atoms

Tracked for Impact Factor

CITESCORE 3.1

Communication

Measurement of the Tensor-Analyzing Power Component T_{20} for Incoherent Negative Pion Photoproduction on a Deuteron

Anna Kuzmenko, Vyacheslav Gauzshtein, Eed Darwish, Alexander Fix, Matvey Kuzin, Michael Levchuk, Alexey Loginov, Dmitriy Nikolenko, Igor Rachek, Yuriy Shestakov et al.

MDPI

https://doi.org/10.3390/atoms11060099

atoms

MDPI

Communication

Measurement of the Tensor-Analyzing Power Component T_{20} for Incoherent Negative Pion Photoproduction on a Deuteron

Anna Kuzmenko [1], Vyacheslav Gauzshtein [1,*], Eed Darwish [2,3], Alexander Fix [1], Matvey Kuzin [1], Michael Levchuk [4,5], Alexey Loginov [6], Dmitriy Nikolenko [7], Igor Rachek [7], Yuriy Shestakov [7,8], Dmitriy Toporkov [7,8], Arseniy Yurchenko [7], Bogdan Vasilishin [1] and Sergey Zevakov [7]

1 Research School of Physics, National Research Tomsk Polytechnical University, 634050 Tomsk, Russia; myk6@tpu.ru (M.K.)
2 Physics Department, Faculty of Science, Taibah University, Medina 41411, Saudi Arabia
3 Physics Department, Faculty of Science, Sohag University, Sohag 82524, Egypt
4 Stepanov Institute of Physics, National Academy of Sciences of Belarus, 220072 Minsk, Belarus
5 Institute of Applied Physics, National Academy of Sciences of Belarus, 220072 Minsk, Belarus
6 Department of Mathematical Physics, Tomsk State University of Control Systems and Radioelectronics, 634050 Tomsk, Russia
7 Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia
8 Physics Department, Novosibirsk State University, 630090 Novosibirsk, Russia
* Correspondence: gauzshtein@tpu.ru

Abstract: New results for the T_{20}-component of the tensor-analyzing power of the incoherent negative pion photoproduction are presented. The experiment was performed for the electron beam energy of 800 MeV at the VEPP-3 storage ring in 2021. To extract the T_{20}-component, we used asymmetry with respect to the change in the sign of the tensor polarization of the deuteron target. Identification of the reaction events was carried out by the detection of two protons in coincidence. Experimental data were compared with the results of statistical simulation, considering the interaction between the NN and πN subsystems in the final state of the reaction.

Keywords: pion photoproduction; tensor polarization; nucleon; tensor-analyzing power

Citation: Kuzmenko, A.; Gauzshtein, V.; Darwish, E.; Fix, A.; Kuzin, M.; Levchuk, M.; Loginov, A.; Nikolenko, D.; Rachek, I.; Shestakov, Y.; et al. Measurement of the Tensor-Analyzing Power Component T_{20} for Incoherent Negative Pion Photoproduction on a Deuteron. *Atoms* **2023**, *11*, 99. https://doi.org/10.3390/atoms11060099

Academic Editor: Chengjian Lin

Received: 2 May 2023
Revised: 9 June 2023
Accepted: 14 June 2023
Published: 15 June 2023

1. Introduction

As a simplest nuclear system consisting of two bound nucleons, deuteron represents an ideal subject for the study of nucleon–nucleon interactions from both theoretical and experimental perspectives. A theoretical description of the deuteron photodisintegration and the π-meson photoproduction on a deuteron was provided in a number of works [1–5]. It was shown that the non-central tensor components of nucleon–nucleon interaction potentially significantly influence the static properties of a deuteron. Furthermore, these components have a notable effect on the differential cross-sections and polarization observables of electro- and photoreactions on a deuteron. Therefore, a study of the tensor polarization observables for π-meson photoproduction on a deuteron provides important information on the deuteron structure, the dynamics of NN and πNN systems at short distances, and the influence of a nuclear environment on the properties of nucleons and nucleon resonances. Most results were obtained using the VEPP-3 electron storage ring at the Budker Institute of Nuclear Physics [6–12].

The first measurement of the tensor-analyzing power components for the reaction of π^--meson photoproduction on a deuteron was obtained in 1992 [9]. These results had very poor statistics (about 1000 events). The next measurement results for the components of tensor analyzing power were obtained from the experiment finished in 2003 [10]. Despite the higher experimental statistics, the results could not be applied to discredit various theoretical models.

In this work, the new preliminary experimental results for the T_{20}-component of the tensor-analyzing power of the reaction $\gamma d \to pp\pi^-$ are presented. The data are compared with the results of a statistical simulation taking the NN and πN rescattering into account in the final state of the reaction.

2. Experiment

The scheme of the experiment is shown in Figure 1. The electron beam energy was 800 MeV. Inside the VEPP-3 accelerator ring, there is a built-in target storage cell, which was supplied by deuterium from a source of polarized atoms (ABS). Detailed information about ABS is given in the work [13].

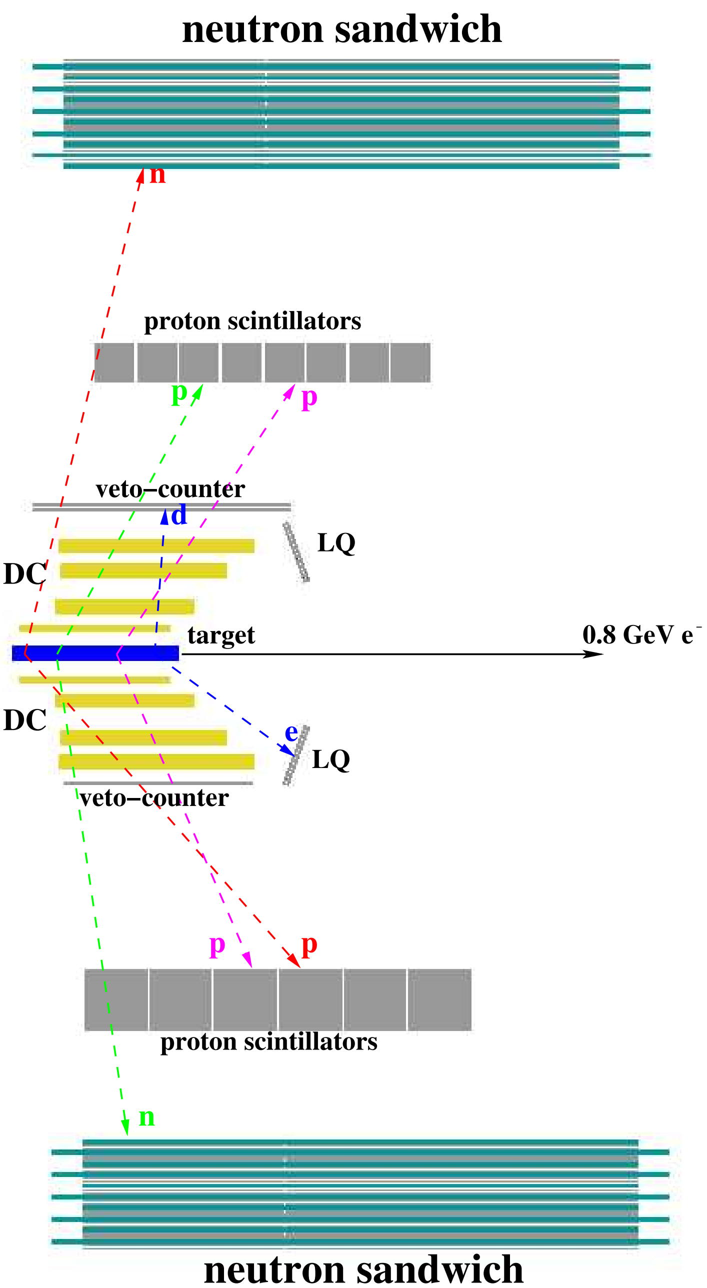

Figure 1. The scheme of the experiment.

Setting up polarization experiments at VEPP-3 involves measuring the asymmetry with respect to the change in the sign of the tensor polarization of the deuteron target. In this case, the contribution of any component of the tensor-analyzing power can be distinguished or canceled when a magnetic field of a certain orientation is applied to the target. A detailed description of the extraction the components of the tensor-analyzing power is given in the works [10–12].

In the absence of vector polarization of the deuteron target, the differential cross-section of the incoherent π^- photoproduction on a tensor polarized deuteron is written as

$$\begin{aligned} d\sigma &= d\sigma_0 \Big\{ 1 + \frac{1}{\sqrt{2}} P_{zz} \big[d^2_{00}(\theta_H)\, T_{20} - \\ &\qquad d^2_{10}(\theta_H)\, \cos\phi_H T_{21} + d^2_{20}(\theta_H)\, \cos 2\phi_H T_{22} \big] \Big\}\,, \end{aligned} \tag{1}$$

where $d\sigma_0$ is the corresponding unpolarized cross-section, and $d^M_{IM}(\theta_H)$ are the Wigner d-functions:

$$\begin{aligned} d^2_{00}(\theta_H) &= \frac{3}{2}\cos^2\theta_H - \frac{1}{2}\,, \\ d^2_{10}(\theta_H) &= -\sqrt{\frac{3}{8}}\sin 2\theta_H\,, \\ d^2_{20}(\theta_H) &= \sqrt{\frac{3}{8}}\sin^2\theta_H\,. \end{aligned} \tag{2}$$

In Equation (1), the factors T_{20}, T_{21}, and T_{22} are the components of the tensor analyzing power of the reaction $\gamma d \to pp\pi^-$, P_{zz} is the degree of tensor polarization of the deuteron target, and the angles θ_H and ϕ_H determine the orientation of the magnetic field of the deuteron target in the coordinate system with the z-axis directed along the initial photon momentum.

The tensor polarization P_{zz} can be expressed in terms of the populations n^S of the deuteron states with the spin projections $S = -1, 0, +1$ on the direction of the magnetic field:

$$P_{zz} = 1 - 3n^0 = 3(n^+ + n^-) - 2\,. \tag{3}$$

In the present experiment, the magnetic field was directed along the photon beam so that $\theta_H = 0$. This implies that, in Equation (1), only the T_{20} component contributed to the differential cross-section. Note that Equation (1) is only valid for coplanar kinematics when the momenta of all three final particles (the two nucleons and the pion) span the same plane.

During the collection of experimental statistics, the sign of the tensor polarization was switched every 30 s. This frequent switching makes it possible to suppress systematic errors. From Equation (1), it follows that the T_{20}-component of the tensor analyzing power can be calculated according to the expression

$$T_{20} = \sqrt{2}\frac{N^+ - N^-}{P^+_{zz}N^- - P^-_{zz}N^+}\,, \tag{4}$$

where $N^+(N^-)$ is the number of registered events for the tensor polarization of the deuteron target equal to $P^+_{zz}(P^-_{zz})$.

The experimental setup trigger was configured to register pn, pp and ed coincidences. The events corresponding to the registration of two protons (pp-coincidences) were used to extract information about the reaction $\gamma d \to pp\pi^-$. The registration of the channel of the elastic scattering of electrons on a deuteron (ed-coincidences) at small transferred momenta allows for the degree of tensor polarization of the deuteron target during the collection of statistics to be measured. For a more detailed description of the principle of operation of the LQ polarimeter, see the work [14].

Despite the almost limiting degree of tensor polarization of deuterons ($P^+_{zz} \approx +1$ and $P^-_{zz} \approx -2$) at the ABS outlet, the degree of tensor polarization is significantly reduced inside the storage cell. This is caused by the interaction between deuterium atoms with the cell walls, with each other, and with the pulsed magnetic field of the storage ring electron beam. According to the LQ polarimeter data, the average degree of tensor polarization of the deuterium target over the entire duration of the experiment was

$$P_{zz}^{+} = 0.39 \pm 0.025 \pm 0.009, \; P_{zz}^{-}/P_{zz}^{+} = -1.7, \tag{5}$$

where the first error P_{zz}^{+} is statistical and the second is systematic.

The results of T_{20} measurements presented in this work correspond to the experimental statistics collected without registration of the scattered electron. With such this experimental setup, most registered events correspond to the polar electron-scattering angle close to 0°. Thus, the contribution to the measured asymmetry from the longitudinal polarization of quasi-real photons will be negligible.

The kinematics of the investigated reaction $\gamma d \to pp\pi^-$ was reconstructed from the measured proton 4-momenta under the assumption that the electron polar scattering angle $\theta_e = 0°$. The polar and azimuth angles of proton emission were measured using drift chambers with an accuracy no worse than 0.6°. The kinetic energy of protons was determined from the amplitude of the light output from the scintillator in which the proton was stopped. The registration interval for such protons is (60–160) MeV. The identification of protons detected by the upper arm was carried out by the $\Delta E/E$ method (Figure 2, left). In the lower arm, protons were identified by their time of flight and amplitude (Figure 2, right). In this case, the time of flight from the thin veto counter to one of the proton scintillators was used. Such traditional hadron detection methods are used in experiments at VEPP-3 [6–12].

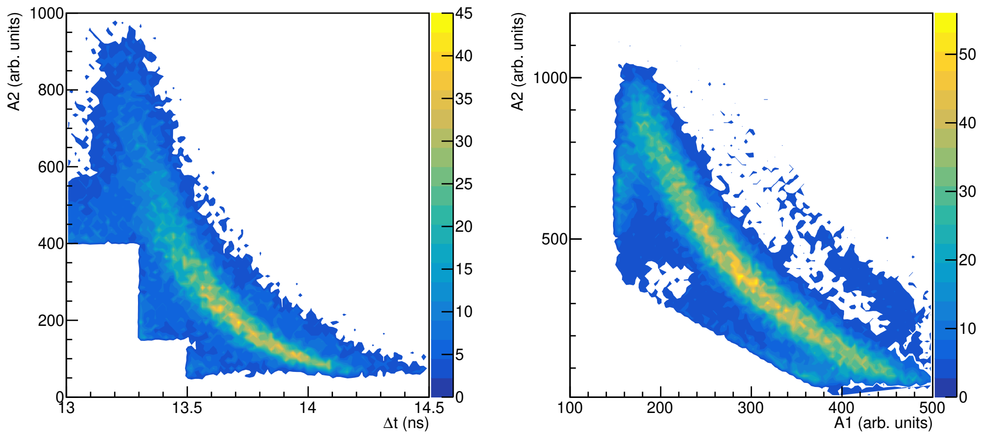

Figure 2. Identification of protons. On the left is a two-dimensional histogram of the distribution of events over the light output amplitude and time of flight for the lower proton scintillator. On the right is a two-dimensional histogram of the distribution of events over the amplitude of the proton scintillator and the thin veto counter for the upper detector.

To estimate the proportion of the inseparable background in the selected statistics of pp-coincidences, statistical simulation was performed using the GEANT4 package and the photoreaction generator GENBOS [15].

The main background processes contributing to pp coincidence are $\gamma d \to pp\pi^-\pi^0$, $\gamma d \to pn\pi^0$, and $\gamma d \to pn$. The contribution to the inseparable background from the processes $\gamma d \to pn\pi^0$ and $\gamma d \to pn$ is explained by the fact that neutrons in a head-on collision can knock out protons, which, in turn, are registered by proton detectors. As a result of the simulation, it was found that the inseparable background is about 7.3%.

3. Results

The results of the experiment are shown in Figure 3. For each point, the measurement error and the averaging interval are shown. The indicated measurement error T_{20} includes the squared sum of the systematic and statistical errors. The largest contribution to the systematic error is the uncertainty in the degree of target polarization. However, due to the relatively small selected statistics for the reaction under study (about 6000 events), the overwhelming contribution to the measurement error is made by the statistical error.

Figure 3 also shows the results for T_{20} obtained by the statistical simulation of the reaction $\gamma d \to pp\pi^-$. The red squares correspond to the full-amplitude simulation with the πN and NN rescattering taken into account. The green triangles correspond to the simulation performed within the framework of the plane-wave impulse approximation, i.e., without taking into account the contributions of the πN and NN rescattering.

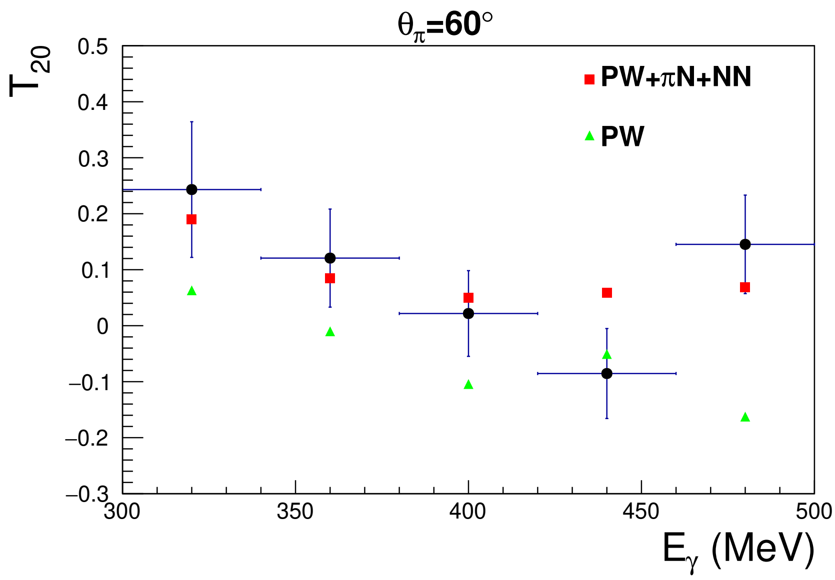

Figure 3. Dependence of T_{20} on the photon energy E_γ for the pion emission angle $\theta_\pi = 60°$. The black circles are the experimental results, the green triangles are the result of simulation in the plane wave approximation, and the red squares are the result of the simulation, taking into account πN and NN rescattering

In a statistical simulation of the reaction, we used the amplitude [16] obtained within the framework of a diagrammatic approach. This amplitude includes impulse approximation contribution as well as the contribution of the final state interaction. This interaction is described in terms of pion–nucleon scattering and nucleon–nucleon scattering. Thus, the amplitude of the reaction was described using the amplitudes of three elementary processes: π^--meson photoproduction on a nucleon, pion–nucleon scattering, and nucleon–nucleon scattering. As an elementary amplitude of the π^--meson photoproduction on a nucleon, we used the amplitude from [17]. This amplitude includes contributions of intermediate states in three different channels of the reaction: the contributions of the Born diagrams in the s-, u-, and t-channels, the contributions of $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$, $F_{15}(1680)$, and $D_{33}(1700)$ nucleon resonances in the s- and u-channels, and the contributions of the ρ and ω vector mesons in the t-channel. As an elementary amplitude for pion–nucleon scattering, we used the amplitude described in [18]. This includes the contributions of the Born diagrams in the s-, u-, and t-channels, the contribution of the vector mesons in the t-channel, and the contribution of the $P_{33}(1232)$ nucleon resonance in the s- and u-channels. As opposed to the π^--meson photoproduction on a nucleon and the pion–nucleon scattering, to consider the nucleon–nucleon scattering, we used a phenomenological description of the amplitude using known experimental phase shifts in the lowest partial waves ${}^1S_0$, ${}^3P_0$, ${}^3P_1$, ${}^3P_2$, ${}^3F_2$, ${}^1D_2$, ${}^3F_3$, and ${}^1G_4$. In the calculations of the amplitude of the $\gamma d \to pp\pi^-$ reaction, we used the deuteron wave function of Bonn potential.

It follows from the above results that the allowance for the πN and NN rescattering in the final state of the reaction $\gamma d \to pp\pi^-$ significantly improves the agreement between the experiment and theory.

4. Discussion

Considering the sensitivity of the presented results to the details of the reaction mechanism in our kinematic region, we can conclude that the agreement between experimental data and statistical simulation is quite satisfactory. To improve the agreement, other possible reaction mechanisms must be considered. The latter may include, for example, the interaction between nucleon resonance and spectator nucleon in the intermediate state, as well as the $\Delta\Delta$ component of the deuteron wave function [19] and additional contributions to the NN interaction, which may be important at small internucleon distances [20–23].

Author Contributions: Investigation: V.G., A.F., E.D., A.L., I.R. and A.K.; Writing: V.G., A.K., E.D. and A.L.; Critical revision: A.K. and A.L.; Final approval: all authors. All authors have read and agreed to the published version of the manuscript.

Funding: The analysis of experimental data was supported by the Russian Science Foundation, Grant No. 22-22-00016.

Data Availability Statement: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Levchuk, M.I.; Loginov, A.Y.; Sidorov, A.A.; Stibunov, V.N. Incoherent pion photoproduction on the deuteron in the first resonance region. *Phys. Rev. C* **2006**, *74*, 014004. [CrossRef]
2. Laget, J.M. Pion photoproduction on few body systems. *Phys. Rep.* **1981**, *69*, 1–84 . [CrossRef]
3. Fix, A.I.; Arenhövel, H. Incoherent pion photoproduction on the deuteron with polarization observables. II. Influence of final state rescattering. *Phys. Rev. C* **2005**, *72*, 064004. [CrossRef]
4. Briscoe, W.J.; Kudryavtsev, A.E.; Strakovsky, I.I.; Tarasov, V.E.; Workman, R.L. On the photoproduction reactions $\gamma d \to \pi NN$. *Eur. Phys. J. A* **2022**, *58*, 23. [CrossRef]
5. Strandberg, B.; Fissum, K.G.; Annand, J.R.M.; Briscoe, W.J.; Brudvik, J.; Cividini, F.; Clark, L.; Downie, E.J.; England, K.; Feldman, G.; et al. Near-threshold π^- photoproduction on the deuteron. *Phys. Rev. C* **2020**, *101*, 035207. [CrossRef]
6. Nikolenko, D.M.; Barkov, L.M.; Dmitriev, V.F.; Dyug, M.V.; Isaeva; Lazarenko, B.A.; Mishnev, S.I.; Rachek, I.A.; Shestakov, Y.V.; Toporkov, D.K.; et al. Measurement of polarization observables in elastic and inelastic electron-deuteron scattering at the VEPP-3 storage ring. *Nucl. Phys. A* **2001**, *684*, 77–85. [CrossRef]
7. Nikolenko, D.M.; Arenhövel, H.; Barkov, L.M.; Belostotsky, S.L.; Dmitriev, V.F.; Dyug, M.V.; Gilman, R.; Holt, R.J.; Isaeva, L.G.; De Jager, C.W.; et al. Measurement of the tensor analyzing powers T_{20} and T_{21} in elastic electron deuteron scattering. *Phys. Rev. Lett.* **2003**, *90*, 072501. [CrossRef]
8. Rachek, I.A.; Barkov, L.M.; Belostotsky, S.L.; Dmitriev, V.F.; Dyug, M.V.; Gilman, R.; Holt, R.J.; Lazarenko, B.A.; Mishnev, S.I.; Nelyubin, V.V.; et al. Measurement of Tensor Analyzing Powers in Deuteron Photodisintegration. *Phys. Rev. Lett.* **2007**, *98*, 182303. [CrossRef]
9. Loginov, A.Y.; Osipov, A.V.; Sidorov, A.A.; Stibunov, V.N.; Voitsekhovskii, B.B.; Nikolenko, D.M.; Popov, S.G.; Rachek, I.A.; Toporkov, D.K.; Tsentalovich, E.P. Investigation of the reaction $D(e,pp)e'\pi^-$ on a tensor polarized deuterium target at high proton momenta. *JETP Lett.* **1998**, *67*, 770–776. [CrossRef]
10. Gauzshtein, V.V.; Gramolin, A.V.; Lazarenko, B.A.; Loginov, A.Y.; Mishnev, S.I.; Nikolenko, D.M.; Rachek, I.A.; Sadykov, R.S.; Shestakov, Y.V.; Toporkov, D.K.; et al. Measurement of tensor analyzing powers of the incoherent pion photoproduction on a deuteron. *Nucl. Phys. A* **2017**, *968*, 23–30. [CrossRef]
11. Lukonin, S.E.; Gauzshtein, V.V.; Levchuk, M.I.; Loginov, A.Y.; Nikolenko, D.M.; Rachek, I.A.; Sadykov, R.S.; Shestakov, Y.V.; Toporkov, D.K.; Zevakov, S.A. Measurement of tensor analyzing power components for the incoherent π^0-meson photoproduction on a deuteron. *Nucl. Phys. A* **2019**, *986*, 75–84. [CrossRef]
12. Vasilishin, B.I.; Fix, A.I.; Gauzshtein, V.V.; Darwish, E.M.; Kuzin, M.Y.; Levchuk, M.I.; Loginov, A.Y.; Nikolenko, D.M.; Rachek, I.A.; Shestakov, Y.V.; et al. Measurement of the tensor analyzing power component T_{20} for the incoherent neutral-pion photoproduction on a deuteron. *Phys. Rev. C* **2022**, *106*, 024003. [CrossRef]
13. Dyug, M.V.; Isaeva, L.G.; Lazarenko, B.A.; Mishnev, S.I.; Nikolenko, D.M.; Rachek, I.A.; Shestakov, Y.V.; Sadykov, R.S.; Toporkov, D.K.; Zevakov, S.A.; et al. Internal polarized deuterium target with cryogenic atomic beam source. *Nucl. Instrum. Methods A* **2002**, *495*, 8–19. [CrossRef]
14. Dyug, M.V.; Lazarenko, B.A.; Mishnev, S.I.; Nikolenko, D.M.; Rachek, I.A.; Shestakov, Y.V.; Sadykov, R.S.; Toporkov, D.K.; Zevakov, S.A.; Osipov, A.N.; et al. Deuterium Target Polarimeter at the VEPP-3 Storage Ring. *Nucl. Instrum. Methods A* **2005**, *536*, 344–349. [CrossRef]

15. Iljinov, A.S.; Pshenichnov, I.A.; Bianchi, N.; De Sanctis, E.; Muccifora, V.; Mirazita, M.; Rossi, P. Extension of the intranuclear cascade model for photonuclear reactions at energies up to 10 Gev. *Nucl. Phys. A* **1997**, *616*, 575–592. [CrossRef]
16. Loginov, A.Y.; Sidorov, A.A.; Stibunov, V.N. Effect of rescattering on polarization observables of the reaction $\gamma d \rightarrow pp\pi^-$ in the delta-resonance region. *Phys. At. Nucl.* **2000**, *63*, 391–398. [CrossRef]
17. Garcilazo, H.; Moya de Guerra, E. A model for pion electro- and photo-production from threshold up to 1 GeV. *Nucl. Phys. A* **1993**, *562*, 521–568. [CrossRef]
18. Olsson, M.G.; Osipowski, E.T. Systematics of low-energy πN scattering. *Nucl. Phys. B* **1975**, *101*, 136–158. [CrossRef]
19. Haidenbauer, J.; Plessas, W. Separable representation of the Paris nucleon-nucleon potential. *Phys. Rev. C* **1984**, *30*, 1822–1839. [CrossRef]
20. Smirnov, Y.F.; Tchuvil'sky, Y.M. Isobaric component of deuteron in the quark model. *J. Phys. G* **1978**, *4*, L1 . [CrossRef]
21. Kukulin, V.I.; Obukhovsky, I.T.; Pomerantsev, V.N.; Faessler, A. New mechanism for intermediate- and short-range nucleon-nucleon interaction. *J. Phys. G* **2001**, *27*, 1851–1864. [CrossRef]
22. Kukulin, V.I.; Obukhovsky, I.T.; Grabmayr, P.; Faessler, A. Isoscalar short-range current in the deuteron induced by an intermediate dibaryon. *Phys. Rev. C* **2006**, *74*, 064005. [CrossRef]
23. Kukulin, V.I.; Rubtsova, O.A.; Platonova, M.N.; Pomerantsev, V.N.; Clement, H.; Skorodko, T. Nature of S-wave NN interaction and dibaryon production at nucleonic resonance thresholds. *Eur. Phys. J. A* **2020**, *56*, 229. [CrossRef]