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MEASUREMENTS OF THE $\vec{n}\vec{p}$ TOTAL CROSS SECTION DIFFERENCES FOR PURE HELICITY STATES AT 1.20, 2.50 and 3.66 GeV

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The quantity $\Delta\sigma_L(\vec{n}\vec{p})$, the difference of $\vec{n}\vec{p}$ total cross sections for antiparallel and parallel longitudinal (L) spin states, has been measured for the first time in an energy region of several GeV using a free polarized neutron beam and a polarized proton target. The new data are discussed together with existing results and modern theoretical predictions. This is the first of a planned series of measurements of $\Delta\sigma_{L,T}(\vec{n}\vec{p})$ in this new energy region.

The investigation has been performed at the Laboratory of High Energies, JINR.

Измерения разностей полных $\vec{n}\vec{p}$ сечений в чистых состояниях по спиральности при 1,20, 2,50 и 3,66 ГэВ

В.И.Шаров и др.

Величина $\Delta\sigma_L(\vec{n}\vec{p})$, разность полных $\vec{n}\vec{p}$ сечений для антипараллельных и параллельных продольных (L) спиновых состояний, впервые измерена в области энергий несколько ГэВ с использованием поляризованного пучка свободных нейтронов и протонной поляризованной мишени. Новые результаты обсуждаются совместно с имевшимся набором данных и с современными теоретическими предсказаниями. Это первые измерения из планируемой серии измерений разностей $\Delta\sigma_{L,T}(\vec{n}\vec{p})$ с продольными и поперечными ориентациями спинов пучка и мишени в этой новой области энергий.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

1. The aim of this letter is to present new $\Delta\sigma_L(\vec{n}\vec{p})$ data over an energy range of several GeV and to prepare for continued measurements of this polarization observable and $\Delta\sigma_T(\vec{n}\vec{p})$ (with transverse orientation of particle spins) in this new energy region. The results were obtained using the new free neutron polarized beam [1] prepared at the JINR LHE accelerator facility [2] that now provides the highest energy polarized neutron beam. The large reconstructed polarized proton target (PPT) [3,4] was used in the present experiment, and this is the first of a planned series of measurements with this PPT.

The total nucleon-nucleon cross section can be written as [5]:

$$\sigma_{\text{tot}} = \sigma_{0\text{tot}} + \sigma_{1\text{tot}}(\mathbf{P}_b, \mathbf{P}_t) + \sigma_{2\text{tot}}(\mathbf{P}_b, \mathbf{k})(\mathbf{P}_t, \mathbf{k}), \tag{1}$$

where $\mathbf{P}_b$ and $\mathbf{P}_t$ are the beam and target polarization vectors, $\mathbf{k}$ is the unit vector in the incident beam direction, $\sigma_{0\text{tot}}$ is the unpolarized total cross section and the spin-dependent contributions $\sigma_{1\text{tot}}$ and $\sigma_{2\text{tot}}$ are related to the observables $\Delta\sigma_{L,T}$ by:

$$-\Delta\sigma_T = 2[\sigma(\uparrow\uparrow) - \sigma(\downarrow\uparrow)]/(P_b P_t) = 2\sigma_{1\text{tot}}, \tag{2}$$

$$-\Delta\sigma_L = 2[\sigma(\rightrightarrows) - \sigma(\rightleftarrows)]/(P_b P_t) = 2(\sigma_{1\text{tot}} + \sigma_{2\text{tot}}). \tag{3}$$

The total cross section differences $\Delta\sigma_T$ and $\Delta\sigma_L$, along with $\sigma_{0\text{tot}}$, are related to the three nonvanishing imaginary parts of the nucleon-nucleon (NN) forward scattering amplitudes via optical theorems. A set of existing data on these observables is used for a direct reconstruction of the amplitudes and for a *NN* phase shift analysis (PSA) [e.g., 6,7].

The existing data on $\Delta\sigma_{L,T}$ (see Ref. [8] and references therein) for *pp*-scattering cover an energy range from 0.2 to 12 GeV. For *np*-scattering, these observables have been measured only to a neutron beam kinetic energy of 1.1 GeV [8]. The goal of the present studies is to obtain detailed $\vec{n}\vec{p}$ data in an energy region of several GeV.

The $\Delta\sigma_L(\vec{p}\vec{n})$ data were first obtained [9] over an energy range from 0.51 to 5.1 GeV using a bound neutron target, i.e., from $\Delta\sigma_L(\vec{p}\vec{d})$ and $\Delta\sigma_L(\vec{p}\vec{p})$ measurements. The values of $\Delta\sigma_L(\vec{p}\vec{n})$ extracted by the authors [9] and in another way [10] disagree with the free $\vec{n}\vec{p}$ data obtained later in the energy range below 1.1 GeV, because there are model-dependent difficulties for extraction of the $\vec{p}\vec{n}$ values from the $\Delta\sigma_L(\vec{p}\vec{d})$ and $\Delta\sigma_L(\vec{p}\vec{p})$ data. The energy behaviour of these $\vec{p}\vec{n}$ data is even different from the free $\vec{n}\vec{p}$ data [8] and they arew not included in the PSA [6]. This is also one of the reasons for obtaining free $\vec{n}\vec{p}$ data in an energy region higher than 1.1 GeV.

2. The transmission method was used to measure $\Delta\sigma_L(\vec{n}\vec{p})$. The neutron flux M before the PPT was determined by a monitor detector (see Fig.1b), and another neutron detector was used to measure the neutron intensity N transmitted through the PPT. For a given neutron beam energy, the measured total cross section difference is given by:

$$\Delta\sigma_L = \frac{1}{n_p P_b P_t} \ln\left(\frac{N^- M^+}{M^- N^+}\right), \tag{4}$$

where n_p is the density of polarized hydrogen nuclei ($\vec{p}/\mathrm{cm}^2$) in the PPT, and N^+/M^+ and N^-/M^- are the normalized rates of the transmission detector for parallel and antiparallel spins, respectively. As the measured value of $\Delta\sigma_L$ depends only on the ratio of monitor and transmission detector rates, the result is independent of the absolute efficiencies of the monitor and transmission detectors. It is only important to keep the detector efficiencies stable, and to keep the detectors at the same location during data taking runs. The neutron beam polarization was reversed every cycle, as requested. This allowed us to minimize the influence of some possible sources of errors, e.g., a possible temporary shift or drift of some neutron beam characteristics. To avoid a systematic uncertainty due to possible detector and target misalignments relative to the beam, the measurements were carried out for both signs of target polarization, and then a simple average of the results was made.

3. The experimental set-up (see Fig.1a,b) included both polarized deuteron and polarized free neutron beam lines [1,2], two beam line polarimeters (absolute and relative) for measuring and monitoring the deuteron polarization, a polarized proton target [3,4], neutron transmission detectors, electronics and data acquisition systems.

The beam of free polarized neutrons with a well-defined value and orientation of the polarization (the same as for the deuteron beam) was obtained by the breakup of vector

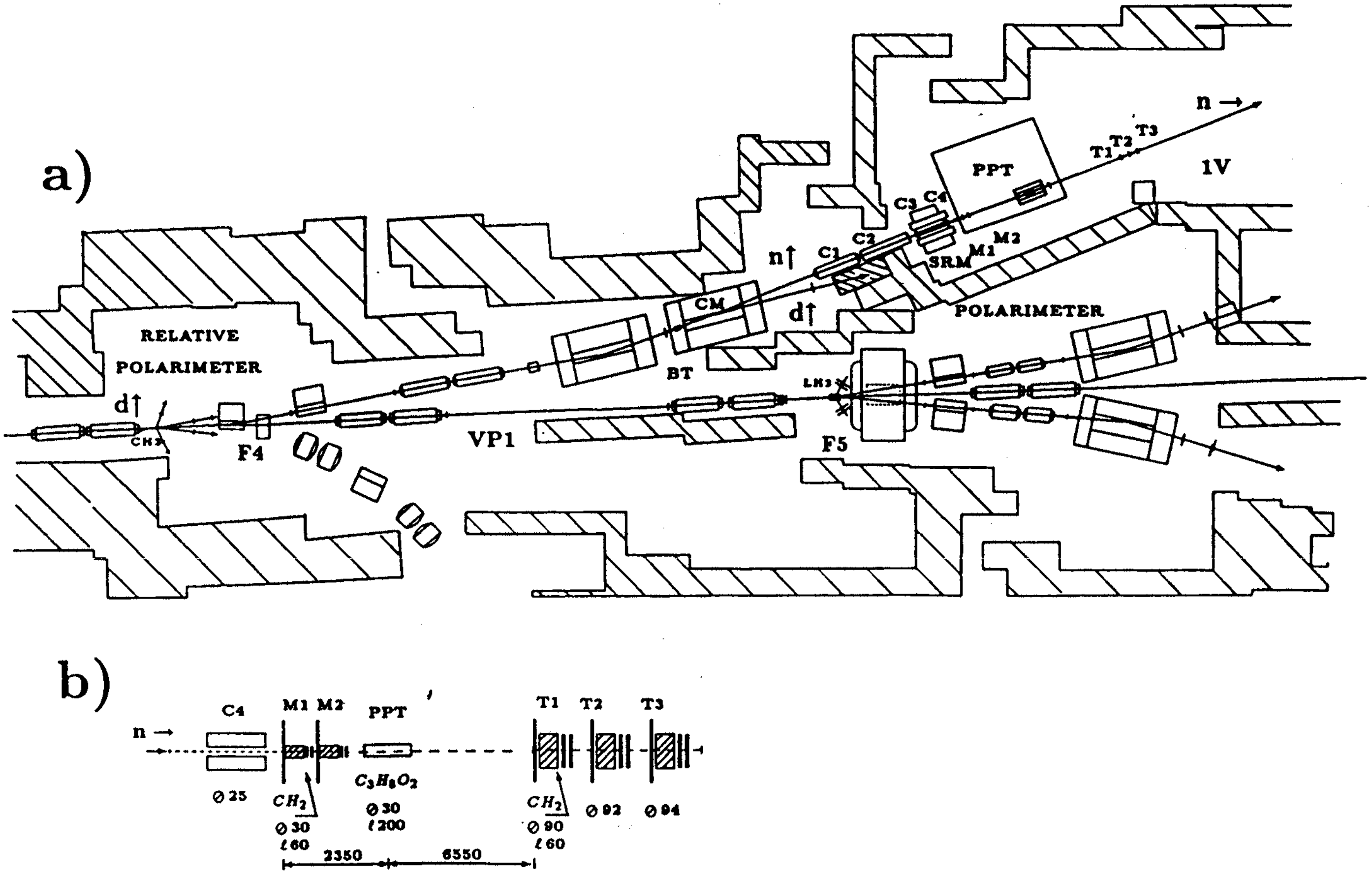

Fig.1. Experimental set-up for $\Delta\sigma_{L,T}(\vec{n}\vec{p})$ measurements. a) Layout of the apparatus in the Experimental Hall. VP1-beam line of extracted, polarized deuterons; 1V — beam line of polarized neutrons; BT-neutron production target; CM-sweeping magnet; C1-C4-set of neutron beam collimators; SRM-neutron spin rotating dipole; and PPT-polarized proton target. b) Layout of detectors for the neutron transmission measurement. M1, M2-monitor neutron detector modules; T1-T3-neutron transmission detector modules

polarized deuterons on the production target BT. The 0° angle breakup process has a high neutron yield with a maximum for a neutron momentum of $p_n = p_d/2$ and FWHM $\simeq 5\%$ [11]. The production target consisted of 17 cm Be and 6 cm C. An intense deuteron beam passed through BT. Charged secondaries and noninteracting deuterons were deflected from the neutron beam direction by a dipole magnet CM and went into a shielded beam dump to reduce the background level in the neutron detectors. To form the required size (30 mm) of the neutron beam spot on the PPT with a suitable angular divergence (~1.5 mrad) and a minimum halo intensity, a set of iron and brass collimators C1-C4 (the total length is 6 m in a path of 7 m) was inserted into the neutron beam line after the CM up to the neutron monitor detector.

The intesity of polarized deuterons was continuously monitored using two calibrated ionization chambers placed in the deuteron beam line before the BT. The values of the deuteron intensity, averaged over each data taking run, were 5.3×10^8, 6.1×10^8, and 6.4×10^8 $\vec{d}/cycle$ at deuteron beam kinetic energies of 2.4, 5.0, and 7.32 GeV, respectively. When preparing the neutron beam line, the neutron flux was measured by an activation method. During these test runs, the neutron beam profiles were also measured using a nuclear emulsion method. The intensities of polarized neutrons, averaged over a data taking run, were 2.7×10^4, 2.0×10^5, and 4.7×10^5 $\vec{n}/cycle$ at neutron energies of 1.2, 2.5, and 3.66 GeV, respectively.

The neutron beam had the same vertical orientation of polarization as the accelerated and extracted deuteron beam. To precess the neutron spins from the vertical to the longitudinal direction, a suitable dipole (spin-rotating magnet SRM) with a horizontal magnetic field and a maximum field integral of 2.7 Teslameters, was mounted before the PPT. The SRM was used after precise magnetic field mapping [12]. During the data taking runs and tuning for each beam momentum, the SRM magnetic field was continuously monitored for stability using a Hall probe.

As follows from [13,14], the relation between the polarizations of the 0° breakup proton with momentum $p_p = p_d/2$ and the incident deuteron is $P_p/P_d \simeq 1$. Assuming identical breakup conditions ($P_n \simeq P_p$), we have measured the polarization of the deuteron beam in order to know the neutron beam polarization. For absolute measurements of deuteron polarization, a fast beam line polarimeter [15] was used. It consisted of a liquid hydrogen target, situated at focus F5 of the extracted beam line VP1 (Fig.1a), and two pairs of detector arms with recoil proton detection and magnetic analysis of scattered deuterons. (This polarimeter operated when the deuteron beam was not deflected towards the neutron beam line 1V). The dp-elastic scattering, with precisely known analysing powers [16] at a deuteron momentum 3 GeV/c, was used as a polarization analyser. Each of the two pairs of polarimeter arms were positioned at kinematically conjugate angles close to the maximum vector analysing power. The positive and negative values of deuteron vector polarization, measured before and after the data taking runs, were close to each other $P_d^+ = +0.530 \pm 0.013$ and $P_d^- = -0.540 \pm 0.012$ with an average value of $|P_d| = 0.535 \pm 0.009$.

During data taking, the deuteron beam polarization was continuously monitored by another polarimeter [17] with a thin tagret 5 mm CH_2 placed inside the deuteron beam line (Fig.1a). Each of the two pairs of arms of this device were positioned at kinematically conjugate angles, close to the maximum analysing power for free *pp* elastic scattering, to measure the left-right asymmetry $\varepsilon(pp)$. The average values of $\varepsilon(pp)$ for all the runs were measured to be 0.2193 ± 0.0015, 0.1410 ± 0.0007, and 0.7514 ± 0.0010, respectively, at 1.2, 2.5, and 3.66 GeV.

A target with frozen proton polarization initially developed for a Fermilab experiment was used [3,4,18,19]. The target material was 1,2-propanediol ($C_3H_8O_2$) with a paramagnetic Cr(5) impurity having a spin concentration of 1.5×10^{20} cm^{-3} [20]. A load of 140 cm^3 propanediol beads in a plastic thin wall capsule 200 mm long and 30 mm in diameter was placed inside the dilution refrigerator. The determination of the density of polarized protons in the PPT was based on the conventional method of measuring volume and weight. The density of hydrogen nuclei was estimated as $n_p = (8.93 \pm 0.27) \times$ $\times 10^{23}\ \vec{p}/\mathrm{cm}^2$. The neutron transmission of the PPT measured before data taking was 0.73. This value is close to the calculated one. The measured transmission of the «empty» target, i.e., a capsule without propanediol beads, was 0.94.

The target polarization measurements were carried out using a computer-controlled NMR system. The typical values of proton polarization were $+0.84$ and -0.90 for positive and negative polarizations, respectively, with ~3% uncertainties. The duration of one continuous data taking run at a given sign of target polarization was 12 hours. Polarization degradation over this period was insignificant, since the nuclear spin relaxation time in the frozen mode at a temperature of 50 mK and the magnetic field of 2.5T was above 1000 hours.

Our neutron detection equipment (Fig.1b) for the $\Delta\sigma_L(\vec{n}\vec{p})$ measurements was analogous to that used in Refs. [21,22]. Each neutron detection module consisted of a veto counter for incoming charged particles followed by a CH_2 converter and two adjoining scintillation counters in coincidence. The converter was placed immediately behind the large veto scintillator, and the neutron flux was measured by detecting charged particles generated by neutrons in the converter. Such a method of neutron detection has a relatively small efficiency (~2%), but the efficiency is quite stable. Using two similar detector modules for monitoring the incident neutron beam let us increase monitor statistics by a factor of ~2. The rates of monitor detector modules were simply added.

To increase the transmission detector statistics, three neutron detection modules were used to determine the flux of neutrons that passed through the PPT without interaction. In this way, the statistics were enlarged by a factor of ~3. The data were analysed separately for each module of the transmission detector, and the result for $\Delta\sigma_L$ was obtained as a weighted average. The solid angle subtended by the transmission detector from the center of the PPT was ~0.2 msr ($\theta_{lab} \sim 0.6°$). It was estimated that the difference between the measured value of $\Delta\sigma_L(\theta = 0.6°)$ and the extrapolated $\Delta\sigma_L(\theta = 0°)$ is less than 0.02 mb, i.e., much smaller than the statistical errors.

Two independent data acquisition systems were used during the data taking runs. The following information was read out by the first one for each accelerator burst from the CAMAC scalers: rates of two ionization chambers used for monitoring the primary deuteron beam intensity; rates of two monitor and three transmission detector modules; rates of accidental coincidences for all the neutron detection modules; and rates of the left and right arms of the continuous deuteron beam polarimeter. This information was recorded, processed, and displayed for on-line monitoring of the performance of the apparatus.

The other data acquisition system was used for monitoring the efficiency stability of each scintillation counter by watching pulse-height distributions.

4. The results of the $\Delta\sigma_L(\vec{n}\vec{p})$ measurements are (7.1 ± 3.7), (-0.85 ± 1.32), and (0.30 ± 0.84) mb at neutron beam kinetic energies of 1.20, 2.50, and 3.66 GeV, respectively. The errors are statistical only. The systematic uncertainty, caused by the measurement uncertainties of beam and target polarization and target thickness (see above), is estimated to be ~5%. Our $-\Delta\sigma_L(\vec{n}\vec{p})$ values are shown in Fig.2 together with the available $\vec{n}\vec{p}$ data [8]. The solid curve presents the fitted $-\Delta\sigma_L(\vec{n}\vec{p})$ energy behaviour from the PSA [6]

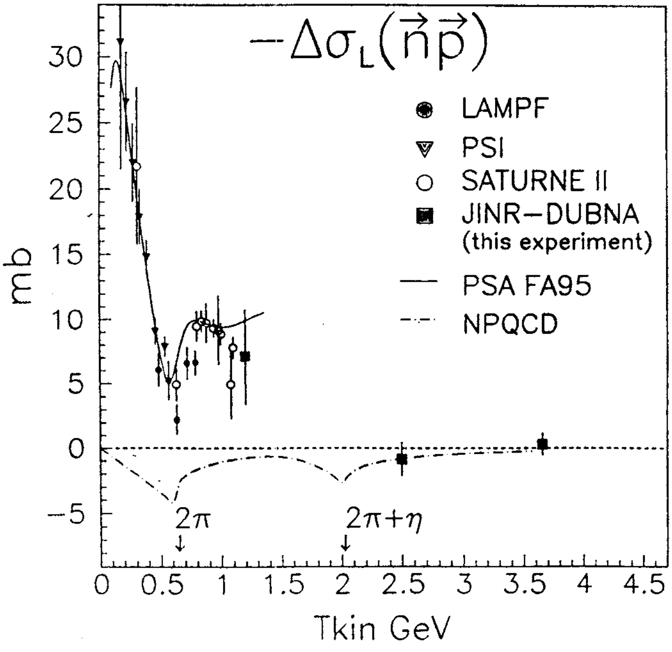

Fig.2. Energy dependence of $\Delta\sigma_L(\vec{n}\vec{p})$ obtained with free neutron polarized beams. ■ this experiment; ●, ▼ and ○ existing LAMPF, PSI, and Saclay data (see references in Ref.[6]). The curves are explained in the text

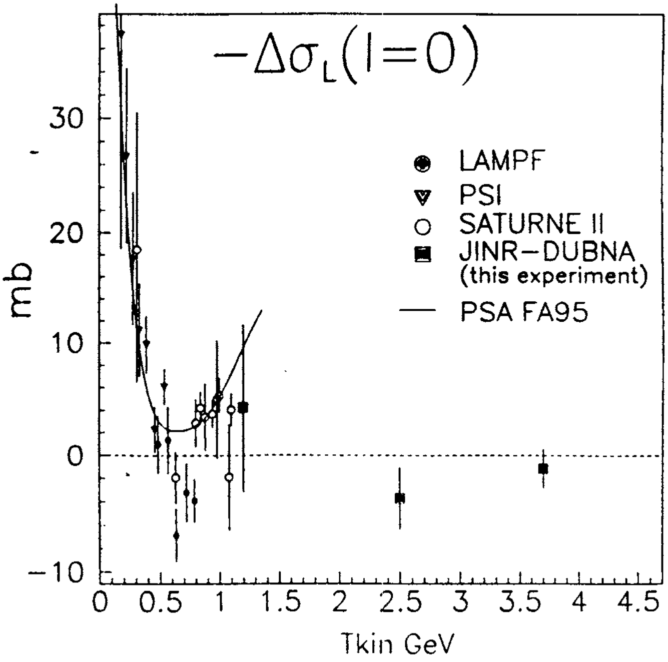

Fig.3. Energy dependence of $\Delta\sigma_L(I=0)$. The notation is the same as in Fig.2

(FA95 solution). The measured $-\Delta\sigma_L$ value at 1.20 GeV is close to results at nearby energies, and the other two show a fast decrease in contrast to the tendency of the PSA solution.

Using the $\vec{n}\vec{p}$ and $\vec{p}\vec{p}$ data, one can deduce values of $\Delta\sigma_L$ for the isospin state $I=0$:

$$\Delta\sigma_L(I=0) = 2\Delta\sigma_L(\vec{n}\vec{p}) - \Delta\sigma_L(\vec{p}\vec{p}). \qquad (5)$$

The values of $\Delta\sigma_L(I=0)$ obtained from our results and the existing $\vec{n}\vec{p}$ and $\vec{p}\vec{p}$ data [8] are plotted in Fig.3 together with the PSA [6] prediction. These new data and the results of upcoming measurements of $\Delta\sigma_{L,T}(\vec{n}\vec{p})$ over the new energy range will be important to extend the evaluation of the characteristics of *NN*-interactions to higher energies.

The investigated energy region corresponds to the possible generation of heavy dibaryons ($M > 2.4$ GeV/c^2). Precise and detailed $\Delta\sigma_{L,T}(\vec{n}\vec{p})$ data will also be very useful to verify the predictions of some modern resonance models. For example, there is a prediction [23] of the possible manifestation of an exotic $^3S_1$ dibaryon ($M = 2.63$ GeV/c^2) in the energy behaviour of $\Delta\sigma_L(\vec{n}\vec{p})$ near 1.8 GeV. There is also a model [24] for the formation of a heavy dibaryon state with a color octet-octet structure in this energy region.

Another interesting prediction for the energy behaviour of $\Delta\sigma_L(\vec{n}\vec{p})$ has also been made recently [25] (see also Ref. [26]). The contribution to $\Delta\sigma_L(\vec{n}\vec{p})$ of the nonperturbative flavour-dependent interaction between quarks (NPQCD) induced by a strong fluctuation of vacuum gluon fields, or instantons [27], was estimated in Ref. [25]. This contribution is shown in Fig.2 by a dash-dotted line and agrees well with the data. An anomalous energy dependence of the instanton-induced interaction near 2π and $2\pi+\eta$ thresholds leads to large contributions of this mechanism to spin-dependent cross sections. Using such a model, one can explain qualitatively the observed dip in the energy dependence of the existing $\Delta\sigma_L(\vec{n}\vec{p})$ data near the 2π production threshold at 0.6 GeV. The magnitude of the instanton contribution near the $2\pi+\eta$ threshold at ~2.0 GeV, is predicted to be ~3 mb, which is sizeable. Hence, more precise and detailed $\Delta\sigma_{L,T}$ measurements over this energy range are needed to test this model.

This instanton model [26] was also used for an analysis of the CERN and SLAC data on the spin-dependent cross sections of longitudinally polarized leptons $(\vec{\mu}, \vec{e})$ on longitudinally polarized protons and deuterons. Thus, a continuation of the $\Delta\sigma_{L,T}$ experiments using the PPT at the polarized nucleon beams of the JINR LHE accelerator will give the possibility of obtaining complementary information concerning the problems of the spin structure of nuclear matter and the QCD vacuum. Such a model is also related to the problem of the anomalous violation of baryon number conservation in weak interactions induced by instantons, which can be experimentally tested at the LHC [25,28]. Hence, the experimental examination of this instanton model will be very useful at intermediate energies,where reasonably large effects for the spin-dependent NN cross sections near production thresholds are predicted.

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