Photoreactions with tensor-polarized deuterium target at VEPP–3

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Abstract. We give an overview of the activity in studying photoprocesses on a tensor-polarized deuterium target, which is carried out at the VEPP–3 electron storage ring. Recent experimental results on tensor asymmetries in two-body deuteron photodisintegration at the photon energy up to 500 MeV, and in coherent pion photoproduction on deuteron are presented. Plans to upgrade the facility and future experiments are discussed. Further progress is connected with the installation of a tagging system for almost–real photons. This would allow us to extend the measurements of polarization observables in photonuclear reactions on deuteron up to a photon energy of 1.5 GeV and permit to perform double polarized experiments – with linear polarized photon beams and tensor/vector polarized deuterium targets.

1. Introduction

At Novosibirsk we use the method of a superthin internal target for the study of electro– and photonuclear reactions [1]. The conception of the method was developed and the first application was done in Budker Institute in 60th-70th. Later it was successfully applied in a number of laboratories worldwide, both at electron and ion rings.

It is one of the advantages of the method – a very efficient utilization of target material, that makes feasible the measurements with a deuterium gas target featuring a high degree of tensor polarization.

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2. Experimental setup

2.1. The internal target

The heart of the Novosibirsk target is the Atomic Beam Source. It is based on a conventional scheme with magnetic spin separation and excitation of Radio Frequency transitions between selected hyperfine states of deuterium. The Novosibirsk ABS is the only one worldwide which uses superconducting sextupole magnets. It produces a jet of up to 8×10^{16} polarized atoms per second with any desirable spin configuration, in particular with very high degree of tensor polarization ($P_{zz} > 0.98$) and at the same time with negligible vector one ($P_z < 0.02$). Such an operation mode is most favorable for the study of tensor asymmetries.

For better utilization of polarized atoms from the ABS, a storage cell has been used. It is a 40 cm long, 30 μm thick aluminum tube, with 24×13 mm^2 elliptical cross–section, coated with *drifilm* and cooled by liquid nitrogen. It provides a thickness gain of 65.

2.2. VEPP–3 storage ring

Experiments are carried out at the VEPP–3 storage ring. The maximal beam energy at VEPP–3 is 2 GeV, the average beam current is 100 mA. The main purpose of VEPP–3 is to serve as a booster ring for VEPP–4 electron-positron collider, but VEPP–3 is used also for internal target experiments as well as a source of synchrotron radiation. The internal target is located in one of straight sections of the ring.

3. Photodisintegration of the deuteron

Two-body deuteron photodisintegration is a fundamental photonuclear process. The first paper on the experimental study of this reaction was published 76 years ago [2].

Taking into account parity conservation the T-matrix of this reaction contains 12 complex amplitudes. In order to fully describe the process one has to measure at least 23 independent observables. Any such “set of 23” must include tensor asymmetries. And this is where the internal target method has no alternatives at present.

The theory of deuteron photodisintegration has a long and rich history. It started with the first paper of Bethe and Peirels back in 1935 [3]. At present, the most sophisticated model for medium photon energies is the one developed by Shcwamb and Arenhövel, further elaborated by Michael Schwamb [4]. It uses a coupled channel approach, takes into account relativistic pion retardation in nucleon-nucleon potentials and in Meson Exchange Currents. It has no free parameters with respect to deuteron photodisintegration, all parameters have been fitted in advance, therefore it has a predictive power.

3.1. Cross section

A general expression for the cross section for polarized spin-1 target and unpolarized photon beam is given by

$$\begin{aligned}\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}\Big\{ 1 - \sqrt{3/4}\; P_z \sin(\theta_H)\sin(\phi_H)\,\boldsymbol{T}_{11}\big(E_\gamma, \theta_p^{CM}\big) \\ +\sqrt{1/2}P_{zz}\Big[(3/2\cos^2(\theta_H) - 1/2)\boldsymbol{T}_{20}(E_\gamma, \theta_p^{CM}) \\ -\sqrt{3/8}\sin(2\theta_H)\,\cos(\phi_H)\,\boldsymbol{T}_{21}(E_\gamma, \theta_p^{CM}) \\ +\sqrt{3/8}\sin^2(\theta_H)\,\cos(2\phi_H)\,\boldsymbol{T}_{22}(E_\gamma, \theta_p^{CM})\Big]\Big\}\,. \end{aligned} \tag{1}$$

Besides the unpolarized part, it contains 4 structure functions - vector analyzing power T_{11} and 3 tensor analyzing powers T_{20}, T_{21}, T_{22}. These functions depend on 2 kinematic parameters. In case of two-body photodisintegration those are photon energy in the Lab frame and proton emission angle in the Center-of-Mass frame. P_z and P_{zz} are parameters of the target polarization. They are determined through relative populations of hyperfine states: $P_z = n_+ - n_-$, $P_{zz} = 1 - 3 \cdot n_0$. The axis of quantization is defined by the external magnetic field. Note that the tensor polarization depends on the population of zero spin projection only and it spans from -1 to $+2$.

3.2. Almost-real photons approach

In photonuclear measurements at Novosibirsk we employ an approach of almost-real photons. That means we actually study electro-disintegration, but select events with electrons scattered at a small angle. Therefore, the transferred 4-momentum is close to zero, which corresponds to photodisintegration. A rough estimation shows that for our experimental conditions (with a cut on θ_e at about 1° and a fraction of energy lost by electron less than 25%) the distortion of tensor asymmetries due to a photon virtuality does not exceed 10^{-3} [5], which is negligible. Note that we didn't detect the scattering electron, but rather reconstruct the photon momentum from reaction products.

3.3. Particle detector

The detector layout, side view, is shown in figure 1. There were two pairs of arms detecting proton and neutron in coincidence. Drift coordinate chambers and 3 layers of scintillators were used in the proton arms. Thick plastic scintillators and thin veto-counters were applied in the neutron arms. Neutron scintillators were placed as far as possible from the target (about 3 meters) to ensure the best time-of-flight performance. Two detector pairs are employed in order to cover two angular ranges in one run.

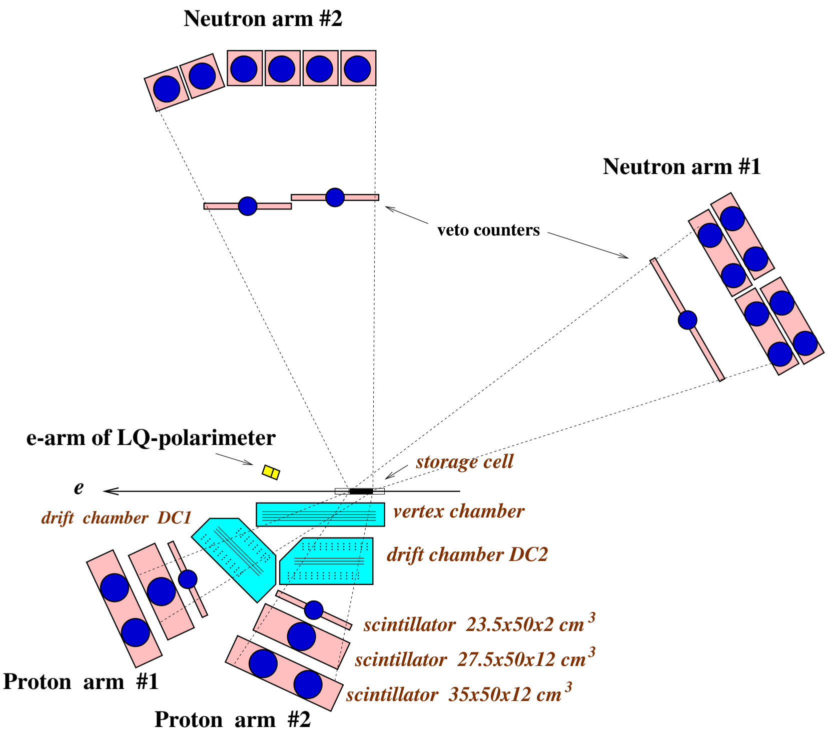

Figure 1. Layout of the particle detector for the measurement of tensor analyzing powers in deuteron photodisintegration.

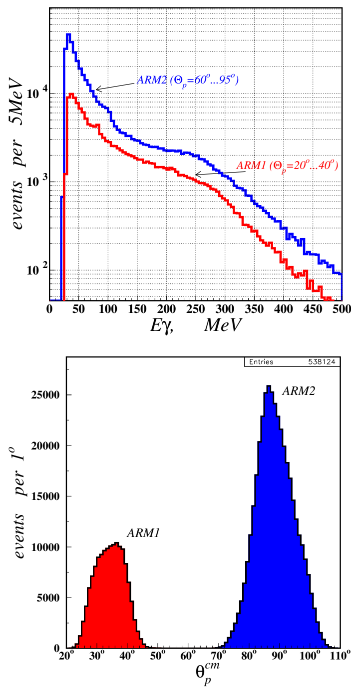

Figure 2. Distributions of the collected events of the process $\gamma + \vec{d} \to p + n$.

3.4. Separation of tensor observables

The quantity which is directly measured is an asymmetry connected to a reversing the sign of target polarization. With an ABS this can be done very fast and often, thus substantially suppressing the systematic errors. The tensor asymmetry is defined as $a^T = \sqrt{2}\,(\sigma^+ - \sigma^-)/(P_{zz}^+\sigma^- - P_{zz}^-\sigma^+)$ – it is a linear combination of three analyzing powers: $a^T = c_0T_{20}+c_1T_{21}+c_2T_{22}$, with coefficients being functions of angles between photon momentum and direction of magnetic field. A separation of T_{2M} can be done by measuring asymmetries at several settings of the magnetic field direction. We chose such three regimes: $\theta_{H1} = 180°$, $\theta_{H2} = 54.7°$, $\theta_{H3} = 125.3°$, with $\phi_H = 180°$ always. Therefore $a_0 \sim c_0T_{20}$, $a_1 \sim +c_1T_{21}+c_2T_{22}$, $a_2 \sim -c_1T_{21} + c_2T_{22}$, so all three analyzing powers are separated unambiguously.

3.5. Results

The data taking run was 4 month long. The average beam current was 80 mA, the target thickness was 3×10^{13} at/cm^2, and the target tensor polarization amounted to $P_{zz} = 0.341 \pm 0.028$. The collected data cover a wide continuous range of photon energies, up to 500 MeV, in two intervals of proton emission angle, as shown in figure 2.

The results for the tensor analyzing powers plotted as a function of photon energy are shown in figure 3. Theoretical curves for three modern models are also shown. One can say that

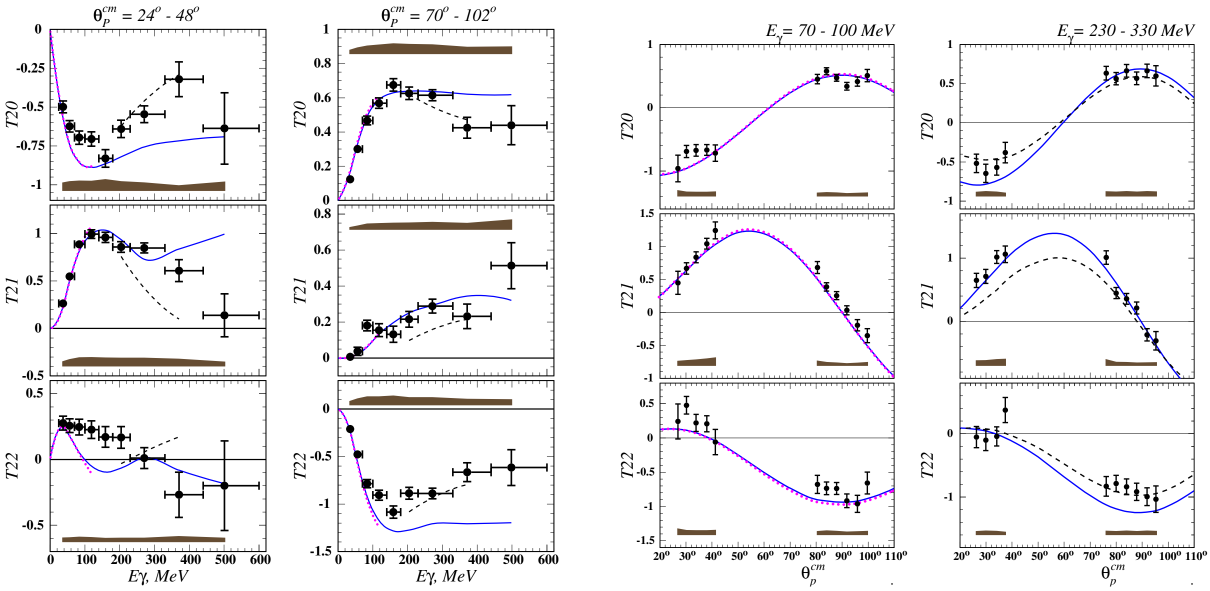

Figure 3. Results for the tensor analyzing powers in $d(\gamma, pn)$ [6]. The two left panels show T_{2M} vs. photon energy for two angular intervals, two right panels – T_{2M} vs. proton angle for two energy intervals. Vertical bars are statistical errors, horizontal bars indicate bin sizes. Systematic errors are shown with shaded bands. Theoretical curves: blue solid – K.-M. Schmitt and H. Arenhövel [7], black dashed – M. Schwamb [4], magenta dotted – M. Levchuk [8].

there is good agreement between theories and data for small energies below the pion production threshold. Above pion production, the calculations become significantly more complex due to the increasing importance of additional channels, the larger effects of relativity, and so on. We see greater variations between data and calculations and between calculations themselves. In several cases, the more modern calculation by Schwamb greatly improve the description of the data. Despite the disagreement in details, it is clear that there is a good overall qualitative description of the polarization data.

Results for T_{2M} versus proton angle are obtained for 8 energy intervals. Figure 3 shows data for two intervals (the complete data set can be found in [6]). One can see a remarkable agreement between data and theory for smaller energy and a better description of data obtained by a novel model of Schwamb at larger energy.

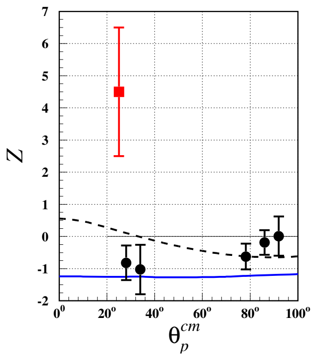

Figure 4. Tensor asymmetry **Z** in deuteron photodisintegration, measured in Bonn [9] (squares). The photon energy used was $E_\gamma =$ 450 MeV. Novosibirsk data [6] are also shown (circles). Theoretical curves are from [7] (solid line) and from [4] (dashed line).

Figure 4 shows the only tensor asymmetry in deuteron photodisintegration measured outside Novosibirsk [9]. It was done at Bonn in 1989, they call it Z-asymmetry and we found it corresponds to the following combination: $\boldsymbol{Z} = \sqrt{2}\,\boldsymbol{T_{20}} + \sqrt{3}\,\boldsymbol{T_{22}}$. Bonn's point is at $E\gamma = 450$ MeV. We can put several of our points here too. One can see that the Bonn result is two to three standard deviations away from theories and from the Novosibirsk data, while the Novosibirsk points agree with theories, although the statistics at this energy is limited.

4. Coherent neutral pion photoproduction on the deuteron

The second reaction channel we study is the coherent neutral pion photoproduction on the deuteron. This is the only pion photoproduction reaction on the deuteron with a two-body final state. Among the issues addressed when studying this reactions are: reaction mechanisms, π^0–deuteron elastic scattering, photoproduction of π^0 on neutron; at threshold – chiral dynamics at neutron, and so on.

Theoretical investigations of this reaction including the predictions of various polarization observables have been performed for a long time using various approaches. At the same time, experimental data on polarization observables in this reaction exist only for Σ – photon beam linear polarization asymmetry. No tensor asymmetries were measured before us.

4.1. First measurement of tensor observables

The very first data on tensor asymmetries in this process were obtained by analyzing the statistics, collected during the deuteron photodisintegration experiment at VEPP–3. Such data were available due to a loose on-line trigger that was used. We selected events of deuteron–gamma coincidence with the deuteron detected in the first proton arm and one photon from π^0 decay detected in the first neutron arm.

Possible contributions of various background processes were considered and found to be small for the chosen energy interval.

The results are shown in figure 5. The same data are plotted either as four photon energy bins, or as four pion angle bins. Two theoretical predictions are shown, both properly integrated inside corresponding bins. Agreement between experiment and theories looks satisfactory within the accuracy of data. The calculation by Alexander Fix seems to describe the data slightly better.

4.2. Proposed new measurement at VEPP–3

We are going to perform a dedicated experiment on measuring T_{20} in coherent π^0–photoproduction on the deuteron with better statistics and lower systematic error and for a wider

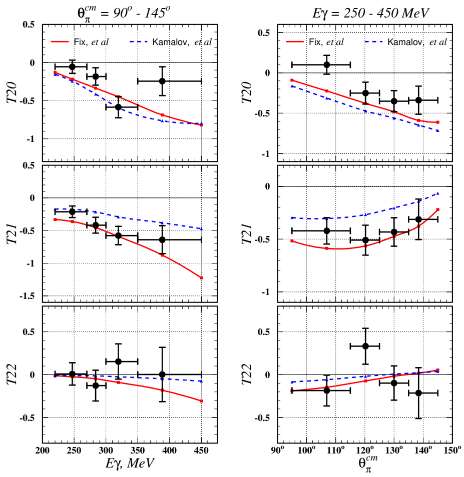

Figure 5. Results of the first measurements of tensor analyzing powers in the reaction $\gamma + \vec{d} \to \pi^0 + d'$ [10]. Vertical bars show statistical errors, horizontal bars are bin sizes. The systematic error is $\approx 9.4\%$. Theoretical curves: dashed lines are from [12], solid lines from [13].

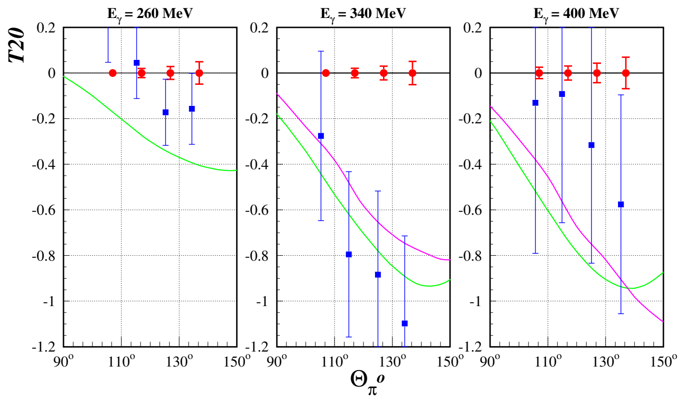

Figure 6. Projected accuracy (red circles) of the measurements of T_{20} in the reaction $\gamma + \vec{d} \to \pi^0 + d'$. Points are arbitrary placed on zero. Also first Novosibirsk data (blue squares) and theoretical curves are shown: solid lines from [11], dashed lines from [12].

kinematic interval. Both γ-quanta from π^0 decay will be detected by a segmented calorimeter comprising 152 CsI(Tl) crystals. The expected accuracy for a 2-month run at VEPP–3 is demonstrated in figure 6.

5. Almost–real photon tagger

Further progress in the studying of photonuclear reactions at VEPP–3 we connect with an introduction of the tagging system for almost real photons. That would allow

- to perform a complete kinematic reconstruction, thus permitting a reliable rejection of the background processes;
- to extend the measurements to higher photon energy;
- to determine the linear polarization of photon, thus enabling Σ–asymmetry measurements and double–polarization experiments: with linear polarized photon beam and tensor–polarized deuterium target.

5.1. Details of the design, status of fabrication

Conceptual layout of the Tagging System is shown in figure 7. This is a top view at the experimental section of VEPP–3. Dipoles D1, D2 and D3 make up a chicane. The target is placed behind the first dipole. The second dipole acts as an electron spectrometer. Two or three two-coordinate GEMs will be used for tracking of scattered electron. Sandwiches comprising tungsten and plastic scintillators layers will be used for triggering.

The basic parameters of the tagger performance have been obtained from the simulations: photon energy range: $(0.5 - 0.75) \cdot E_{beam}$; photon energy resolution from 1.4% down to 0.4%. For at least a half of the events, the orientation of the electron scattering plane can be determined with a 10° resolution, which is sufficient for the study of Σ–asymmetries.

The first and third dipoles have already been manufactured and tested. The second magnet is being fabricated. We expect to be ready to start a production run using the tagger in 2013.

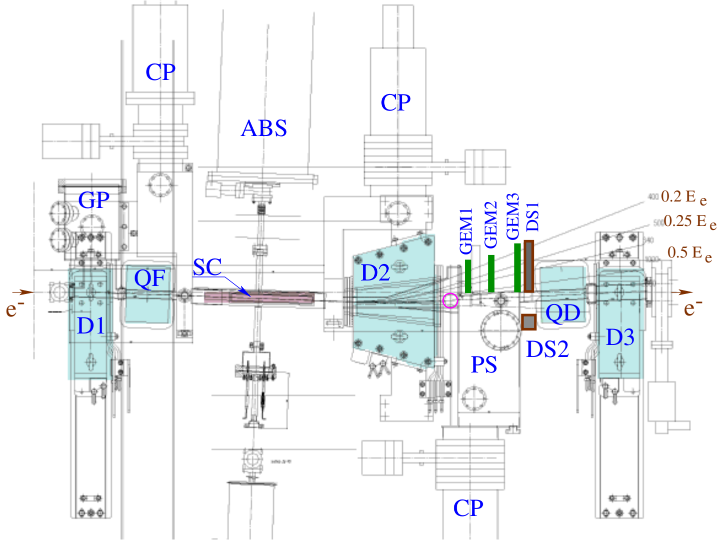

Figure 7. Layout of the Photon Tagger at VEPP–3 experimental section. D1,D2,D3 – dipoles, QF,QD – quadrupole lenses, ABS – atomic beam source, SC – storage cell, CP – cryopumps, DS1,DS2 - trigger sandwiches.

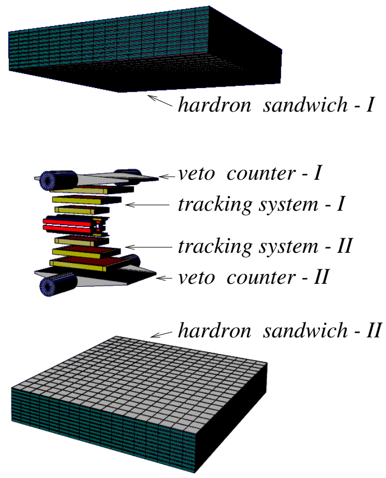

Figure 8. Proposed detector layout for the new deuteron photodisintegration experiment.

5.2. *The proposed experiment*

As an example of an experiment with the new almost-real photon tagger we consider an extension of the two-body deuteron photodisintegration measurement to higher photon energy - up to 1.5 GeV. Besides general interest to obtain new polarization data for this fundamental process, this measurement may also add new information to the question where does the transition from meson-baryon to quark-gluon picture of deuteron occur? Constituent counting rule and Hadron Helicity Conservation hypothesis of perturbative QCD allow to predict asymptotic behavior for differential cross section and polarization observables. Thus, differential cross section should obey a $\mathbf{s}^{-11}$ scaling; most polarization observables should go to zero, while Σ-asymmetry should approach -1, and T_{20} should go to $-\sqrt{2}$.

The present experimental status for $\theta_P^{cm} = 90°$, where the pQCD regime can be achieved at lowest photon energy, is as follows [14]. JLab's measurements of differential cross section seem to demonstrate the asymptotic scaling starting already from $E_\gamma \approx 1$ GeV. Some polarization observables do confirm this behavior – *e.g.,* the induced proton polarization p_y, measured at JLab, but some others do not confirm – *e.g.,* Σ–asymmetry, measured at Yerevan. The proposed measurement at VEPP–3 at similar photon energies should check the pQCD expectations for the tensor asymmetry T_{20} which does not vanish in the pQCD limit.

The layout of a particle detector which is going to be built for such an experiment is shown in figure 8. The detector consists of two identical arms measuring proton and neutron in coincidence. Each arm includes a set of drift wire chambers for tracking and multilayer iron/scintillators sandwiches with two–coordinate segmented read-out for high-efficient detection of neutrons.

The projected accuracy of the measurement of T_{20} and Σ for a photon energy range $E_\gamma = 1.0 - 1.5$ GeV is shown in figure 9.

6. Summary

- Using the method of superthin internal targets in electron storage ring and the approach of almost-real photons, a precise measurement of energy and angular dependencies of tensor

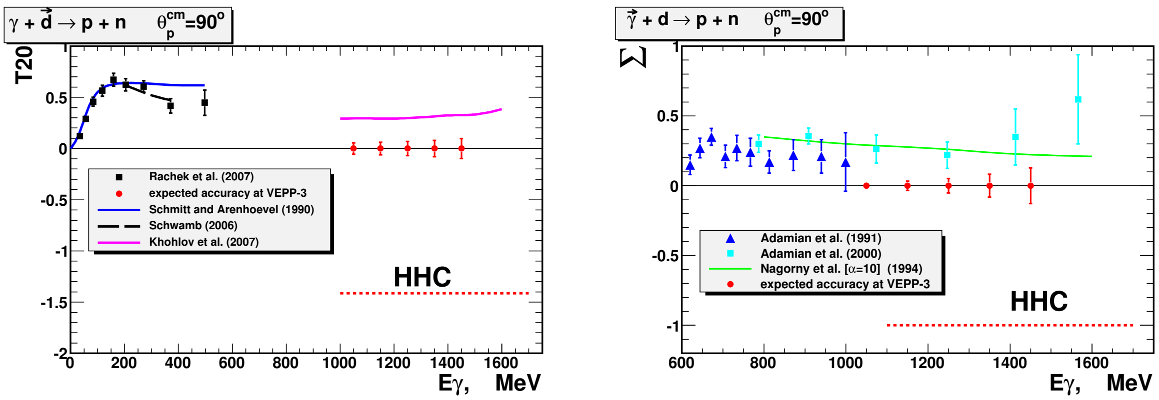

Figure 9. Projected accuracy of the measurement of T_{20} and Σ for a 4–month run at VEPP–3 with the Tagger and new particle detector (red circles). Points arbitrary placed on zero. Existing data points: for T_{20} from [6], for Σ from [15].

analyzing powers in deuteron two-body photodisintegration were performed for photon energy up to 500 MeV.

- The first experimental data on tensor asymmetries in coherent π^0–photoproduction on deuterium were obtained. New extended measurements are being prepared.
- Future progress is associated with the introduction of the Tagger System for almost–real photons, which is under construction now.
- A banner experiment with the almost-real photon's tagger will be the measurement of T_{20} and Σ in two-body deuteron photodisintegration at $E_\gamma = 1.0 - 1.5$ GeV, $\theta_p^{cm} = 90°$.

Acknowledgments

The authors wish to acknowledge the staff of VEPP–3 for the excellent performance of the ring during the data collection runs. These works were supported in part by Russian Foundation for Basic Research under grants 01-02-16929-a, 04-02-16434-a, 05-02-17080, 05-02-17688-a, 08-02-00624-a, 08-02-01155-a; by Federal Agency for Education, State Contract P522; by Federal Agency for Science and Innovation, Contract 02.740.11.0245.1; by US DOE grant: DE-AC02-06CH11357; and by US NSF grant: PHY-03-54871.

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