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ЛАБОРАТОРИЯ НЕЙТРОННОЙ ФИЗИКИ

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CHOICE OF THE PROPER SET OF NEUTRON-DEUTERON SCATTERING LENGTHS FROM EXPERIMENTS ON TRANSMISSION OF POLARIZED NEUTRONS THROUGH A POLARIZED DEUTERON TARGET

The neutron-deuteron doublet and quartet scattering lengths (a_2 and a_4) belong to the few fundamental constants permanently used for checking the accuracy of any solution of the nuclear three-body problem. Unfortunately the experimental data still remain as ambiguous as 15 years ago when the following two alternative sets of n-d scattering lengths were determined/1/:
I) $a_2 = 0.7 \pm 0.3$ fm, $a_4 = 6.38 \pm 0.06$ fm; II) $a_2 = 8.26 \pm 0.12$ fm, $a_4 = 2.6 \pm 0.2$ fm. Even though in more than 20 theoretical works indications were obtained for the correctness of set I (see, for example, ref./2/) the choice of the proper set should have been done experimentally. Indeed, up to now all theoretical considerations are based on approximate models of nuclear forces, and the mathematical solutions are also approximate. Moreover, recently some theoretical arguments were advanced favouring set II/3/.

One can distinguish between the two sets by means of measurements with polarized neutrons and polarized deuterons. In case of complete polarization the n-d collisions proceed through the quartet state when the spins of the neutron and the deuteron are parallel, whereas the doublet is the most probable for antiparallel spins. In the first set, a_4 is larger than a_2 and there fore for parallel spins the total scattering cross section is larger and the transmission T of the sample is smaller than that antiparallel spins: $T_{par} < T_{anti}$, $\epsilon_0 = (T_{par} - T_{anti})/(T_{par} + T_{anti}) < 0$. In the second set, a_4 is smaller than a_2, hence $\epsilon_0 > 0$. These conclusions are valid for the neutron energy $E_n \gtrsim 1$ eV when the beam attenuation is determined by the total cross section. For much smaller neutron energy and a monocrystalline sample, the attenuation is due only to the incoherent scattering which vanishes for parallel orientation of the neutron and deuteron spins; consequently we have for the both sets $\epsilon_0 > 0$.

The measurements of ϵ_0 were carried out on the pulsed fast reactor IBR by the time-of-flight method. The lay-out of the experiment is shown in fig. 1.

The neutron beam was polarized by transmission through a polarized proton target[4]. The neutron polarization varied from $f_n = 0.5 - 0.7$ to $f_n \approx 1$ depending on neutron energy. A monocrystal of deuterated lanthanum magnesium double nitrate $(Nd^{142}_{0.005}\ La_{0.995})_2\ Mg_3(NO_3)_{12} \times 24\ D_2O$ was used as a deuteron target. The admixture of ordinary hydrogen to deuterium was less than 0.5%. The thickness of the crystal passed by the neutron beam was 35 mm, the transverse dimensions being $15 \times 24 mm^2$. The deuterons were polarized dynamically[5] at frequency 64 Ghz and temperature $1.3^{\circ}K$. Deuteron polarization was controlled by observing the deuteron nuclear magnetic resonance (NMR) signal. The absolute value of polarization could not be obtained in this way, as the NMR detector used could not measure the unenhanced deuteron signal. The sign of deuteron polarization was determined by comparing the deuteron NMR signal with that of fluorine in teflon, the latter being detected at the same NMR frequency but at diminished magnetic field.

Between the proton and deuteron targets, a spin rotator was placed which allowed to rotate the neutron spin by 180°. The following detectors were placed in the neutron beam: BF_3- monitors in front of (M_1) and behind (M_2, M_3) the proton target; $B^{10}F_3$- counter bank (BC), and boron liquid detector (LD) behind the deuteron target. The pulses from all detectors were counted by scalers and those from M2, BC and LD were analyzed by multichannel time analyzers. After each 10^5 counts of the monitor M1 (which took about 800 sec.), the neutron spin direction was reversed. In the first measuring cycle (32 counting intervals) the deuteron polarization was positive (that is it had the same direction as the magnetic field), while in the second 38-interval cycle deuteron polarization was negative (that is opposite to the magnetic field).

The values of $\epsilon_0 / f_n = (T_+ - T_-)/(T_+ + T_-) f_n$ obtained from these measurements are presented in fig.2 (here T_+ and T_- are the transmissions of the deuteron polarization parallel or antiparallel to the magnetic field in the deuteron target, respectively). Note that for the first cycle (full points in fig.2) one has $\epsilon = \epsilon_0$ while for the second cycle (open points) $\epsilon = -\epsilon_0$. The correction $\Delta(\epsilon/f_n)$ which was due to a difference in the counting rates of the monitor M2 for the two neutron spin directions (fig. 2) was subtracted from the first cycle data. This difference in the counting rates resulted from some drift of proton polarization. In the second cycle no such correction was required.

As it can be seen from fig.2., the both detectors BC (open and full circles) and LD (open and full squares) gave negative values of ϵ_0 / f_n in both cycles. Check measurements with zero polarization in the deuteron target gave no effect.

Before making any conclusions one has to consider the effect of other non-zero spin nuclei of the deuteron target which get also polarized by the dynamic method. For small values of double transmission effect $(\epsilon_0 / f_n \ll 1)$, one can obtain the following relation:

$$\frac{\epsilon_0}{f_n} = ½(1+\phi) n_d \sigma_p^d f_N^d \Big(1 + \sum_{i \neq d} \frac{n_i \sigma_p^i f_N^i}{n_d \sigma_p^d f_N^d}\Big), \qquad (1)$$

where n_i, σ_p^i and f_N^i are the number of nuclei per cm^2 of the target, the polarization cross section and the polarization for i-nuclei, respectively; ϕ is the spin rotator efficiency $(0{,}6 < \phi < 1)$. For a neutron energy $E_n \gtrsim 1$ eV, the polarization cross section is given by the expression:

$$\sigma_p = 4\pi \frac{I}{2I+1} (a_-^2 - a_+^2), \qquad (2)$$

where I is the nuclear spin, a_+ and a_- are the neutron scattering lengths for total angular momenta $I + 1/2$ and $I - 1/2$, respectively ($a_- = a_2$ and $a_+ = a_4$ for $I = 1$). Significant contributions to the sum in formula (1) are made only by N^{14} and La^{139}. The pertinent data for these nuclei are presented in table 1. It follows from these data that the sign of the double transmission effect is defined by deuterium (see table 2). Consequently the observed negative sign of ϵ_0 indicates the validity of set I of n-d scattering lengths.

The lack of data on spin dependence of neutron absorption in N^{14} and La^{139} precludes any definite conclusions from the observed energy dependence of ϵ_0. Measurements are under preparation to clarify this point. Now one can only note that the dependence observed is compatible with the expected change of ϵ_0 for set I at a very low neutron energy.

Basing on the experiments described we conclude that the correct set of n-d scattering lengths is the first one, in which the quartet scattering length is larger than the doublet one ($a_4 > a_2$). This result is in agreement with the expectations of the most of theoretical works/2/ and does not confirm the arguments in ref./3/.

Using our results we can also derive the values of the deuteron polarization $f_N^d = 0{,}12 \pm 0{,}05$ and $-0{,}07 \pm 0{,}03$ obtained in the first and the second cycles, respectively.

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Table 1. Relative contributions of H^2, N^{14} and La^{139} to the double transmission effect.

Nucleus	Spin I	$\frac{n_i}{n_d}$	$\frac{f_N^i}{f_N^d}$	σ_{p_1} barn ($E_n \gtrsim 1$ eV)	$n_i \sigma_p^i f_N^i / n_d \sigma_p^d f_N^d$	
					Set I	Set II
H^2	1			$-1.68+0.04$ (set I) 2.57 ± 0.10 (set II)	1	1
N^{14}	1	0.25	0.65 ± 0.20 a)	-3.45 ± 0.49 b)	0.33 ± 0.11	-0.22 ± 0.075
La^{139}	7/2	1/24	2.25 c)	$-3.9+2.6$ or 4.2 ∓ 2.9 d)	$0.22+0.15$ or -0.23 ± 0.16	$-0.14+0.10$ or 0.15 ∓ 0.10

a) The ratio obtained by comparing the NMR signals of H^2 and N^{14}. The dynamic polarization conditions were identical to those used in the first cycle of neutron measurements.

b) The absolute value of σ_p calculated using the data from refs.[6,7]. The sign of σ_p follows from the fact that a negative energy $3/2^+$ resonance level is responsible for most part of the slow neutron scattering cross section of N^{14} [8].

c) Since the nuclear Zeeman splittings are about the same for H^2 and La^{139}, their polarizations are taken to be proportional to I+1 as it follows from the simple theory for $f_N \ll 1$.

d) The absolute value of σ_p calculated using the data from ref.[6]. The sign of σ_p is unknown.

Table 2

Values of the sum in expression (1)

The sign of σ_p^{La}	Set I	Set II
-	0.55±0.20	-0.36±0.13
+	0.10±0.20	-0.07±0.13

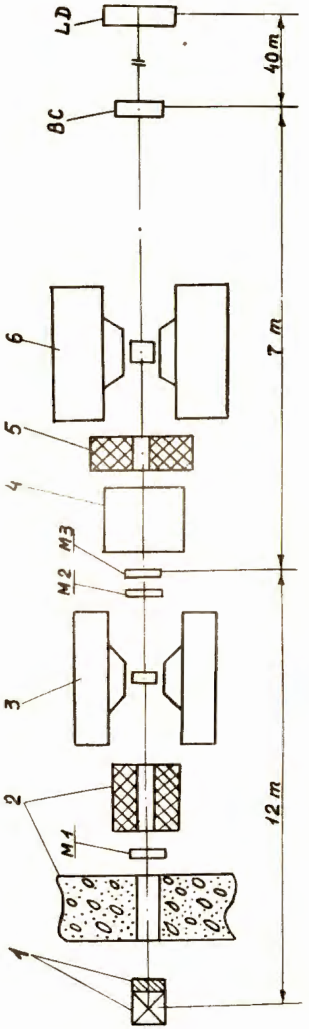

Fig. 1. The lay - out of the experiment: 1 - pulsed fast reactor IBR with moderator, 2 - shield and collimator of the neutron beam, 3 - polarized proton target, 4 - spin rotator, 5 - collimator, 6 - polarized deuteron target.

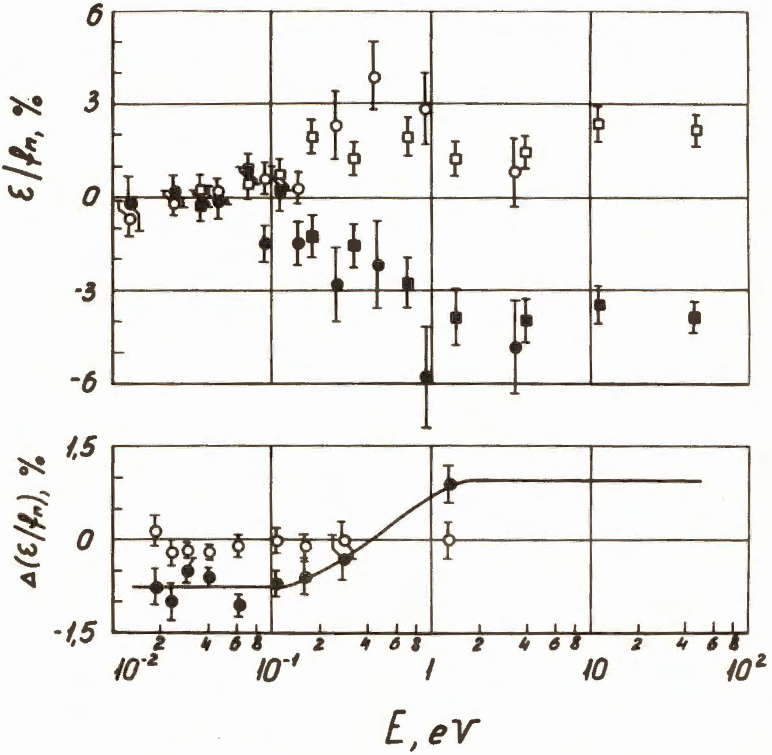

Fig. 2. Double transmission effect ϵ/f_n for polarized deuteron target (the upper part of the figure) and the correction $\Delta(\epsilon/f_n)$ (the bottom part) versus neutron energy.