Study of the Nucleon Spin Structure in Strong and Electromagnetic Interactions

Изучение спиновой структуры нуклона в сильных и электромагнитных взаимодействиях

Project "GDH & SPASCHARM & NN"

TEMA 04-2-1126-2015/2019

Dubna—Protvino—Prague—Moscow—Mainz—Glasgow—Los Angeles—Basel—Lund—Zagreb—Pavia—Lund—Kharkov—Bochum Bonn–Amherst–Giessen–Halifax–Jerusalem–Kent–Regina–Sackville Washingtion–York

Annotation

Dubna

2020

Study of the Nucleon Spin Structure in Strong and Electromagnetic Interactions

Project "GDH & SPASCHARM & NN"

Dubna, Dzhelepov Laboratory of Nuclear Problems, JINR
N.A. Bazhanov, N.S. Borisov, A.S. Dolzhikov, A.N. Fedorov, I.V. Gapienko, I. Gorodnov, G.M. Gurevich, V.L. Kashevarov, A. Kovalik, E.S. Kuzmin, A.B. Lazarev, A.B. Neganov, Yu.A. Plis, A.A. Priladyshev, A.B. Sadovski, Yu.A. Usov, Yu.N. Uzikov, V.P. Volnykh

Dubna, Flerov Laboratory of Nuclear Reactions, JINR
M.P. Ivanov

Dubna, Bogoliubov Laboratory of Theoretical Physics, JINR
S.B. Gerasimov, S.S. Kamalov

Contents

1 Introduction

The vast scope of experimental data on nuclear reaction cross sections accumulated during the decades of measurements appears nonetheless not exhaustive without taking into consideration the dependence on spins of the interacting particles. Only polarization experiments permit to evolve all independent amplitudes describing the specific reaction. In other words, only polarization measurements allow to obtain a complete information about any physical process under study.

Theoretical and experimental studies in this field are traditional for JINR [1]. In recent years, the improvements in experimental methods have opened up new opportunities for the investigation of the polarization degrees of freedom of the nucleon.

This project covers three spin physics problems:

1) Experimental study of single-spin asymmetries in the production of miscellaneous light particles with the use of 28 GeV π^--beam at first stage and the study of single-spin and double-spin asymmetries in dozens of reactions including charmonium production with the use of polarized proton beam (SPASCHARM project).

The ultimate goal of the SPASCHARM project is to study spin structure of the proton, starting with determination of gluon contribution into the proton spin at large values of the Bjorken variable x through a study of spin effects in charmonium production. This will allow to understand charmonium hadronic production mechanism and to extract gluon polarization $\Delta g(x)$ at large x.

2) Experiments with a real photon beam: meson photoproduction on nucleons and nuclei and Compton scattering on nucleons. The main goals: experimental verification of the Gerasimov-Drell-Hearn (GDH) sum rule, investigation the helicity structure of partial reaction channels, resolve the excitation spectrum of light-quark baryons, search for missing baryon resonances and exotic states (dibaryons, narrow nucleon resonances), studying the structure of hadrons.

3) Measurement of $\Delta\sigma_T$ and $\Delta\sigma_L$ in the nd transmission experiment at neutron energies < 16 MeV where limited experimental data exist and where the theory predicts the essential effect of the 3NF. This part of the project is the continuation of the same quantities measurements in neutron-proton scattering being performed previously.

Technically, three parts of the project are unified by the use of the frozen-spin polarized proton and deuteron targets.

2 SPASCHARM

High sensibility to gluon content of the interacting particles is one of the main features of charmonium production in hadronic interactions. In case of collision of two longitudinally polarized protons it is used to define gluon polarization $\Delta G/G$ in the proton. A polarized proton beam is needed to make this study. It will be used at the second stage of the experiment after the completion of measurements of single-spin asymmetries in charmonium production.

The presence of polarization for both protons and antiprotons in the CP neutral p$\tilde{\text{p}}$ -system potentially opens up opportunities for studying and comparing CP conjugate reactions in this system. It allows us to look at CP invariance in a new perspective, inaccessible to collisions of unpolarized particles. It is interesting that the LHCb collaboration has just presented at the Rencontres de Moriond EW and in a special CERN Seminar the first observation of CP violation in charm particle decays. The final result, which uses essentially the full data sample collected by LHCb so far, is given by the quantity $\Delta A_{CP} = (-0.154 \pm 0.029)\%$, whose difference from zero quantifies the amount of CP violation observed [2].

Strategics of the SPASCHARM experiment:

Stage 1. Single-spin asymmetry on the beamline 14 (2018-2021) [3], including the first measurements of polarization and buildup.

Stage 2. Creation of the polarized proton and antiproton beams (research is planning to be started in $2022 - 2023$).

At the first stage unpolarized beams will be used. The first stage envisages a study of the single-spin asymmetry A_N of light particles consisting of u-, d- and s-valence quarks. Transverse single-spin asymmetries are very well known for a long time. In the Standard Model QCD at leading twist level all A_N are small or close to zero. But the experiments show very large A_N (up to 40 %) in the confinement region. To discriminate the existing theoretical approaches and to stimulate the development of the new ones, a systematic study of A_N for a big number of miscellaneous inclusive and exclusive reactions is needed, especially in the confinement region, which is the most unclear for theory. This systematic study is the main goal of the first stage of the SPASCHARM project [4–7]. This will finally prepare the experimental setup to the second stage of the project where only one new thing will be needed — namely a polarized proton beam from U-70.

Double-spin effects in dozens of reactions will be measured with the use of polarized target and beam (proton and antiproton) to investigate spin dynamics and proton spin structure.

Latest achievements issues in the determination of polarized parton distribution functions, driven by new measurements in polarized proton-proton collisions at the Relativistic Heavy Ion Collider, allowed to estimate [8] that the gluon contribution is positive in different approaches and equals $\Delta g = 0.20^{+}0.06_{-}0.07$ for DSSV14 [9] and $\Delta g = 0.23 \pm 0.06$ for NNPDFpol1.1. [10]. Nevertheless, these results are model dependent while SPASCHARM measurements will give unique possibility to measure Δg directly.

Information about gluon polarization might be obtained through simultaneous measurements of A_{LL} in inclusive production of χ_{c2} and J/Ψ. This experiment was proposed at Fermilab (P838) at 200 GeV as a continuation of E704 [11]. The Fermilab's PAC pointed out that physics was very interesting, but an intensity of the polarized proton beam from Λ-hyperon decays was small, so the statistics would not be enough. The experiment was not approved.

The goal of the proposed experiment is to measure double-spin asymmetry A_{LL} with the use of longitudinally polarized beam and target in the process:

$$p_{\rightarrow} + p_{\rightarrow} \rightarrow \chi_{c2}(J/\Psi) + X, \ (\chi_{c2} \rightarrow J/\Psi + \gamma). \tag{1}$$

J/Ψ will be registered via $\mu^+\mu^-$ decay due to Bremsstrahlung in e^+e^- decay mode. The charmonium states under study are $J/\Psi(3096, J^{PC} = 1^{--})$, $\chi_{c1}(3510, J^{PC} = 1^{++})$ and $\chi_{c2}(3555, J^{PC} = 2^{++})$. The measured experimental asymmetry is given by

$$A_{LL} = \frac{1}{P_B P_T} \cdot \frac{I^{++} - I^{+-}}{I^{++} + I^{+-}} \tag{2}$$

where P_B is the beam polarization, P_T is the target polarization, I^{++}, I^{+-} are the number of events normalized to the incident beam intensity. The helicity (++) and (+−) states correspond to (→→) states and (←→), respectively, where arrows indicate the beam and target spin direction in the laboratory system.

The experimental setup SPASCHARM includes:

- wide aperture spectrometer with GEM, drift chambers and proportional chambers;
- electromagnetic calorimeter, and
- muon detector.

Fine segmented electromagnetic calorimeter of "shashlik" type with energy resolution $\Delta E/E$ about 3% will be constructed. It is critically needed to detect very precisely γ-quanta from χ-decays to separate χ_{c1} and χ_{c2} through high precision energy resolution of the calorimeter. We propose to measure simultaneously the double-spin asymmetry A_{LL} for inclusive χ_{c2}, χ_{c1} and J/Ψ by utilizing the 45 GeV longitudinally polarized proton beam on a longitudinally polarized target. The principle point for this experiment is a separation of the two charmonium states with the spins equal to 1 and 2, namely $\chi_{c1}(3510)$ and $\chi_{c2}(3555)$. The Monte-Carlo simulations for 45 GeV have been made. We can see that the two states of interest are well separated.

2.1 Polarized frozen-spin target at Protvino

The authors of the project suggest to use the modernized frozen-spin target based at the one, developed earlier at LNP JINR [12, 13].

The target includes a stationary cryostat with a dilution refrigerator, an electromagnet, a high-frequency generator providing the dynamic polarization and a NMR-signal detection array.

In the DNP mode, the magnet poles are in the position when the magnetic circuit is closed, the magnetic field is as high as 2.5 T and the homogeneity is no worse than 10^{-4} within the target volume. When the poles are open, the magnetic field is 0.4 T in a gap of 20 cm and the homogeneity is 10^{-2}.

Target material is 1,2-propanediol $C_3H_8O_2$ (volume 20 cm^3) with a paramagnetic Cr(V) impurity. The maximum obtained proton polarization was 93% and 98% for positive and negative values, respectively. In the DNP mode, $T = 200$ mK. A transistor with quartz oscillator with output power of $\approx$ 400 mW at a frequency of $\approx$ 67 GHz is used for the dynamic build-up of polarization. Polarization time necessary to obtain $0.8P_{max}$ is $\approx$ 40 min.

In the frozen spin mode the target is maintained at a temperature of 20 mK in the holding magnetic field of 0.45 T. Under these conditions, the spin relaxation time was $\approx$1200 h for positive polarization and 800 h for negative polarization.

The target polarization measurement is carried out using a multipurpose Q-meter with phase shift detector at operating frequency of about 102 MHz [14].

2.2 Main results

First data to study single-spin asymmetries in the SPASCHARM experiment were being taking in 2018. Data taking run will be carried out using a negative particle beam and a Dubna polarized frozen target in 2019.

1. The polarized proton and antiproton beam project at U-70 accelerator V.V. Abramov (Serpukhov, IHEP & Kurchatov Inst., Moscow) et al.. 2018. 7 pp. Published in Nucl. Instrum. Meth. **A 901** (2018) 62.

2. Measurements of the Beam and Target Analyzing Powers and Spin Correlation Parameter ANN in Elastic pp Scattering at 45 Gev/c. V.V. Abramov (Serpukhov, IHEP) et al.. 2018,

Published in KnE Energ.Phys. **3** (2018) 326.

3. Comparative study of the inclusive asymmetries induced by polarized protons and antiprotons at 16 GeV/c at the U–70 accelerator V.A. Okorokov (Moscow Phys. Eng. Inst.) et al.. Oct 16, 2017. 7 pp. Published in J. Phys. Conf. Ser. **938** (2017) no.1, 012014.
4. Polarized proton and antiproton beams for the SPASCHARM experiment at U-70 accelerator I.I. Azhgirey et al, Published in J. Phys. Conf. Ser. **798** (2017) no.1, 012177.
5. Study of single-spin asymmetries with polarized target at the SPASCHARM experiment at U-70 accelerator V.V. Abramov (Serpukhov, IHEP) et al.. 2017. 5 pp. Published in J.Phys.Conf.Ser. 798 (2017) no.1, 012096.
6. Beam polarimetry at the SPASCHARM experiment at IHEP U-70 accelerator A.A. Bogdanov (Moscow Phys. Eng. Inst. & Kurchatov Inst., Moscow) et al.. 2017. 5 pp. Published in J. Phys. Conf. Ser. **798** (2017) no.1, 012179.
7. Simultaneous measurements of spin observables A_N and A_{NN} in elastic pp scattering (extension of the SPASCHARM program at U-70). V.V. Abramov (Serpukhov, IHEP) et al.. 2017, Published in J. Phys. Conf. Ser. **938** (2017) no.1, 012006.

2.3 Working plan

2020:

– Data taking run will be carried out using a negative particle beam and a Dubna polarized frozen target. The magnet of the polarized target will be optimized (it is necessary to achieve field uniformity at the level of 0.012%). The technical design of the polarized beam-line will be finished while the construction will started (subject to appropriate funding).

2021:

– Data taking run will be carried out using a negative particle beam and a Dubna polarized frozen target. Single spin asymmetries will be measured in inclusive production of charged pions. Conceptual design of the SPASCHARM experiment will be prepared and published (in Russian) as well as the proposal to study systematically spin effects in elastic reactions.

2022:

– Single-spin asymmetry in inclusive production will be measured for such “lying on the surface” resonances like $\rho(770)$, $\omega(782)$, $\eta\prime(958)$, $f_0(980)$, $a_0(980)$, $f_2(1270)$. The possibility to measure the polarization of Λ hyperon and the alignment of vector mesons will be investigated also. The concept of the polarized beam tagging system will be developed and prototypes of the detectors of the tagging system will be developed and tested.

3 GDH

The MAinz MIcrotron at the Institute for Nuclear Physics at the Johannes Gutenberg University was built in 1979. The first stage was MAMI-A1 where the exploitation of the microtron principle led to a maximum electron energy of 14 MeV. It was followed by MAMI-A2 in 1983 when the 183 MeV facility was put into operation. In 1991 MAMI-B was completed, producing electrons up to 855 MeV. MAMI-B is a continuous wave electron accelerator with 100% duty cycle, a maximum current of 100 μA and maximum energy of 855 MeV.

In 2006 the beam energy of Mainz electron accelerator has been increased from 855 MeV (MAMI-B) to 1604 MeV (MAMI-C) while preserving the outstanding beam quality. The photon tagger system of A2 collaboration was accordingly upgraded to make use of the extended energy range and provides now energy-marked circularly polarized photons with the maximum energy over 1550 MeV. In order to tag the high energy part of the bremsstralung spectrum, a dedicated end-point tagging spectrometer was developed. It is specially important for the measurement of η' meson photoproduction. Using a diamond crystal as a radiator allows to obtain linearly polarized photons.

Program of experiments is directed at the study of various aspects of the QCD spin-flavor structure of the nucleons. It includes the verification of Gerasimov-Drell-Hearn (GDH) sum rule for proton and neutron in a wider energy range. Precise measurements of the helicity asymmetry of meson photoproduction with different final states (including neutral ones) will give more detailed information on nucleon resonance properties and multipole amplitudes. Measurements using different combinations of beam and target polarizations will allow the determination of polarization observables with high quality. An extraction of the spin polarizabilities of nucleons from experimental data is also envisaged.

The multipole analysis of the obtained experimental data with the help of the gradually improving MAID package [15] provides a firm basis for a theoretical treatment.The last modification of the package [16] is already available on-line:
https://maid.kph.uni-mainz.de/eta2018/etamaid2018.html. Presently there is also an intense theoretical activity to improve and optimize various calculational schemes including the Lattice QCD and the Chiral Perturbation Theory.

Experiments are conducted with the photon beam of the electron accelerator MAMI C, Mainz, Germany. Main experimental apparatus:

1) Tagged photon beam (unpolarized, circular polarization, linear polarization).

2) Detector system:

- 4π photon spectrometer CB/TAPS (100% solid angle covering for particles decaying into two or more secondary photons, 97% of 4π for single photons, detection of neutrons and charged particles is also possible at restricted energy regions.

- Crystal Ball (CB) overlaps polar angle range $(20 - 160)^\circ$ and TAPS: $(1 - 20)^\circ$. CB consists of 672 NaI(Tl) crystals with 15.7 radiation lengths.

- TAPS consists of 366 BaF_2 crystals with 12 radiation lengths and is supplemented by 5-mm plastic scintillator in front of each module (VETO).

- MWPC, 2 cylindrical multi-wire proportional chambers for vertex reconstraction, target position correction (z), and beam position control (x, y).

- PID (Particle Identification Detector) consists of a barrel of 24-mm-thick plastic scintillator strips. This is a VETO detector for photons in Crystal Ball, also it works as $\Delta E/E$ detector for charged particles identification in Crystal Ball.

- Recoil proton polarimeter. Method: detection of proton scattered in the graphite analyzer

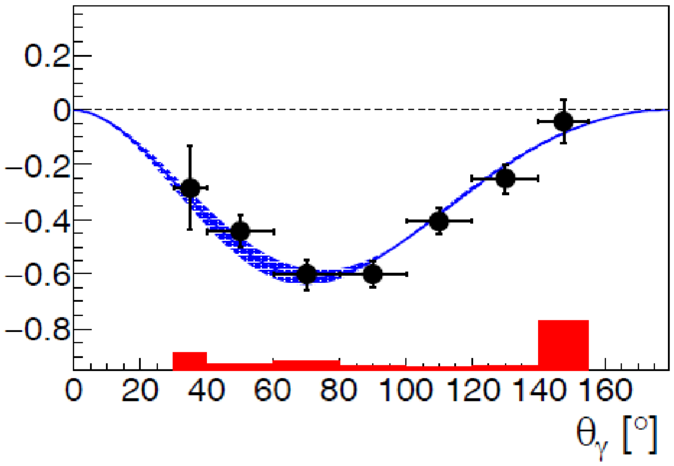

Figure 1: Beam asymmetry Σ_3 in the range 119-139 MeV. Points – experiment, the curve – ChPT calculation (publication [1]).

and comparison its angle with kinematic reconstruction.

3) Dubna-Mainz Frozen Spin Target (available since 05.2010).

For the double polarization measurements planned with the Crystal Ball detector on polarized protons and deuterons a specially designed, large horizontal ^{3}He/^{4}He dilution refrigerator has been built in cooperation with the Joint Institute for Nuclear Research [17–24]. Superconducting holding magnet permits longitudinal and transverse polarizations. Trityl doped butanol and deuterated butanol are the best materials for this experiment.

Main parameters are:

At a total tagged photon flux of 5×10^7 and a target temperature 30 mK relaxation times of about 2000 hours was obtained [25].

Target proton density in 2 cm diameter cell: $N_T \approx 9.1 \cdot 10^{22}$ cm^{-2} (including dilution and filling factors).

Maximum polarizations at 2.5 T are: for protons - ≃90%, for deuterons - ≃75%.

Average proton polarization $P_p = 70\%$.

Average neutron polarization $P_n = 50\%$

3.1 Main results

1. The first ever successful experiment with the active polarized target has been realized at the beam of circularly polarized tagged photons of the MAMI accelerator (Mainz). High efficiency and low threshold for the detection of the recoil protons in the target open new perspectives for the study of the proton spin structure and extraction of the model-independent data. Polarization observables for π^0 and π^+ photoproduction has been measured, as well as Compton scattering asymmetries allowing to extract model-independent data on the proton spin polarizabilities.

2. First ever measurements of the beam asymmetry Σ_3 for Compton scattering below pion photoproduction threshold have been performed (Fig. 1) by A2 collaboration at the polarized energy marked photon beam of the MAMI accelerator (Mainz). The results confirm the existing

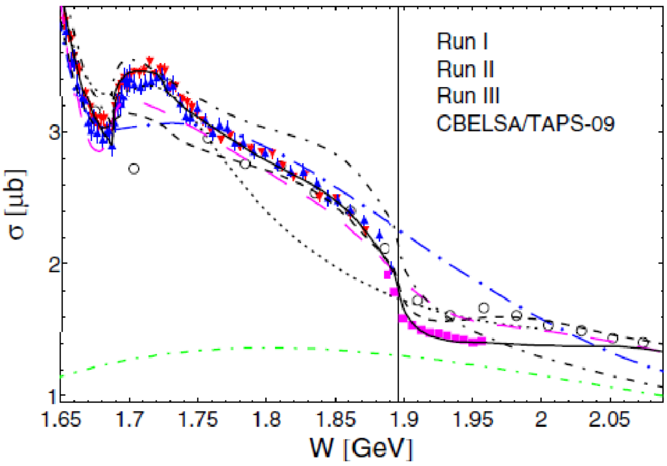

Figure 2: $\gamma p \to \eta p$ total cross section.

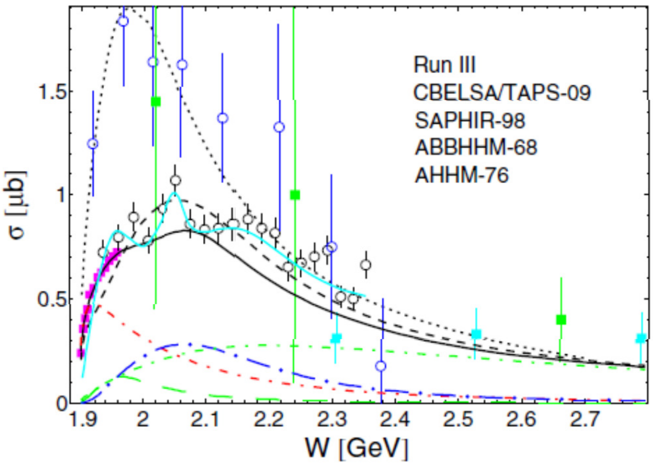

Figure 3: $\gamma p \to \eta' p$ total cross section.

predictions of perturbation theory and dispersion relation models and deviate notably from the Born term in which the contributions of the proton polarizabilities are not included. The results obtained show that the extraction of the scalar polarizabilities from the beam asymmetry below the threshold provides an alternative to the extraction from the unpolarized Compton scattering cross section (publication [1]).

3. The reactions $\gamma p \to \eta p$ and $\gamma p \to \eta' p$ have been measured from their thresholds up to the center-of-mass energy $W = 1.96$ GeV with the tagged-photon facility at the Mainz microtron MAMI. Differential cross sections were obtained with unprecedented accuracy, providing fine energy binning and full production-angle coverage. A strong cusp is observed in the total η photoproduction cross section at the energies in vicinity of the η' threshold, $W = 1896$ MeV ($E_\gamma = 1447$ MeV) (Fig. 2). This behavior in combination with the steep rise of the total η' -photoproduction cross section from its threshold (Fig. 3) is explained in a revised ηMAID2017 isobar model by a contribution of the N(1895)$1/2^-$ nucleon resonance. The new precision data allowed to determine properties of this resonance (publication [2]).

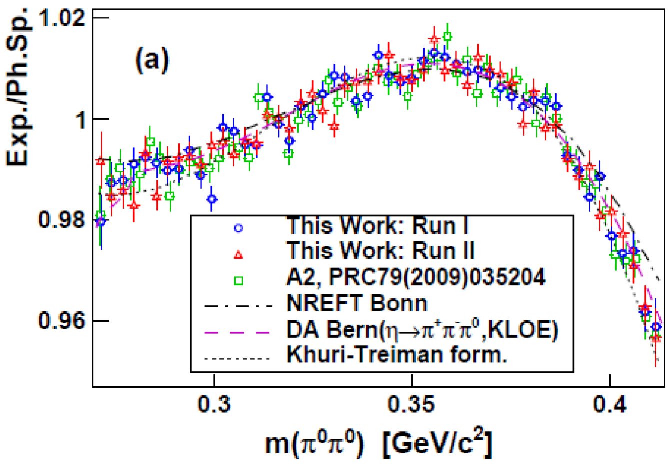

Figure 4: Explanation in the text.

4. The decay $\eta \to 3\pi$, which is forbidden by isospin symmetry, mostly occurs due to the difference in the mass of the u and d quarks. A precision measurement of this decay for both charged and neutral modes can be used as a sensitive test for the magnitude of isospin breaking in QCD. The A2 collaboration has measured the reaction $\gamma p \to \eta p$ with high statistics at the MAMI accelerator. Most precise, at the moment, data on the $\eta \to 3\pi^0$ decay were obtained from these measurements, which allowed the detailed study of its dynamics. The present data are compared to recent theoretical calculations (Fig. 4) (publication [3]).

PUBLICATIONS: 1. V. Sokhoyan, N.S. Borisov, G.M. Gurevich, A.B. Lazarev, A.B. Neganov, Yu.A. Usov et al. Determination of the scalar polarizabilities of the proton using beam asymmetry Σ_3 in Compton scattering. Eur. Phys. J. **A 53** No. 2 (2017) 14.

2. V.L. Kashevarov, N.S. Borisov, G.M. Gurevich, A.B. Lazarev, A.B. Neganov, Yu.A. Usov et al. Study of η and $\eta\prime$ photoproduction at MAMI. Phys. Rev. Lett. **118** Iss. 21, 212001 (2017).

3. S. Prakhov, N.S. Borisov, G.M. Gurevich, A.B. Lazarev, A.B. Neganov, Yu.A. Usov et al. High-statistics measurement of the $\eta \to 3\pi^0$ decay at the Mainz Microtron. Phys. Rev. **C 97** No. 6, 065203 (2018).

4. P. Adlarson et al., Measurement of the $\omega \to \pi^0 e^+ e^-$ and $\eta \to e^+ e^- \gamma$ Dalitz decays with the A2 setup at MAMI. Phys. Rev. **C 95** (2017) 035208.

5. P. Adlarson et al., Measurement of the $\pi^0 \to e^+ e^- \gamma$ Dalitz decay at the Mainz Microtron. Phys. Rev. **C 95** (2017) 025202.

6. L. Witthauer et al., Helicity-dependent cross sections and double-polarization observable E in η hotoproduction from quasifree protons and neutrons. Phys. Rev. **C 95** (2017) 055201.

7. M. Dieterle et al., First measurement of the polarization observable E and helicity-dependent cross sections in single π^0 photoproduction from quasi-free nucleons. Phys. Lett. **B 770** (2017) 523.

8. P. Adlarson et al., Measurement of the decay $\eta' \to \pi^0 \pi^0 \eta$ at MAMI. Phys. Rev. **D 98** (2018) 012001.

9. M. Dieterle et al., Photoproduction of π^0 Mesons off Protons and Neutrons in the Second

and Third Nucleon Resonance Region. Phys. Rev. **C 97** (2018) 065205.

10. A. Käser et al., First measurement of helicity-dependent cross sections in $\pi^0\eta$ photoproduction from quasi-free nucleons. Phys. Lett. **B 786** (2018) 305.

11. M. Bashkanov et al., Deuteron photodisintegration by polarized photons in the region of the $d^*(2380)$. Phys. Lett. **B 789** (2019) 7.

3.2 Working plan

2020:

– Commissioning of the new frozen spin target for experiments with Crystal Barrel/ELSA facility at the Bonn University.

2021:

– Precision large-acceptance measurements of the beam-spin asymmetry for deuteron photodisintegration in the region of the exotic six-quark state d*(2380).

2022:

– Study of the spectrum and properties of the baryon resonances through the measurements of the polarization observables in meson photoproduction.

4 NN-interactions

The problem of nuclear forces is one of the oldest but still most essential problems in nuclear physics. Recent advances in the development of few-body methods coupled with a significant increase in computational resources allow one to perform accurate microscopic calculations of three- and even four-nucleon scattering observables and of the spectra of light nuclei. This opens the door for precise tests of the underlying dynamics and, in particular, of the role and structure of the three-nucleon forces (3NF).

When speaking about NN and 3NF one should keep in mind, that any unitary transformation of the Hamiltonian does not change physics. However, that unitary transformation which relates two two-body interaction potentials, which are equivalent on-shell but different in the off-shell region, generates three-body forces [26].

The modern approach of the Effective Field Theory considers two- and three-nucleon forces jointly, i.e., selfconsistently [27–29]. The last results on theory of NN and 3NF are in the papers [30–33]. This approach is widely applied for low energy nuclear physics and nuclear astrophysics. Necessary low-energy parameters of the theory have to be extracted from experimental data [34].

Nuclear forces obey a certain hierarchy implying that 3NF effects are much smaller, on average, than 2NF. This can be demonstrated by the inclusive total np and nd scattering data measured at Los Alamos. First calculations including the 3NF have shown that current models of the 3NF can explain approximately 1/2 of deviation of the calculations from the data. These observations demonstrate the need for exclusive measurements which can provide a significantly larger sensitivity to 3NF effects for specific regions in phase space or for other observables than total cross sections [35].

In the past decades, detection systems suitable for the study of certain aspects of the dynamics of the three-body systems have been developed at various laboratories. The use of polarized beams and/or polarized targets has been very common in the past two decades. In addition to protons and deuterons, neutron beams have also been extensively used at TUNL, Bonn, Erlangen, PSI, Uppsala, LANSCE and RCNP. The obvious disadvantage of the neutron beam is that it cannot be manipulated in the beam lines so that experiments are more difficult. In contrast to charged particle detectors where efficiencies close to 100% can be achieved, the efficiency of the neutron detectors is generally lower and requires a complicated calibration. All this issues are not particularly a problem in these experimental studies. Moreover the theoretical estimates are model independent since Coulomb distortions are absent when one uses neutron beams.

The spin-dependent cross-section difference, $\Delta\sigma_L$(nd), in the nd total cross section has been shown to be sensitive to the same 3NF components that correct the triton binding energy problem. $\Delta\sigma_L$ is the difference in the nd total cross section for beam and target spins parallel and anti-parallel to each other, with both spins aligned with the beam momentum axis. $\Delta\sigma_T$ is similarly defined. Theoretical calculations predict that the Tucson-Melbourne three-nucleon force changes $\Delta\sigma_L$ by 5-10% [36] from its value calculated using only NN interaction potentials. The total cross-section difference $\Delta\sigma_L$(nd) was measured firstly at TUNL [37] for incident neutron energies of 5.0, 6.9 and 12.3 MeV. The results were compared to the theoretical predictions based on the CD Bonn NN potential calculations, with and without the inclusion of the TM-3NF, "but are not of sufficient precision to distinguish the presence or absence of three-nucleon force contributions to the cross-sections".

At the Charles University Nuclear Center the measurements of $\Delta\sigma_L$(np) and $\Delta\sigma_T$(np) were performed using the transmission method, i.e., the relative difference in attenuation of a polarized neutron beam passing through a polarized proton target was measured. A polarized neutron beam was based on the Van de Graaff electrostatic accelerator HV 2500 of the Nuclear Center, Charles University (now belongs to IEAP CTU), using the reaction T(d,n)^{4}He with a deuteron beam ($E_d = 1.82$ MeV). To achieve a monoenergetic collimated neutron beam, the associated particle method was used [38]. The transversely polarized neutron beam with an energy $E_n = (16.2 \pm 0.1)$ MeV was emitted at an angle $\theta_{lab} = (62.0 \pm 0.7)^\circ$. The value of neutron polarization was taken from [39] and amounts $P_n = (-13.5 \pm 1.4)\%$. The physical results obtained in Prague permit a new view to the earlier data in this energy range. Earlier, experimental results of other authors (Bonn, Erlangen, Triangle Universities) supported the hypothesis on the minimum value of $\epsilon 1$ in the vicinity of 15 MeV. Our results disproved this, which is in good accord not only with the other experimental data in this energy range, but with model predictions, in particular [42, 43].

The PPT has been transformed into the frozen spin deuteron polarized target (DPT). Deuterated 1,2 propanediol with a paramagnetic Cr (V) impurity having a spin concentration about 10^{20} cm^{-3} is used as a target material. The maximum deuteron vector polarization achieved was 40%. The DPT was described in detail in [24, 41].

The last 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 on the measurement of the cross-section difference. Now a modernization of the facility is in progress with the aim to increase the deuteron polarisation of the polarized target and the intensity and polarization of the neutron beam. We will replace our current target material (propanediol) with the novel material, trityl-doped butanol. With this material, polarizations as high as $\simeq$ 80% were achieved by the Mainz group [44]. To improve the parameters of the neutron beam it is proposed to use the reaction T(d,n)^{4}He with polarized deuterons of an energy 100-150 keV. This can be achieved using the known Kaminsky's method [45, 46]. As a first step, it will be production of the polarized deuteron beam with an energy up to 200 keV using channeling of the unpolarized deuteron beam through magnetized Ni film. The electron polarization of the produced deuterium atoms arises from the preferential attachment of electrons of one spin sign. The electron polarization is transferred to the nuclei by the hyperfine interaction. He obtained 500 nA/cm^2 of channeled deuterium atoms with an energy of 100-200 keV with nuclear polarization $P_{zz} = -0.32 \pm 0.010$. The first proposal concerning the nuclear polarization via a pick-up of polarized ferromagnetic electrons was made by Zavoiskii in 1957 [47].

Feldman et al. [48] 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.

The scheme and photo of the experimental setup [49] are shown in Figs. 5, 6. We propose to apply the Sona method, zero-field transitions with total transfer of the electron polarization to deuterons in the atomic beam [50]. 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. We use two permanent magnets (2×20 cm) with a changing distance between the poles ($B_{\max} = 0.1$ T). The charged deuterons are deflected by electric and magnetic fields.

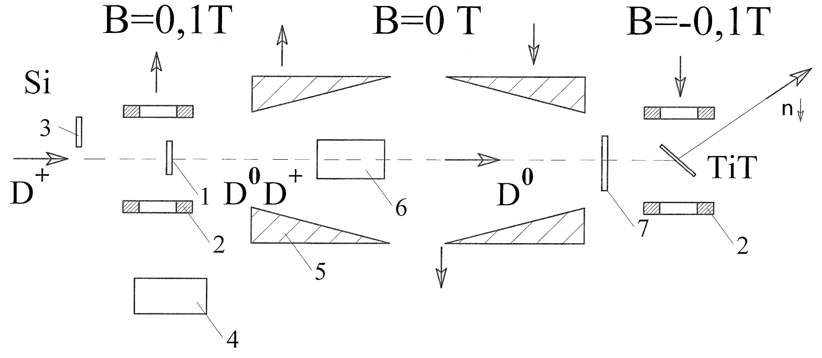

Figure 5: Scheme of the polarized deuteron source; 1 – nickel foil, 2 – permanent magnet (0.07 T), 3 – solid state detector, 4 – a goniometer, 5 – polarizing permanent magnets (for the Sona transitions), 6 – electrostatic plates, 7 – the target of a polarimeter.

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 the Cu disc mounted on the goniometer.

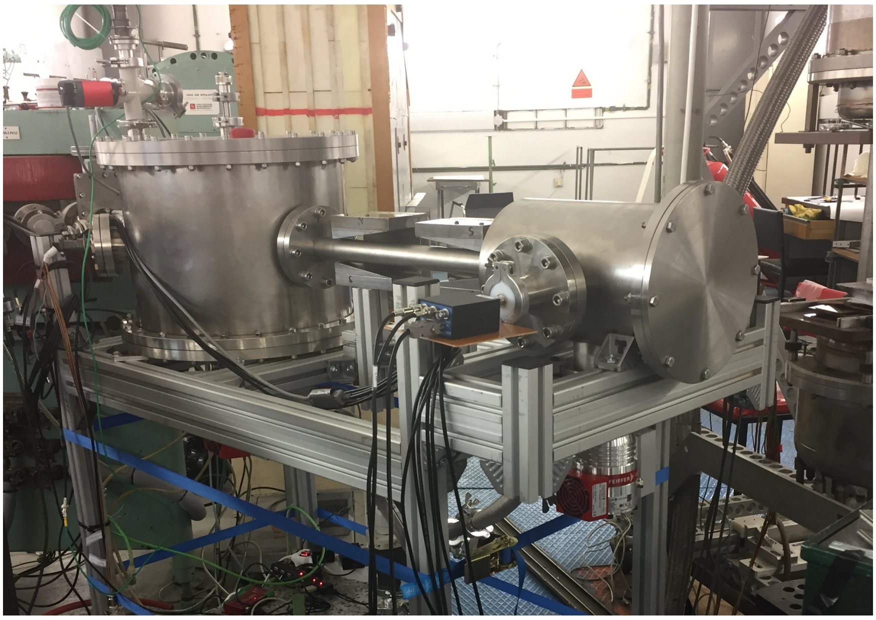

Figure 6: Photo of the experimental setup.

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 [51].

The deuteron vector polarization may be measured using the reaction $D(d,p)T$ [52]. At first, we decided to measure the tensor polarization with TiT target as the cross section for the reaction $T(d,n)^4He$ [53] is approximately 200 times higher than for dd-reaction.

The cross section depends on the c.m. angle between the spin and α particle direction ϑ [45, 53]:

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

For measurements we used two values for ϑ: $\vartheta = 90^\circ$ and $\vartheta = 20^\circ$. As a result, $P_{zz} = -0.12 \pm 0.04$ (theoretical value is $P_{zz} = -0.33$ at the deuteron energy of 500 keV for the Ni foil thickness 1.5 μm (the deuterium atom energy is 250 keV). During this experiment the goniometer was at a random position, and we used only the first magnet of the Sona transition system and the detector was at a small magnetic field. It seems possible that the effect of channeling permits to increase the available deuterium current at the target and polarization.

If the target material TiT_N contains N = 1.5 tritium atoms/titanium atom, the total yield of neutrons is 1.5×10^7 neutrons per steradian per one μA of deuterons. At the beam radius of 3 mm we will have $\simeq 0.15$ μA of deuterium atoms. With a solid angle 3×10^{-4} the neutron beam would be $\simeq 6 \times 10^2$ neutrons/s.

According to [42, 43] statistical error for $\Delta\sigma_{L,T}$ may be written as

$$\Delta\sigma_{L,T} = \frac{\ln\xi(antiparallel) - \ln\xi(parallel)}{\omega P_b P_t}, \tag{4}$$

where ω – deuteron surface density of polarized target, deuterons/cm^2, P_b, P_t – the polarization of the beam and target, respectively, and $\xi = N_{det}/N_{mon}$, where N_{det} and N_{mon}

– neutron counting rates of the detector and monitor, respectively. The monitor counts the neutron intensity before the polarized target.

Absolute statistical error is

$$\delta(\Delta\sigma) = \frac{\sqrt{2}}{\omega P_b P_t} \times \sqrt{\frac{1}{\bar{N}_{mon} t} + \frac{1}{\bar{N}_{det} t}}, \tag{5}$$

where $\bar{N}_{mon,det} = \frac{1}{2}(N_{mon,det}(par.) + N_{mon,det}(antipar.)$

For the polarized target (propanediol) $\omega = 3 \times 10^{-4}$ mbarn^{-1}. At $P_t = 0.8$ и $P_b = 0.6$, one obtains $1/\omega P_b P_t \approx 7 \times 10^4$ mbarn.

If the detector efficiency is 10^{-2}, and solid angle 3×10^{-4}, then at $N_{mon} \simeq N_{det} = 6$ neutrons/s to get $\delta_{stat}(\Delta\sigma) = 10$ mbarn it is necessary $t = 180$ hours of data taking for two values of polarization sign.

At a neutron energy of 14 MeV $\Delta\sigma_T \approx -300$ mbarn. Including 3NF decrease the cross section difference [36] to 20 mbarn, so we can detect this difference.

4.1 Main results

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

For a nonchanneled beam (the goniometer in a random position), the tensor polarization measurements were carried out with a TiT target in the reaction $\mathrm{T}(d,n)^4\mathrm{He}$. Our result is $P_{zz} = -0.12 \pm 0.04$ for a weak field at the target.

1. Yu.A. Plis et al., Research and Development of the Polarized Deuteron Sources for the Van de Graaff Accelerator. Physics of Particles and Nuclei Letters. **16** (2019) 256-263; preprint JINR E13-2018-69. Dubna, 2018.

4.2 Working plan

2020:
– Experiments on channeling at the stand of the polarized deuteron source.
– Upgrade of all the systems of the deuteron polarized target at Prague.
– Preparation of a new stable microwave source.

2021
– Manufacture of the polarized neutron source on the base of polarized deuteron source and its connection with the polarized deuteron target.
– The exact measurement the vector and tensor polarizations of the deuterons.
– Preparation of the design of the necessary steps to use new target material based on Trityl-doped butanol in Prague.

2022
– To prepare apparatus for measurements of the neutron polarization via scattering on the ^{4}He target.

– To make the electronics and to measure the neutron polarization.

– The measurement of the polarization observables at the experiments with polarized neutron source and polarized deuteron target.

The project includes 21 participants from JINR. Authors of the project have publications at least on one part of the Project.

5 Form No 26

Proposed schedule and necessary resources for realization of the project "SPASCHARM-GDH-NN" (k$)

Title of expense item	Total cost	Laboratory proposal for distribution of finances		
		2020	2021	2022
1. The modification of the UHF system of the polarized target	15.0	9.0	2.0	4.0
2. Design and preparation of the parts of "Active Target"	6.0	4.0	2.0	-
3. Modification of the polarization measurement system	4.0	2.0	2.0	-
4. Purchase of standard devices	41.0	16.0	14.0	11.0
Total (equipment)	66.0	31.0	20.0	15.0
Materials	26.0	10.0	8.0	8.0
TOTAL	158.0	72.0	48.0	38.0
Finance sources				
Budget expenses				
a) direct (immediate)	201.0	71.0	65.0	65.0
b) grant of Germany (BMBF)	30.0	10.0	10.0	1.0
c) grants of CR	54.0	18.0	18.0	18.0
Total immediate expenses	**285.0**	**99.0**	**93.0**	**93.0**

Table 1:

Leaders of the Project	A. Kovalik, Yu.A. Usov
Deputies of the Leaders	Yu.A. Plis, Yu.N. Uzikov

6 Form No 29

Estimate of the expenses for the Project "SPASCHARM-GDH-NN" (k$)

	Title of expense item	Total cost	2020	2021	2022
1	R & D agreement expenses	12.0	8.0	2.0	2.0
2	Job cost at the LNP's experimental shop	3.0	1.0	1.0	1.0
3	Materials	66.0	22.0	22.0	22.0
4	Transport expenses	4.5	1.5	1.5	1.5
5	Unforeseen expenses	6.0	2.0	2.0	2.0
6	Electronic instruments	45.0	15.0	15.0	15.0
6	Annual contribution to "A2" -collaboration	24.0	8.0	8.0	8.0
7	Travel expenses	124.5	41.5	41.5	41.5
	inclusive				
	a) to nonruble zone countries	108.0	36.0	36.0	36.0
	b) to ruble zone countries	12.0	4.0	4.0	4.0
	c) visits to JINR	4.5	1.5	1.5	1.5
Total immediate expenses		285.0	99.0	93.0	93.0

Table 2:

Leaders of the Project	A. Kovalik, Yu.A. Usov
Deputies of the Leaders	Yu.A. Plis, Yu.N. Uzikov
Director of the Laboratory	V.A Bednyakov
Assistant director on finance	G. A. Usova

References

[1] A.V. Efremov, in Proc of 15th Intern. Spin Physics Symposium Upton, 2002, p.235.

[2] http://lhcb-public.web.cern.ch/lhcb-public/Welcome.html.

[3] V.V. Abramov et al. J. Phys. Conf. Ser. **798** (2017) 012096.

[4] V.V. Mochalov et al. Int. J. Mod. Phys. Conf. Ser. **40** (2016) 1660106.

[5] V.V. Abramov et al. Nucl. Instr. and Meth. **A 901** (2018) 62.

[6] V.D. Apokin et al., in Proc. of the IV Workshop on high energy spin physics, Protvino (1991) 288.

[7] V.D. Apokin et al., Russ. J. Phys. Atom. Nucl. **45** (1987) 840.

[8] E.R. Nocera, Achievements and open issues in the determination of polarized parton distribution functions, Int. J. Mod. Phys. Conf. Ser. **40** (2016) 1660016; arXiv:1503.03518 [hep-ph].

[9] D. de Florian et al., Phys. Rev. Lett. **113** (2014) 012001.

[10] E.R. Nocera et al., Nucl. Phys. **B 887** (2014) 276

[11] M.E. Beddo et al., Fermilab proposal P838, January 1991.

[12] N.S. Borisov et al., JINR communications 13-10253, Dubna, 1976.

[13] N.S. Borisov et al., Sov. Phys. JETP **60** (1984) 1291.

[14] N.A. Bazhanov, A.I. Kovalev, LIYaP, preprint No. 1642, 1990, Leningrad.

[15] D. Drechsel, S.S. Kamalov, L. Tiator,
Unitary isobar model - MAID2007,
Eur. Phys. J. **A 34** (2007) 69.

[16] L. Tiator, M. Gorchtein, V.L. Kashevarov et al.,
Eta and Eta prime Photoproduction on the Nucleon with the Isobar Model Eta MAID2018,
Eur. Phys. J. **A 54** (2018) 210.

[17] B.S. Neganov, N.S. Borisov and M.Yu. Liburg, JETP **50** (1966) 1445.

[18] B.S. Neganov, Vestn. Akad. Nauk SSSR **12** (1968) 49.

[19] F. Lehar et al., Nucl. Instr. and Meth. **A 356** (1995) 58.

[20] N.A. Bazhanov et al., Nucl. Instr. and Meth. **A 402** (1998) 484.

[21] Yu.A. Usov, Nucl. Instr. and Meth. **A 526** (2004) 153.

[22] Yu.A. Usov. Frozen spin target developed at Dubna. History and Traditions. XVI International Workshop in Polarized Sources, Targets and Polarimetry. PSTP2015, Ruhr-University Bochum, Germany, 14-18 September 2015, PoS (PSTP2015) 021.

[23] G.M. Gurevich, A.A. Lukhanin, F. Maas, Yu.A. Plis, A.O. Sidorin, A.V. Smirnov, A. Thomas, Yu.A. Usov. On the feasibility of using an extracted polarized antiproton beam of the HESR with a solid polarized target. XVI International Workshop in Polarized Sources, Targets and Polarimetry. PSTP2015, Ruhr-University Bochum, Germany, 14-18 September 2015, PoS(PSTP2015)043.

[24] Yu.A. Usov. Frozen spin target developed at Dubna. Hystory and Traditions. XVI International Workshop in Polarized Sources, Targets and Polarimetry. PSTP2015, Ruhr-University Bochum, Germany, 14-18 September 2015, PoS(PSTP2015)021.

[25] A. Thomas et al., Nucl. Phys. **B 79** (1999) 591.

[26] W.N. Polizou , W. Glöckle, Few-Body Syst. **9** (1990) 97-121.

[27] E. Epelbaum, H.-W. Hammer, Ulf-G. Meißner, Rev. Mod. Phys. **81** (2009) 1773.

[28] L. Platter, Phys. Rev. **C 74** (2006) 037001.

[29] J. Rotureau et al., Phys. Rev. **C 85** (2012) 034003.

[30] D.R. Entem et al., Phys. Rev. **C 96** (2017) 024004.

[31] P. Reinert, H. Krebs, E. Epelbaum, Eur. Phys. J. **A 56** (2018) 86.

[32] E. Epelbaum et al., Phys. Rev. **C 99** (2019) 024313.

[33] S. Binder et al., Phys. Rev. **C 98** (2018) 014002.

[34] Yu.N. Uzikov, Three-nucleon forces and some aspects of nuclear astrophysics, in The Universe Evolution, nuclear astrophysics. Eds. I. Strakovsky, L. Blokhintsev. New York: Nova Science Publisher, Inc., 2013. pp.269-292. ISBN 978-1-62808-547-7.

[35] Yu.N. Uzikov, On the contribution of three-body forces to Nd interaction at intermediate energies. JETP Lett. **75** (2002)5; Pis'ma v ZHETF , **75** (2002) 7.

[36] H. Witala et al., Phys. Lett. **B 447** (1999) 216.

[37] R.D. Foster et al., Phys. Rev. **C 73** (2006) 034002.

[38] I. Wilhelm et al., Nucl. Instr. & Meth. **A317** (1992) 553.

[39] M. Koch et al. Nucl. Phys. Spring Meeting, Salzburg, 1992.

[40] N.S. Borisov et al., Nucl. Instr. & Meth. **A 345** (1994) 421.

[41] N.S. Borisov et al., Nucl. Instr. & Meth. **A 593** (2008) 177.

[42] J. Broz et al., Z. Phys. **A 35** (1996) 401.

[43] J. Broz et al., Z. Phys. **A 359** (1997) 23.

[44] S.T. Goertz et al., Nucl. Instr. & Meth. **A 526** (2004) 43.

[45] M. Kaminsky, Phys. Rev. Lett. **23** (1969) 819.

[46] M. Kaminsky, in Proc. of 3rd Int. Symp. on Polarization Phenomena in Nuclear Reactions, Madison, 1970, p. 803.

[47] E.K. Zavoiskii, J. Exp. Theor. Phys. **32** (1957) 408; english translation, Sov. Phys. – JETP **5** (1957) 338.

[48] L.C. Feldman et al., Radiation Effects **13** (1972) 145.

[49] Yu.A. Plis et al., Research and Development of the Polarized Deuteron Sources for the Van de Graaff Accelerator. Physics of Particles and Nuclei Letters. **16** (2019) 256-263; preprint JINR E13-2018-69. Dubna, 2018.

[50] P.G. Sona, Energia Nucleare. **14** (1967) 295-299.

[51] G.G. Ohlsen, Rep. Progr. Phys. **35** (1972) 717.

[52] A.A. Naqvi, G. Clausnitzer, Nucl. Instr. & Meth. **A 324** (1993) 429.

[53] A. Galonsky et al., Phys. Rev. Lett. **2** (1959) 349.