}{N_L} + \frac{1}{N_{R0}} + \frac{1}{N_{L0}}}. \tag{7}$$

According to the calculations, for the real magnetic field value the tensor polarization after the Sona transitions is not equal to zero, $P_{zz} \approx 0.1$. In this case we use the general formula

$$\sigma(\theta, \phi) = \left[1 + \frac{3}{2} \sin \beta \cos \phi P_z A_y(\theta) - \cos \beta \sin \beta \sin \phi P_{zz} A_{xz}(\theta) - \tag{8}\right.$$

$$\left. - \frac{1}{4} \sin^2 \beta \cos 2\phi P_{zz} A_{xx-yy}(\theta) + \frac{1}{4}(3\cos^2 \beta - 1) P_{zz} A_{zz}(\theta) \right]. \tag{9}$$

For $\beta = 90°$ and $\phi = 0°$

$$\sigma_L(\theta) = \sigma_{0L}(\theta) \left[1 + \frac{3}{2} P_z A_y(\theta) - \frac{1}{4} P_{zz} A_{xx-yy}(\theta) - \frac{1}{4} P_{zz} A_{zz}(\theta) \right] \tag{10}$$

and for $\phi = 180°$

$$\sigma_R(\theta) = \sigma_{0R}(\theta) \left[1 - \frac{3}{2} P_z A_y(\theta) - \frac{1}{4} P_{zz} A_{xx-yy}(\theta) - \frac{1}{4} P_{zz} A_{zz}(\theta) \right]. \tag{11}$$

According to Ad'yasevich [22], 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 measurements of deuteron vector polarization are in progress.

The tensor polarization was estimated with TiT target by measuring the angular distribution of α particles emitted in the reaction $T(d,n)^4$He [23].

The cross section depends on the c.m. angle between the spin and the particle direction:

$$\sigma(\theta) = \sigma_0 \left[1 - \frac{1}{4}(3\cos^2\theta - 1)P_{zz} \right]. \tag{12}$$

As a result, $P_{zz} = -0.12 \pm 0.04$ (theoretical value is $P_{zz} = -0.33$) at a deuteron energy of 500 keV for the foil thickness 1.5 μm (real energy is 250 keV). Feldman's result is $P_{zz} = 0.14 \pm 0.06$. During the first experiments the goniometer was at a random position, and we used only one magnet of the Sona transition system.

4. ADIABATICITY

The polarized deuterium atoms enter a region where the value $B_z = B_0(1 - 2x/L)$ is decreasing, and if this decrease is slow enough (adiabatic), each state follows the corresponding energy line. Ionization at a low field gives ideally the deuteron tensor polarization $P_{zz} = -1/3$ and vector polarization $P_z = 1/3$.

We have to take into account the finite beam dimension and therefore the presence of the transverse component

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

For estimate we set $\alpha = 0$.

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 it is normal to the beam direction.

We begin from the Schrödinger equation for movement along the axis x

$$\frac{d\psi(x)}{dx} = -\frac{i}{\hbar v}\hat{H}(x)\psi(x) =$$

$$= -\frac{i}{\hbar v}\left[-\mu_J\hat{\boldsymbol{\sigma}}_J\mathbf{B}(x) - \mu_d\hat{\mathbf{S}}_d\mathbf{B}(x) + \frac{1}{3}\Delta W\hat{\boldsymbol{\sigma}}_J\hat{\mathbf{S}}_d \right]\psi(x), \tag{13}$$

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

$$\psi(x) = C_1(x)\varphi_e^+\varphi_d^+ + C_2(x)\varphi_e^+\varphi_d^0 + C_3(x)\varphi_e^+\varphi_d^- +$$
$$+ C_4(x)\varphi_e^-\varphi_d^+ + C_5(x)\varphi_e^-\varphi_d^0 + C_6(x)\varphi_e^-\varphi_d^-. \tag{14}$$

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Table 1. **Zero transition**

B_0, T	z_1, mm	v, m/s	L, m	C	P_z	P_{zz}
0.066	1.5	$4.2 \cdot 10^6$	0.5	C_1	0.999	0.998
				C_2	0.939	0.823
				C_3	0.00908	−1.710
				avr	0.649	0.0371
	2.5			C_1	0.996	0.989
				C_2	0.849	0.577
				C_3	0.0331	−1.274
				avr	0.626	0.0971
0.085	1.5	$4.2 \cdot 10^6$	0.5	C_1	0.999	0.997
				C_2	0.924	0.777
				C_3	0.00209	−1.634
				avr	0.642	0.0468
	2.5			C_1	0.994	0.983
				C_2	0.822	0.496
				C_3	0.0226	−1.118
				avr	0.613	0.120

Table 2. **Zero transition. Chief results**

B_0, T	z_1, mm	v, m/s	L, m	C	P_z	P_{zz}
0.066	1.5	$4.2 \cdot 10^6$	0.5	avr	0.649	0.0371
	2.5				0.626	0.0971
0.085	1.5	$4.2 \cdot 10^6$			0.642	0.0468
	2.5				0.613	0.120
0.085	$1.5 \cdot 10^{-3}$	$3 \cdot 10^6$			0.637	0.0658

Table 3. **Transition to the 1 mT field**

B_0, T	z_1, mm	v, m/s	L, m	$B_{\min}$, mT	C	P_z	P_{zz}
0.085	1.5	$4.2 \cdot 10^6$	0.5	1	C_1	0.998	0.993
					C_2	0.295	−1.102
					C_3	−0.437	−0.674
					avr	0.285	−0.261
	2.5				C_1	0.993	0.980
					C_2	0.290	−1.096
					C_3	−0.436	−0.657
					avr	0.282	−0.258
0.2	2.5	$4.2 \cdot 10^6$	0.5	1	C_1	0.987	0.962
					C_2	0.234	−1.233
					C_3	−0.426	−0.665
					avr	0.265	−0.312

The results of calculations are presented in Tables 1–3. The polarization values are $P_z = |C_1|^2 + |C_4|^2 - |C_3|^2 - |C_6|^2$ and $P_{zz} = 1 - 3(|C_2|^2 + |C_5|^2)$.

We make the approximate estimates, in which we compare the angular velocity of magnetic field and the spin precession. 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

$$\coth \theta = \frac{B_x}{B_z}, \quad \frac{1}{\sin^2 \theta} \frac{d\theta}{dx} = \frac{1}{z_1}, \quad \frac{d\theta}{dx} = \frac{1}{z_1} \frac{B_z^2}{B_x^2 + B_z^2}. \tag{15}$$

Generally,

$$\omega_B(x) = \frac{d\theta}{dx} v = \frac{4z_1 v}{L^2[(1 - 2x/L)^2 + 4z_1^2/L^2]}. \tag{16}$$

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

$$\omega_B(L/2) = \frac{v}{z_1}. \tag{17}$$

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

$$\omega_B(0) = \frac{4z_1 v}{L^2(1 + 4z_1^2/L^2)}. \tag{18}$$

The angular velocity of the spin precession ω_P is

$$\omega_P(x) = \frac{1}{\hbar} \left[\frac{\Delta W}{2} - \mu_e B(x) - \frac{\mu_d B(x)}{2} - \frac{\Delta W}{2} \sqrt{1 + \frac{2}{3} X(x) + X(x)^2} \right], \tag{19}$$

where

$$B(x) = \sqrt{B_x(x)^2 + B_z^2} = B_0 \sqrt{\left(1 - \frac{2x}{L}\right)^2 + \frac{4z_1^2}{L^2}}, \quad X(x) = \frac{B(x)}{B_c}. \tag{20}$$

The angular velocity of the precession in zero crossing is

$$\omega_P(L/2) = \frac{2\mu_e}{3\hbar} B(L/2) = \frac{2\mu_e}{3\hbar} B_z = \frac{2\mu_e}{3\hbar} \frac{2B_0 z}{L}. \tag{21}$$

For $B_0 = 7 \cdot 10^{-2}$ T, $z_1 = 2$ mm, $L = 0.4$ m and the atom velocity $v = 4 \cdot 10^6$ m/s, $\omega_B(L/2) = 2 \cdot 10^9$ rad/s and $\omega_P(L/2) = 3.9 \cdot 10^7$ rad/s.

Thus, the velocity of precession of the atoms in the zero transition region $3.9 \cdot 10^7$ rad/s is much less than the velocity of field rotation $2 \cdot 10^9$ rad/s; i.e., the spin does not follow the field.

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

So, we have adiabatic transition.

CONCLUSIONS

The experimental setup has been developed to produce the beam of deuterium atoms of energies 100–400 keV with polarized nuclei and to measure vector and tensor polarizations of deuterons.

The ultimate aim is to produce a highly polarized 14-MeV neutron beam for measuring the neutron–deuteron total cross section differences $\Delta\sigma_L(nd)$ and $\Delta\sigma_T(nd)$ using the frozen-spin polarized deuteron target (as first experiment).

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

For a nonchanneled beam (the goniometer is in a random position), the tensor polarization measurements were carried out with a TiT target in the reaction $\text{T}(d,n)^4\text{He}$. Our result is $P_{zz} = -0.12 \pm 0.04$ for weak field at the target. Feldman's result is $P_{zz} = -0.14 \pm 0.06$.

We continue experiments to get the nuclear polarized deuterium beam with an energy of about 150 keV and vector polarization up to 2/3 via pick-up of electrons in a magnetized single-crystal nickel foil.

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