Experiments with Internal Targets

at the VEPP-3 Electron Storage Ring


Abstract—An overview of the recently completed, current, and planned experiments with internal targets at the VEPP-3 electron–positron storage ring in Novosibirsk is given. The results of the experiment to separately measure the deuteron form factors in elastic ed scattering in the range of momentum transfer $Q^2 = 8–15$ fm$^{-2}$ are provided. The results of measuring the tensor analyzing power components of the tensor-polarized deuteron photodisintegration reaction in the range of $\gamma$-quantum energies $E_\gamma = 25–600$ MeV are presented. The tensor analyzing powers of the coherent photoproduction of a neutral pion on a tensor-polarized deuteron have been measured for the first time. The almost-real photon tagging system being created is discussed. The status of the experiment under way to determine the contribution of two-photon exchange to the elastic ep scattering cross section is described.

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1. INTRODUCTION

The method of an internal target in a charged-particle storage ring, one of the modern methods in nuclear physics, is used in many laboratories worldwide. Interest in this method stems largely from the fact that it has a number of attractive advantages [1]. For example, it is characterized by a high efficiency of using stored particles, which opens the possibilities for obtaining a high specific luminosity. This, in turn, is particularly important for using unique beams (e.g., of positrons). Another important consequence of a high efficiency is that a relatively low background level can be achieved in experiments. Since the actual target thickness is very small, the kinematic parameters of the secondary particles, including those of slow nuclear fragments and recoil nuclei, are not distorted in passing through the target and, hence, can be measured with a high accuracy. Another advantage related to the smallness of the target thickness is the possibility of carrying out experiments with unique targets, such as, for example, polarized gas targets. Finally, a continuous mode of operation allows coincidence experiments to be conducted.

The method of an internal target in a charged-particle storage ring was proposed and first used in nuclear-physics experiments in the late 1960s at the Institute of Nuclear Physics (INP), Siberian Branch of the Russian Academy of Sciences, Novosibirsk [1]. Almost all advantages of the internal-target technique have been realized at INP over the succeeding period. For example, a number of experiments were conducted at the VEPP-2 electron storage ring to study the properties of light nuclei with coincidence detection of the scattered electron and nuclear decay products, including the slow particles. Experiments with a tensor-polarized deuterium gas target have also been conducted here for the first time.

In this paper, we give an overview of the recently completed, current, and planned experiments with...
internal targets at the VEPP-3 electron–positron storage ring. In the second section, we give general remarks on the tensor-polarized deuteron experiments and describe them. The three completed experiments to measure the tensor observables in electron–deuteron scattering are described in the next three sections. In the sixth section, we give a description of the almost–real photon tagging system being created, which will extend the possibilities for carrying out experiments with internal targets at VEPP-3. The current experiment to measure the contribution of two–photon exchange to the elastic electron–proton scattering is described in the seventh section. This contribution will be determined by comparing the cross sections for elastic scattering of electrons and positrons by a proton. This experiment is important because it will possibly explain the recently revealed dramatic contradiction between new polarized measurements and old data on the proton form factors.

2. TENSOR-POLARIZED DEUTERON EXPERIMENTS

The simplest nuclear system, a deuteron, is an ideal ground for testing the validity of views on the properties of strong interactions. Therefore, a host of both experimental and theoretical works are devoted to its investigation. The works devoted to the interaction of a deuteron with electrons and photons occupy a special place because the interpretation of these reactions is relatively simple [2, 3].

Measuring the polarized observables allows the process under study to be analyzed much more thoroughly than measuring the differential cross section alone. This is because, in contrast to the differential cross section, which is the sum of the squares of the reaction amplitudes, the polarized observables contain interference terms in various combinations. Therefore, they can be more sensitive to low amplitudes and interesting effects with a small contribution to the differential cross section, such as the subnucleon degrees of freedom and relativistic corrections.

Although it became clear even at early stages of deuteron studies that the noncentral (tensor) components of the nucleon–nucleon interaction forces largely determine the pattern of reactions, especially in short-range interactions, their investigation in electro– and photoreactions on a deuteron has begun only recently. One of the reasons is the absence of dense tensor-polarized targets with a sufficiently high polarization in extracted beam experiments. The method of an internal target in a storage ring allows such studies to be successfully carried out or, more specifically, makes it possible to work with a pure, without impurities, deuterium target with a high (vector or tensor) polarization that does not require strong magnetic fields with the possibility of obtaining any spin states with fast switching of the polarization direction and sign.

New versions of a polarized target and particle detectors had been created at INP by the late 1990s. This allowed the tensor observables in elastic scattering and photoprocesses on a deuteron to be measured.

The experiments with a polarized gas target were carried out at the VEPP–3 storage ring at an electron energy of 2 GeV and a beam current of ≈100 mA. The beam lifetime in the presence of an internal target was about 3 h.

The internal gas target of the storage ring [4] consists of polarized deuterium atoms injected in the form of a jet with an intensity of $8 \times 10^{16}$ at $s^{-1}$ into a thin-walled T-shaped storage cell with open edges. Bouncing from the cell walls, the atoms can multiply cross the electron beam circulating through it, thereby increasing the target thickness. The jet of atoms was produced by a polarized atomic beam source (ABS). The classical scheme for the separation of atoms with various magnetic moments in a nonuniform magnetic field, as in the well-known Stern–Gerlach experiment, forms the basis for the source. A nonuniform magnetic field is generated by five superconducting sextupole magnets S1–S5 (Fig. 1). The high-frequency (HF) medium (MFT) and strong (SFT) field transition blocks that allow the populations of magnetic sublevels to be changed are placed after the third and fifth magnets.

The vector ($P_z$) and tensor ($P_{zz}$) polarizations of the target are expressed in terms of $n^+$, $n^0$, $n^-$ (the populations of deuteron states with spin projections of $+1, 0, -1$) as

$$P_z = n^+ - n^-, \quad P_{zz} = 1 - 3n^0.$$

In our experiments, the vector polarization of the jet atoms at the exit from the source was maintained close to zero ($|P_z| < 0.02$), while the tensor polarization of the jet atoms was close to the limiting one ($P_{zz} \approx +1$ or $\approx -2$). The ABS scheme and the populations of hyperfine sublevels for deuterium atoms as they move along the source axis are presented in Fig. 1. During the experiment, a small fraction of the jet atoms was directed into the Breit–Rabi polarimeter to continuously monitor the operating efficiency of the HF transition blocks and the stability of the ABS parameters. To specify the polarization direction, a uniform magnetic field with a strength up to 90 mT was applied to the target.

The atoms in the storage cell undergo a certain number of collisions with its wall, causing their polarization to decrease. In addition, the HF field of
the circulating electron bunch and the spin-exchange collisions between atoms can lead to depolarization of the target atoms. To determine the mean polarization of the target atoms, we used a polarimeter based on measuring the elastic ed scattering asymmetry in the range of low momentum transfer (LQ polarimeter), for which the tensor analyzing power of the reaction is known [5].

The polarized observables are usually extracted from experimental asymmetries of various types. When experiments with ABS are carried out, measuring the asymmetry related to the switching of the sign of polarization $P_{zz}$ is most efficient from the viewpoint of minimizing the systematic errors. Such switching has absolutely no effect on the operation of the accelerator and detectors. It can be done frequently, thereby suppressing the errors caused by the drift of the detector and target parameters.

The tensor asymmetry is defined by the expression

$$a^T = \sqrt{2} \frac{N^+ - N^-}{P_{zz}N^+ - P_{zz}N^-},$$

where $N^+$ ($N^-$) is the number of recorded events at target polarization $P^+_{zz}$ ($P^-_{zz}$). If we take into account the difference in luminosity integrals in $N^+$ ($N^-$) and apply corrections for the presence of a background, then Eq. (1) can be rewritten via $\sigma^+$ and $\sigma^-$, the cross sections for the reaction with a target that has opposite signs of the tensor polarization:

$$a^T = \sqrt{2} \frac{\sigma^+ - \sigma^-}{P_{zz}\sigma^+ - P_{zz}\sigma^+}.$$  

(2)

Apart from the unpolarized part, the differential cross section for the process in the case of a tensor-polarized deuterium target is defined by three tensor analyzing power (TAP) components of the reaction, $T_{20}$, $T_{21}$, and $T_{22}$ (see the formulas below). A determination of each of the components $T_{2M}$ generally requires three measurements of the asymmetry $a^T$ with different angles between the direction of the magnetic field orienting the target polarization axis and the momentum transferred to the deuteron. In this case, three independent equations to find $T_{2M}$ will be obtained.
In Sections 3–5, we discuss our experiments on elastic and inelastic electron–deuteron scattering. In the case of inelastic scattering, the products of various reactions were detected, while the electrons producing these reactions were not detected. Formally, these reactions should be attributed to electroprocesses on a deuteron. However, in our experiments, the electron scattering angle is close to zero in most of the events, with the virtual photon being almost on the mass shell. Therefore, these processes can be interpreted as photoreactions (this issue is also discussed below).

3. ELASTIC \textit{ed} SCATTERING

As has already been mentioned, theoretical and experimental deuteron studies play an important role in determining the properties of nucleon–nucleon interactions and investigating the subnucleon degrees of freedom. The interrelationship between these properties and experimental observables is particularly transparent in elastic electron–deuteron scattering, where the theoretical description in terms of form factors has been well developed, because the electromagnetic interaction is relatively weak.

Under the assumption of \( P \) and \( T \) invariance, the electromagnetic structure of the deuteron is completely described by three form factors: the charge monopole, \( G_C(Q^2) \), charge quadrupole, \( G_Q(Q^2) \), and magnetic dipole, \( G_M(Q^2) \), ones, which depend only on the momentum transfer squared. The two deuteron structure functions,

\[
A = G_C^2 + \frac{8}{9} \tau G_Q^2 + \frac{2}{3} \tau G_M^2, \quad B = \frac{4}{3} \tau (1 + \tau) G_M^2,
\]

where \( \tau = Q^2/4M_d^2 \) and \( M_d \) is the deuteron mass, can be found from a series of measurements of the differential cross sections \( d\sigma_0/d\Omega \) for elastic unpolarized \( \text{ed} \) scattering under various kinematic conditions [2, 3]. The form factors \( G_C \) and \( G_Q \) can be determined separately only through additional measurements of the polarized observables. The cross section for electron scattering by a tensor-polarized deuteron can be written as [6]

\[
\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \left[ 1 + \frac{P_{zz}}{\sqrt{2}} \left( \frac{3 \cos^2 \theta_H - 1}{2} - \frac{1}{2} T_{20} \right) - \sqrt{\frac{3}{2}} \sin(2\theta_H) \cos(\phi_H) T_{21} + \sqrt{\frac{3}{2}} \sin^2(\theta_H) \cos(2\phi_H) T_{22} \right].
\]  

(3)

Here, the angles \( \theta_H \) and \( \phi_H \) specify the orientation of the target polarization relative to the virtual photon momentum (the \( z \) axis), with the azimuthal angle being measured from the scattering plane. Given this expression, the formula for the tensor asymmetry can be rewritten as

\[
\alpha_T = \sum_{M=0}^{2} c_M T_{2M},
\]  

(4)

where \( c_M \) depend on the orientation of the target polarization and the arrangement of the detectors.

In elastic scattering, the TAP components can be expressed in terms of the deuteron form factors:

\[
T_{20} = - \frac{\sqrt{2} \tau}{3S} \left[ 4G_C G_Q + \frac{4\tau}{3} G_Q^2 + \frac{1}{2\epsilon} G_M^2 \right],
\]

\[
T_{21} = \frac{2}{S} \sqrt{\frac{\tau^3(1 + \epsilon)}{6\epsilon}} G_Q G_M, \quad T_{22} = \frac{\tau}{2\sqrt{3S}} G_M^2,
\]

where \( S = \sqrt{\frac{1}{2} + \tan^2(\theta_e/2)B} \), \( \theta_e \) is the electron scattering angle, and \( \epsilon \) is the polarization of the virtual photon:

\[
\epsilon = \left[ 1 + 2(1 + \tau) \tan^2 \frac{\theta_e}{2} \right]^{-1}.
\]  

(5)

The polarized observables in elastic scattering were previously measured using various techniques: with recoil deuteron polarimeters (the electron beam and the target are not polarized) [7–9], with an internal polarized gas target (the electron beam is not polarized) [10–14], and a single experiment with a polarized solid target [15].

The data of the experiment under discussion [16] were collected in 1999–2000. The particle detector that detected the scattered electrons and recoil deuterons in coincidence consisted of two almost identical systems located on different sides of the median plane of the storage ring. Each of the systems had an electron detection arm and a deuteron arm. The angular acceptance was \( \theta_e \approx 16^\circ–30^\circ \) in polar angle and \( \phi_e \approx -30^\circ \) to \( +30^\circ \) in azimuthal angle for one of the systems and \( \phi_e \approx 150^\circ–210^\circ \) for the other system. The deuteron detectors covered a solid angle matched with that of the electron detectors.

The target polarization axis lay in the vertical plane in such a way that the recoil deuterons in one of the detection systems were emitted, on average, parallel to the target polarization direction. We see from Eqs. (3) and (4) that, in this case, the component \( T_{20} \) makes a major contribution to \( \alpha_T \). At the same time, in the other detection system, the mean deuteron emission angle with respect to the target polarization direction was close to \( \pi/2 \). In this case, the contribution from \( T_{21} \) dominates. Since the magnetic deuteron form factor (and, hence, \( T_{22} \)) is known from unpolarized measurements, the information obtained in the experiment is sufficient to find both \( T_{20} \) and \( T_{21} \).
The particle trajectories were reconstructed using track detectors (drift chambers). The electron energies were measured with electromagnetic calorimeters composed of CsI and NaI crystals. Three layers of plastic scintillators were placed in the deuteron arms after the drift chambers. These served to measure the recoil deuteron energy and to identify the particles, which was needed to select elastic scattering events against the background of a large number of ep coincidences in quasi-elastic scattering. To select ed scattering events, we also used kinematic correlations of elastic scattering, namely, the deuteron energy–deuteron emission angle, the deuteron emission angle–electron scattering angle, and the correlation between the electron and deuteron azimuthal angles.

The angular acceptance of the detector was divided into six intervals where the corresponding mean values of the momentum transfer squared were 8.41, 9.88, 11.78, 14.50, 17.67, and 21.56 fm$^{-2}$. In each interval, we found the asymmetry $a^T$ and then the TAP components $T_{20}$ and $T_{21}$. The data obtained, along with the available unpolarized measurements (on the deuteron structure functions $A(Q^2)$ and $B(Q^2)$), allowed the charge deuteron form factors $G_C$ and $G_Q$ to be determined.

The experimental results are presented in Fig. 2. Also shown here are the data from previous measurements, along with the results of several theoretical calculations. The results obtained are consistent with the previous measurements and surpass them in accuracy in the range $8–15$ fm$^{-2}$. The measurements were performed in an important range of momentum transfer where the charge monopole form factor becomes zero. The corresponding value of $Q^2$ at which this occurs was found by taking into account these and previous measurements to be $17.41 \pm 0.32$ fm$^{-2}$.

The experimental results were compared with theoretical calculations. A nonrelativistic impulse approximation with the Paris potential [17] was used in one of these calculations. The calculations [18, 19] are based on nonrelativistic models with relativistic corrections and with allowance made for the meson exchange currents. Finally, the calculations [20, 21] were performed in a relativistic approach. Comparison shows an advantage of the relativistic calcula-
tions in describing the entire data set. Yet, we see that
the behavior of GQ is not described well by any of the
presented calculations.

4. TENSOR-POLARIZED DEUTERON
PHOTODISINTEGRATION

The two-body deuteron photodisintegration is
among the most intensively studied, both theo-
retically and experimentally, photoprocesses on a
deuteron. Given the number of spin states for each
of the particles involved in the process and the law of
parity conservation in electromagnetic interactions,
the spin structure of the reaction \( \gamma + d \to p + n \)
requires \( n = 12 \) complex amplitudes for a com-
plete description of the process. The observables are
quadratic forms that include specific combinations
of the real and imaginary parts of the 12 complex
amplitudes. The total number of all possible observ-
ables related to various combinations of initial photon
and deuteron states and final proton and neutron
states is \( 2n^2 = 288 \), but most of these observables
are linear and quadratic combinations of others. To
obtain exhaustive information about the process, at
least \( 2n - 1 = 23 \) independent observables must be
measured as functions of the photon energy and the
proton emission angle.

Arenhövel et al. [22] consider an algorithm for the
formation of such minimal sets of observables and
propose several variants. Any such “set-23” nec-
essarily includes several observables related to the
tensor polarization of the target. Therefore, an ex-
perimental study of the tensor-polarized deuteron pho-
todisintegration is a necessary contribution to the
database on this very important (for photonuclear
physics) process.

4.1. Extracting Polarized Observables

The differential photodisintegration cross section
in the case of a tensor-polarized deuteron target and
an unpolarized photon beam is described by a formula
similar in structure to Eq. (3) for the elastic scat-
tering cross section in which the angles \( \theta_H \) and \( \phi_H \)
specify the orientation of the magnetic field vector in a
coordinate system with the z axis directed along the
photon momentum. The TAP components \( T_{20} \), \( T_{21} \),
and \( T_{22} \) of the reaction are functions of two kinematic
parameters. \( E_\gamma \) and \( \theta_p^{zz} \), the \( \gamma \)-quantum energy in
the laboratory frame and the proton emission angle in
the proton-neutron center-of-mass frame, are com-
monly chosen.

The polarized observables are extracted from mea-
surements of the asymmetry \( a^T \) (Eqs. (1), (2), (4)). In
the experiment at VEPP-3 [23], the asymmetry was
measured for three magnetic field orientations: \( \theta_{H0} =
180^\circ \), \( \theta_{H1} = 54.7^\circ \), and \( \theta_{H2} = 125.3^\circ \), while \( \phi_H =
180^\circ \) in all three cases; \( a_{0T}^T \sim c_0 T_{20} \), \( a_{1T}^T \sim (+c_1 T_{21} +
c_2 T_{22}) \), and \( a_{2T}^T \sim (-c_1 T_{21} + c_2 T_{22}) \), respectively, and
all three components \( T_{2M} \) are extracted unambigu-
ously.

4.2. Detector

The detection system consisted of two pairs of pro-
ton and neutron arms. Each proton arm is a system
of drift chambers and a scintillation hodoscope made of
three \( 2 + 12 + 12 \)-cm-thick scintillators. Each neu-
tron arm is a layer of 20- or 24-cm-thick scintilla-
tors with a 2-cm-thick charged-particle veto coun-
ter located in front of it. Using the two pairs of arms al-
lowed the events to be simultaneously recorded in two
ranges of proton emission angles (\( \theta_p^{zz} = 25^\circ - 45^\circ \)
and \( 75^\circ - 105^\circ \)).

The experimental data were collected from Octo-
ber 2002 to January 2003. The mean polarization de-
termined with the LQ polarimeter was \( P_{zz}^+ = 0.341 \pm
0.025 \pm 0.012 \). Here, the first error is related to the
uncertainty in determining the experimental asym-
metry in the polarimeter and the second error is re-
lated to the uncertainty in TAP of the elastic \( ed \)
scattering reaction, on which the polarimeter operation
is based [5]. The ratio \( r = P_{zz}^-/P_{zz}^+ \) of the polariza-
tions for two polarization states was found using the
data with both polarized and unpolarized deuterium
targets to be \( r = -1.70 \pm 0.15 \). The mean thickness
of the polarized target was \( 3 \times 10^{13} \) at cm\(^{-2} \). The
total integral of the beam current distributed approxi-
ately equally between three orientations of the guid-
ing magnetic field was 200 kC.

4.3. Experimental Data Processing

From the input data, we selected 37.5 million can-
cidate events for the process \( \gamma d \to pn \). The pho-
todisintegration events were selected by identifying
the particles (the proton in the proton arm and
the neutron in the neutron arm) and verifying the
kinematic correlations inherent in this process. We
selected a total of 540,000 events. The inseparable
background from the process \( \gamma d \to pn\pi^0 \) remained
in these events. The contribution of the background
from this reaction was estimated from the shape of
the distribution of events in the difference of the
proton and neutron emission angles. The background
fraction ranged from 2% to 7%, depending on the
photon energy.

The main source of the systematic error is the un-
certainty in the target polarization \( P_{zz} \) measured with
the LQ polarimeter: \( \delta T_{2M}/T_{2M} P_{zz} = 8.5 \times 10^{-2} \).
Other contributions to the systematic error are related
Fig. 3. TAP components of the deuteron photodisintegration reaction versus photon energy—the experimental data [23]. The statistical error and the range of integration over the photon energy are shown for each data point. The dark bands indicate the systematic errors. The curves represent the theoretical predictions: [25] (dotted), [26] (long dashes, dash-dotted, solid), and [27] (short dashes).

to the uncertainty in the orientation of the polarization axis, i.e., in the angles $\theta_H$ and $\phi_H$, which define the angular coefficients of $T_{2M}$, and to inaccurate reconstruction of the photon energy $E_\gamma$ and the proton emission angle $\theta_{p,c.m.}$. We also considered the following contributions to the systematic error: the false asymmetry that could result from the experimental conditions not being identical for various polarization regimes; the error related to the contributions of the longitudinal lepton current components to the cross section in the experimental technique used—the selection of events near the “photon point” from the more general process of electrodisintegration. We established that these errors were negligible in the experimental conditions at VEPP-3.

4.4. Experimental Results

The data obtained cover fairly large continuous ranges of photon energies and proton emission an-
Fig. 4. TAP components of the deuteron disintegration reaction versus proton emission angle in the center-of-mass frame—the experimental data [23]. The range of integration over the angle $\theta_p^{\text{c.m.}}$ is $4^\circ$ for each data point. The notation is the same as that in Fig. 3.
gles. We chose the following three divisions of the statistics into intervals.

(1) For comparison with the previous experiment at VEPP-3 [24], the part where the kinematic acceptances of the two experiments coincided ($\langle \theta_p^{cm} \rangle \approx 88^\circ$, $E_\gamma = 34–464$ MeV) was selected from the new data; these statistics were divided into eight $E_\gamma$ intervals, the same as those in the first experiment at VEPP-3.

(2) To analyze the dependence of the TAP components of the reaction on the photon energy with a high statistical accuracy, the data were divided into two $\theta_p^{cm}$ intervals corresponding to the two detector arms: $\theta_p^{cm} = 24^\circ – 48^\circ$ and $70^\circ – 102^\circ$. Each of these $\theta$ intervals was divided into nine $E_\gamma$ intervals. Thus, 18 experimental points were obtained for each component $T_{2M}$ in this division.

(3) To analyze the angular dependence of the TAP components of the reaction, the data were divided into eight photon energy ranges. In each range, the statistics were divided into $10–12 \theta_p^{cm}$ intervals, each with a width of $4^\circ$. As a result, 91 experimental points were obtained for each component $T_{2M}$ in this division.

For each interval ($\theta_p^{cm}, E_\gamma$), we calculated the three TAP components with statistical and systematic errors. The results of the measurements [23] are presented in Figs. 3 and 4. These figures also show the results of several calculations obtained in terms of present-day theoretical models:

— the calculation in the diagram approach [25] (dotted curve);

— the calculation based on the model [26] using Siegert’s theorem and the Bonn $NN$ potential (solid curve);

— the calculation in the coupled-channels approach incorporating the relativistic pion retardation mechanism [27] (dashed curve).

The numerical results of the measurements can be found in [28, 29].

4.5. Discussion

The old and new experimental data on the components $T_{20}$ and $T_{22}$ are in good agreement. Although the two experiments were conducted using the same technique, they have many differences in details: different targets (different ABSs, cells, guiding field configurations and strengths, and spin states in the target), different detectors, polarimeters, etc. Therefore, the close coincidence between the results of the two measurements suggests that the disregarded systematic error is small and, accordingly, the results are reliable.

The accuracy of the new data on $T_{2M}$ up to an energy $E_\gamma \approx 400$ MeV is sufficient to choose a theoretical model that better describes the reaction.

Despite some differences in details, on the whole, the theoretical models describe well the polarized data, confirming the validity of the theoretical views on this process.

The extent to which the theoretical calculations agree with the experimental data on $T_{2M}$ is similar to what is also observed for other polarized observables, such as the photon asymmetry $\Sigma$ and the proton polarization $p_y$. The following can be noted:

— At low $E_\gamma$, the agreement between theory and experiment is good.

— The quality of the description deteriorates with increasing photon energy.

— A more detailed calculation incorporating the relativistic pion retardation mechanism [27] improves significantly the agreement between experiment and theory.

The experimental angular dependences of the components $T_{2M}$ are well described by theories and better agreement with the model [27] is also observed here.

5. COHERENT PHOTOPRODUCTION OF A NEUTRAL PION

The coherent photoproduction of a neutral pion on a deuteron is one of the important processes in nuclear physics that provides valuable information about the deuteron structure and the pion–nucleon and nucleon–nucleon interactions. The presence of only two particles in the final state simplifies the calculations and allows more definite predictions both about their interaction and about the intermediate states of the proton–neutron pair to be made. In addition, this reaction occupies a special place because the rescattering and interaction effects in the final state play a major role here due to the cancellation of the leading terms in the amplitude.

Whereas the theoretical studies of this reaction with predictions on the differential cross sections and on various polarized observables have long been conducted using various approaches to describing the process, detailed experimental data on the cross sections have appeared only in recent years, after the launch of facilities with continuous electron/photon beams (MAMI, TJNAF, etc.) [30–32]. There are only a few measurements of the $\Sigma$ asymmetry from the polarized observables of this reaction, while no data on the TAP of the reaction are available.

Having analyzed the statistical material of the deuteron photodisintegration experiment described above, we selected events from the reaction $\gamma d \rightarrow$
$d\pi^0$, which allowed the TAP of this reaction to be measured [33]. The reaction products were detected in coincidence: the recoil deuteron was recorded by one proton arm, while one of the $\gamma$-quanta from the neutral pion decay was recorded by the corresponding neutron arm.

In contrast to the deuteron photodisintegration, where the momenta of both partners of the two-body reaction were determined, here complete information was available only for the recoil deuteron. For the process $\gamma d \rightarrow d\pi^0$, this is enough to reconstruct the reaction kinematics, but the question about the contribution of other processes whose products can give $d\gamma$ coincidences in the detector arises. For example, these include such coherent photoproduction reactions as $\gamma d \rightarrow d\pi^0\pi^0$, $\gamma d \rightarrow d\eta$, $\gamma d \rightarrow d\pi^0\pi^+\pi^-$, and the Compton scattering process $\gamma d \rightarrow \gamma d$.

Out of these reactions, experimental data are available only for the $\eta$-meson photoproduction and Compton scattering. There are also theoretical predictions on the coherent photoproduction of pairs of $\pi^0$ mesons [34] and on the coherent production of an $\eta$ meson [35]. An upper limit can be estimated using this information. This estimate shows that the contribution of the listed processes to the detector count rate must be small, no more than $1-2\%$.

There is no reason to believe that the process $\gamma d \rightarrow d\pi^0\pi^+\pi^-$ or the coherent photoproduction of other mesons ($\rho, \omega, \phi$, etc.) can make a considerably larger contribution.

The assumption about the dominance of the reaction $\gamma d \rightarrow d\pi^0$ in our case is also confirmed by the similarity of the experimental and simulated (in GEANT4) distributions of events in particle angles and energies. In the simulations, we used the data from [30, 31] for the differential reaction cross sections.

Below, we consider events with deuteron energies in the range $\approx 20-70$ MeV. At higher energies, the number of $d\gamma$-coincidence events is small. In addition, a large number of $\gamma p$-coincidence events appear here, which makes it difficult to identify the deuterons. As our simulations showed, the appearance of a large number of $\gamma p$-coincidence events is explained by the photoproduction of a $\pi^0$ meson on a quasi-free proton.

In selecting $d\gamma$-coincidence events, it was required that the deuterons stop in the first scintillation counter (there is no signal in the next layer of scintillators). Under this condition, the deuteron energies fell within the above range, while the proton energies lie in the range $\approx 15-50$ MeV. The deuterons were identified using the time-of-flight technique. In selecting $\gamma$-quanta in the neutron arm, we used a time-of-flight constraint; in addition, the absence of a signal in the veto counter was required.

Since the cross section for the reaction $\gamma d \rightarrow d\pi^0$ on a polarized deuteron is written identically with the deuteron photodisintegration reaction (with the only difference that the TAP components of the reaction here are functions of the photon energy $E_\gamma$ and the pion emission angle $\theta_{\pi^0}^{c.m.}$), the experimental asymmetry and the TAP components are obtained in a similar way.

The experimental results are presented in Fig. 5. The left panels show the dependences of $T_{2M}$ on the photon energy; all of the events falling into the range of angles $\theta_{\pi^0}^{c.m.} = 90^\circ-145^\circ$ are taken. The right panels show the dependences of $T_{2M}$ on the pion emission angle, with the range of photon energies being $250-450$ MeV. The statistical error and the averaging (over $E_\gamma$ or $\theta_{\pi^0}^{c.m.}$) intervals are shown for each data point.

The uncertainties in the target polarization make the largest contribution to the systematic error: the contributions from the statistical and systematic errors in $P_{zz}$ are 7.3% and 2.6%, respectively. In contrast to the photodisintegration, the error in $T_{2M}$ is large here, because the contribution from the longitudinal form factors is neglected. At small electron scattering angles $\theta_e$, it increases quadratically with this angle [29]:

$$\frac{\Delta T_{2M}}{T_{2M}} \approx \frac{\theta_e^2(1 - x)^2}{x^2(1 - x/2)^2},$$

where $x = E_\gamma/E$. To determine the error, this expression was averaged over the working $E_\gamma$ range and over $\theta_e$ in the range from zero to an angle corresponding to a transferred momentum of 100 MeV/c (above this momentum, the cross section for the process drops due to the decrease in the deuteron form factor). In the averaging, we used the distribution of equivalent photons in energy and emission angle from [36]. As a result, the error for this effect was 5%. The uncertainty from the contribution of other reactions was estimated to be 2%. The total systematic error in $T_{2M}$ was found to be 9.4%. We see that the statistical errors are dominant.

Since the averaging (over the photon energy and the pion emission angle) intervals for the experimental points are large, it was necessary to take this into account when comparing the data obtained with theoretical predictions. For this purpose, the results of the calculations were averaged with weights corresponding to the distribution of events in the intervals referring to each experimental point. To perform this procedure, sufficient information was available only in two calculations, [37] and [38]. In their calculations, Kâmalov et al. [37] applied a microscopic description.
in momentum space and took into account the interaction in the final state in the multiple-scattering approximation. In his calculations, Fix [38] used the elementary MAID2003 amplitude, applied the impulse approximation, and disregarded the pion–deuteron interaction in the final state. A similar model was used by this author in [39]. We see from Fig. 5 that, on the whole, there is good agreement between the data and the calculations; a slight preference may be given to the calculations [38].

It should be noted that, in addition to the experiments described above, we studied the negative pion photoproduction reaction ($\gamma d \rightarrow pp\pi^-$), where two protons were detected in coincidence. The tensor observables of this reaction [40–42] were first measured at the VEPP-3 storage ring simultaneously with the experiments to study elastic $ed$ scattering [12] and two-body deuteron photodisintegration [24]. The study was continued after the polarized target and the magnetic system of VEPP-3 had been upgraded. The measurements [43, 44] were performed simultaneously with the experiment [16]. The behavior of the TAP component $T_{21}$ of the reaction was investigated in the range of photon energies 300–900 MeV. The experimental results were compared with the calculations based on the theoretical models presented in [45]. We continue to analyze the experimental data.

6. ALMOST-REAL PHOTON TAGGING SYSTEM

Further progress of the experiments is associated with the introduction of an almost-real photon tagging system (PTS) at VEPP-3. It will allow a series of measurements of the polarized observables with photon energies up to 1.5 GeV to be made in various reactions with photon absorption. For example, the deuteron photodisintegration experiment, where, according to unpolarized measurements, the transition

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**Fig. 5.** Results of the experiment [33] on the TAP components for the reaction $\gamma d \rightarrow d\pi^0$: as a function of the photon energy (left); as a function of the $\pi^0$-meson emission angle in the center-of-mass frame (right). The curves represent the theoretical calculations: Kamalov et al. [37] (dashed), Fix [38] (solid).
to a quark–gluon description of the reaction is observed already at an energy \( \approx 1 \text{ GeV} \) [46], is expected to be continued.

The PTS creation will be an important step in developing the technique for experiments with internal targets at the VEPP-3 storage ring. The system will simplify radically the reconstruction of events from various reactions. This is particularly true for the case of two-body reactions, such as the deuteron photodisintegration and the coherent production of a neutral pion, an \( \eta \) meson, or vector mesons. For example, in the case of deuteron photodisintegration, this will allow one to lower the requirements for the detector—to record only the proton and neutron emission directions. Obviously, the solid angles of such detectors are easier to make large. At fixed luminosity of the experiment, this will make it possible to advance into the range of higher photon energies, where, in addition, difficulties in measuring the energies of both protons and neutrons arise. For example, at a photon energy of 1 GeV (accordingly, \( E_p \approx E_n \approx 500 \text{ MeV} \)), both the total absorption method and the time-of-flight method used at lower energies work poorly. For the coherent production of mesons, obviously, one may restrict oneself only to the deuteron detection for the reconstruction of events, which also simplifies considerably the creation of detectors.

PTS is located inside the experimental straight-line section and does not disrupt the storage ring beam optics. PTS has three “warm” dipole magnets (\( D_1, D_2, \) and \( D_3 \) in Fig. 6) with magnetic field integrals of 0.248, 0.562, and 0.314 T m. The internal target lies between the first and second magnets. The electrons that lost their energy through a particular reaction on the target and that retained the direction of their motion close to the initial one are deflected from the storage ring beam trajectory by the strong field of the second magnet and are expelled through a window from the vacuum chamber of the storage ring. The system of position-sensitive detectors (PD1 and PD2) determines the flight coordinates of these electrons; a trigger sandwich scintillator (\( S_2 \)) is located after the position-sensitive detectors. Anticoincidences with the sandwich scintillator \( S_1 \) allows most of the events from the bremsstrahlung of electrons on target nuclei to be rejected.

The PTS electron energy acceptance is in the range from \( \approx E_0/4 \) to \( \approx E_0/2 \), where \( E_0 \) is the storage ring beam electron energy. At \( E_0 = 2.0 \text{ GeV} \), the coverage in electron energy will be from 0.5 to 1.0 GeV or in photon energy from 1.0 to 1.5 GeV; the resolution in photon energy will be from 14 to 4 MeV at the corresponding ends of the photon spectrum. The angular acceptance in horizontal and vertical angles will be \( \pm 20 \text{ mrad} \) (resolution \( \approx 2 \text{ mrad} \)) and \( \pm 10 \text{ mrad} \) (resolution \( \approx 1 \text{ mrad} \)), respectively.

As we see, the angular acceptance of the tagging system exceeds its resolution in electron emission.
angles by an order of magnitude. This allows the polar and azimuthal angles of the electron to be reliably measured in approximately half of the recorded events, which makes it possible to determine the transverse photon polarization. Thus, PTS enables double-polarization experiments to be carried out.

7. TWO-PHOTON EXCHANGE AND ELASTIC SCATTERING OF ELECTRONS AND POSITRONS BY A PROTON

Investigating the electromagnetic form factors of the proton, the most important characteristics of this particle, provides a deeper insight into its nature, along with the nature of the interaction between its constituent quarks. Until recently, the two-proton form factors, electric \( G_E(Q^2) \) and magnetic \( G_M(Q^2) \), that characterize the distribution of charges and currents in it, respectively, have been determined by separating the longitudinal and transverse contributions to elastic electron–proton scattering. The differential elastic scattering cross section in the one-photon approximation and under the assumption of \( P \) and \( T \) invariance is given by the following expression [47]:

\[
\frac{d\sigma}{d\Omega} = \sigma_{\text{Mott}} \left[ \frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \frac{\theta_e}{2} \right], \quad (6)
\]

where \( \sigma_{\text{Mott}} \) is the Mott cross section, \( \theta_e \) is the electron scattering angle, and \( \tau = Q^2/4M_p^2 \). Using the definition of \( \varepsilon \) (5), Eq. (6) can be written as

\[
\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{Mott}}}{\varepsilon(1 + \tau)} \left[ \tau G_M^2 + \varepsilon G_E^2 \right]. \quad (7)
\]

As we see from (7), the contribution from the electric form factor to the cross section decreases with increasing \( Q^2 \), causing difficulties in its determination by this technique.

In studying the nucleon form factors, the technique of polarized experiments has been developed since the mid-1990s. In such measurements, the contributions from small form factors can be enhanced to increase the accuracy of their measurements. The systematic errors of these measurements are also small. For example, a series of accurate measurements of the ratio \( G_E(Q^2)/G_M(Q^2) \) was performed in TJNAF in a wide range of momentum transfer [48, 49]. In these experiments, the ratio of the transverse (\( P_t \)) and longitudinal (\( P_l \)) recoil proton polarizations was measured in elastic scattering of longitudinally polarized electrons by an unpolarized hydrogen target. In this case, the ratio of the proton form factors is expressed directly in terms of the ratio of \( P_t \) to \( P_l \) [50]:

\[
\frac{G_E}{G_M} = \frac{P_t}{P_l} \frac{E + E'}{2M_p} \tan \frac{\theta_e}{2},
\]

where \( E \) and \( E' \) are the electron energies before and after the scattering, and \( M_p \) is the proton mass.

The results of the polarized measurements turned out to be quite unexpected: the ratio \( G_E/G_M \) depends strongly on \( Q^2 \), while it was previously thought that this ratio changes only slightly and is close to unity and the form factors themselves roughly follow the dipole formula.

A careful analysis of the previous unpolarized measurements clearly showed that these two techniques yield conflicting results [51]. This conclusion is also confirmed by the results of new accurate unpolarized measurements performed in TJNAF [52].

The most probable cause of these disagreements is presumed to be the illegitimacy of using the one-photon approximation in interpreting the results of unpolarized measurements. However, applying the two-photon exchange corrections runs into difficulties: on the one hand, there are no proper calculations and, on the other hand, there are no sufficiently accurate experimental data.

The two-photon exchange contribution can be determined experimentally by comparing the cross sections for elastic scattering of electrons and positrons by a proton. Such experiments were conducted previously, in the 1960s (see [53] and references therein), but the accuracy of these measurements was not high enough. In the experiment to be carried out at INP at the VEPP-3 storage ring [54], the electron/positron beam energy will be 1.6 GeV; the detection system will allow the measurements to be made simultaneously at momentum transfers of 0.4 and 1.6 (GeV/c)^2.

Figure 7 presents the expected accuracy of the VEPP-3 experiment to measure \( R \), the ratio of the cross sections for elastic scattering of electrons and positrons by a proton. Also presented here are the results of existing measurements. The dashed curve in the figure indicates the results of fitting \( R \) based on global data from [55]. Since the mean momentum transfer of these measurements was \( \approx 0.5 \) (GeV/c)^2 at \( \varepsilon < 0.5 \), the slope in the experiment at VEPP-3 is expected to be higher (solid curve).

By now, a number of preparatory works have been performed on the experiment under discussion: the particle detectors, the luminosity monitor, the hydrogen gas target, etc., have been created. The first session was conducted at VEPP-3 in 2007, during which the storage ring operation was tested in the required modes, the detector and target operation was checked, and the measurement of the electron/positron beam energies at the edge of the spectrum for \( \gamma \)-quanta from the Compton backscattering
of laser radiation by this beam was tested. The statistics collection session is scheduled to be conducted in 2009.

8. CONCLUSIONS

The experiments with internal targets have been carried out at the Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences, for several years.

Data on the TAP components in elastic scattering, photodisintegration, and pion photoproduction reactions were obtained at VEPP-3 in the experiments with an internal tensor-polarized deuterium gas target.

The experimental results on elastic scattering are consistent with the previous measurements and surpass them in accuracy in the range $8-15$ fm$^{-2}$. The measurements were performed in an important range of momentum transfer where the charge monopole form factor becomes zero. Comparison of the data with theoretical predictions reveals an advantage of the relativistic calculations in describing the data.

The tensor observables in photoreactions have been measured so far only in Novosibirsk.

Data in a wide kinematic range were obtained in the deuteron photodisintegration reaction. At low $E_{\gamma}$, there is good agreement between theory and experiment. The quality of the description deteriorates with increasing photon energy; here, a more detailed calculation incorporating the relativistic pion retardation mechanism improves significantly the agreement between experiment and theory.

Qualitative agreement with available theoretical predictions is observed in the reaction of coherent photoproduction of a neutral pion on a deuteron. The experiment is expected to be continued in a setup where, apart from the deuteron, both $\gamma$-quanta from the neutral pion decay will be detected by a calorimeter composed of 150 CsI crystals. Such a measurement will allow the statistical error to be reduced by several times and will lower the systematic uncertainties.

The negative pion photoproduction reaction is studied in parallel with the experiments carried out at VEPP-3. The results are analyzed by a group from Tomsk (Nuclear Physics Institute at Tomsk Polytechnical University).

Further progress of the experiments with polarized targets is associated with the introduction of an almost-real photon tagging system at VEPP-3, whose construction has already begun. Apart from extending the possibilities for the experiments with polarized targets, PTS will allow the transverse photon polarization to be determined in half of the recorded events. This opens the possibilities for conducting double-polarization experiments.

The current experiment at VEPP-3 is the measurement of the ratio of the cross sections for elastic positron/electron scattering by a proton. Such measurements are important, because they will possibly explain the recently revealed dramatic contradiction between new polarized measurements and old data on the proton form factors. The statistics are expected to be collected in 2009.\(^9\)

\(^9\)The experiment has already been performed; an analysis of respective data is under way.
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