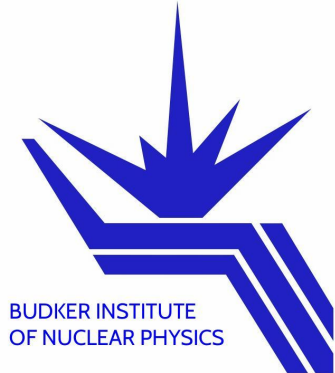




AFAD 2026

Asian Forum for Accelerators and Detectors

13-17 October 2026 Shanghai, China



DEUTERON facility at VEPP-3 storage ring: experimental status and perspectives

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Shanghai, China
October 2026

Outline

1. Physical program
2. DEUTERON facility
3. Experiment
4. Results
5. Conclusions

Physical program of the DEUTERON experiment

Global aim: study **tensor forces** of nuclear interaction at short distances ~ 1 fm.

Concrete purpose of experiment – measure **tensor analyzing power** in elastic and inelastic **electron scattering on tensor polarized deuteron target**.

Processes under study:

elastic electron–deuteron
scattering

$$ed \rightarrow e'd'$$

photoproduction of
 π -mesons on a deuteron

$$\gamma d \rightarrow \pi^- pp$$

$$\gamma d \rightarrow \pi^0 d$$

$$\gamma d \rightarrow \pi^+ \pi^- d$$

$$\gamma d \rightarrow \pi^0 pn$$

photodisintegration of
tensor polarized deuteron
(discussed in this report)

$$\gamma d \rightarrow pn$$

Photon Tagging System of the DEUTERON facility

Key feature of the experiment – detect **electrons scattered at small angles** less than 1° .

In this case $Q^2 \approx 0$, and the scattering process ($e d \rightarrow e' p n$) is equivalent to the **photodisintegration process** ($\gamma d \rightarrow p n$).

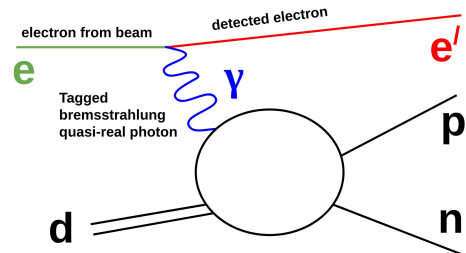
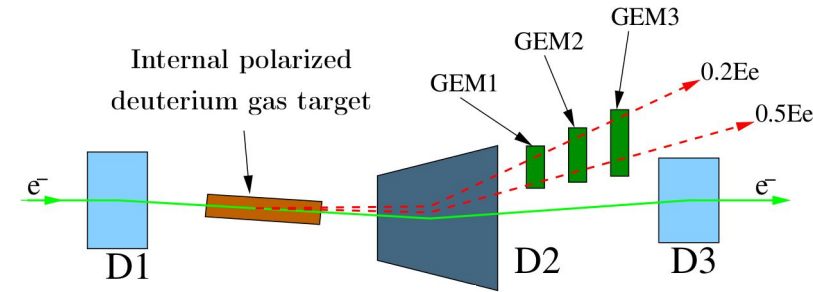
Initial electron beam $E_e = 800$ MeV.

Quasi-real photons $E_\gamma = 350 - 680$ MeV.

D1, D2, D3 – dipole magnets.

GEM = **Gas Electron Multiplier** detector.

Energy resolution of Photon Tagging System $\sim 1\%$.



GEM detectors measure coordinates

of scattered electron track, **angle θ is extracted**, electron **energy is calculated** based on electron kinematics in the magnetic field.

$$\alpha_0 = 37 \text{ mrad}$$

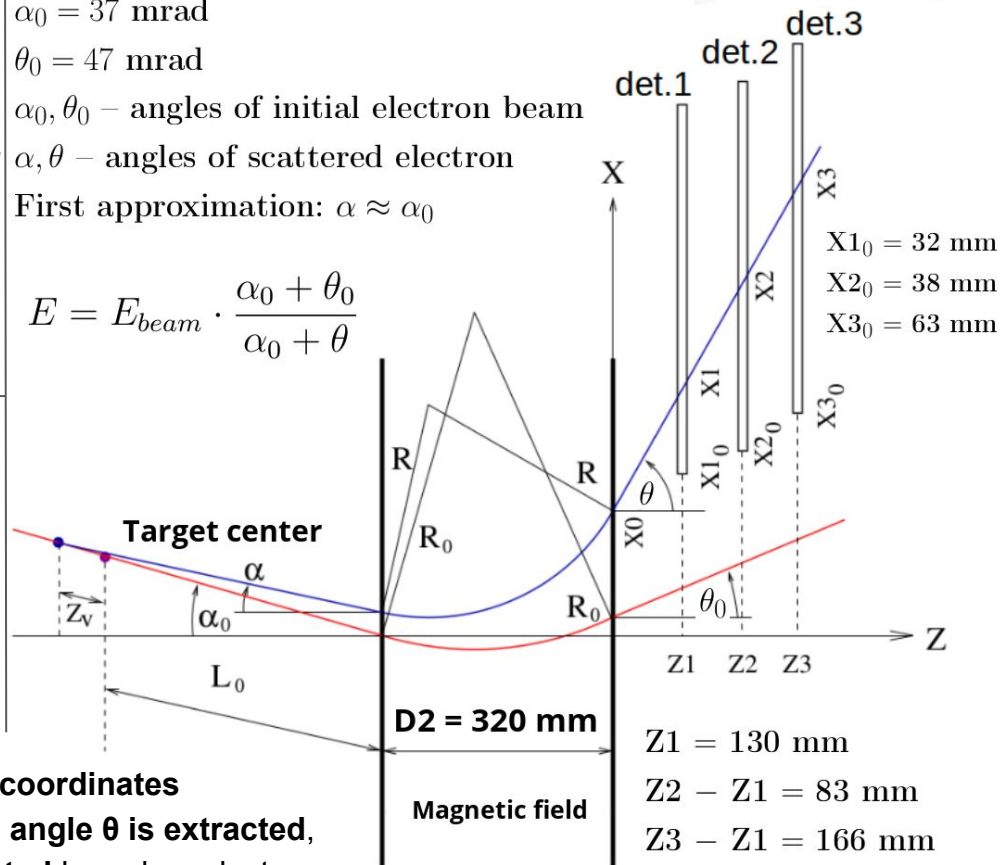
$$\theta_0 = 47 \text{ mrad}$$

α_0, θ_0 – angles of initial electron beam

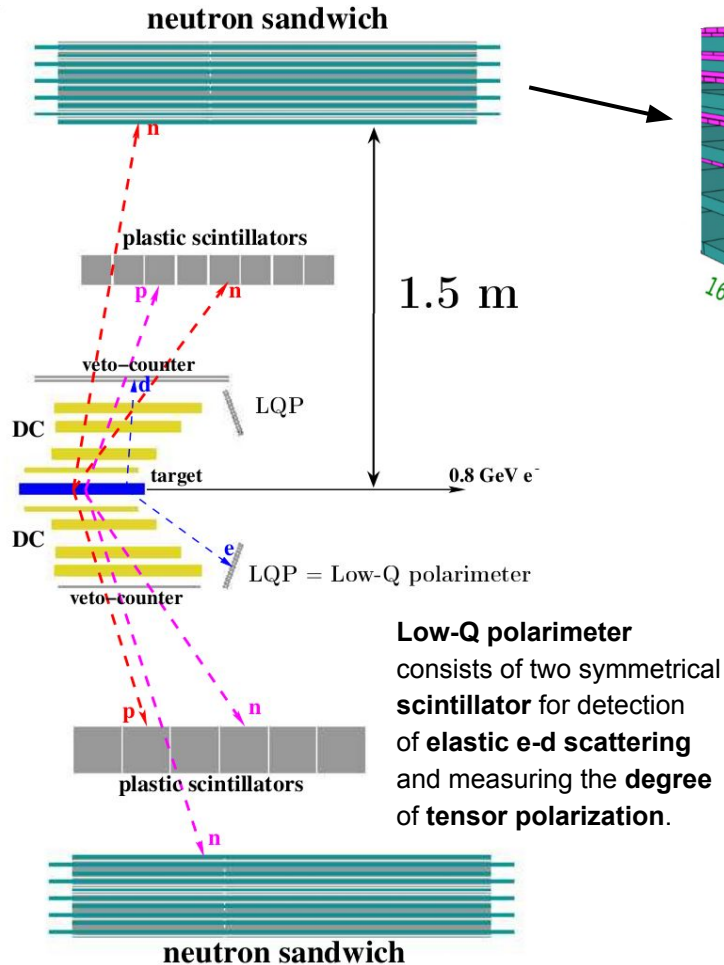
α, θ – angles of scattered electron

First approximation: $\alpha \approx \alpha_0$

$$E = E_{beam} \cdot \frac{\alpha_0 + \theta_0}{\alpha_0 + \theta}$$



Detector system of the DEUTERON facility



Neutron sandwich detector consists of **iron** and **scintillator** layers. **Two-coordinated segmented readout** is used. **Neutron detection efficiency** is about **40%**.

Particle identification:

neutrons: veto + time-of-flight (TOF);
protons: TOF + $\Delta E/E$ analysis.

Detector system comprises **two symmetric arms above and below target**.

Proton and **neutron** are detected in **different arms** of the detector.

Polar angle acceptance with experimental cuts $\theta = 45^\circ - 85^\circ$.

Azimuthal angle acceptance $\Delta\phi \approx 60^\circ$ for each arm.

Drift chambers (DC) for **charged particle track reconstruction**.

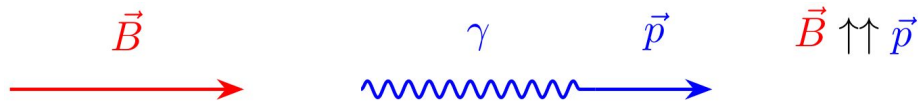
Veto counters to **distinguish between charged and neutral particles**.

Plastic **scintillators** for **proton** and **neutron** detection.

Proton detection efficiency is about **80%**.

Extract T_{20} from the measured polarization asymmetry

Deuteron **polarization axis** is directed along **magnetic field**.
Polarization **axis** coincides with **direction** of quasi-real photon.
In this case differential **cross-section of photodisintegration** can be expressed with **tensor analyzing power** component T_{20} .



$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \cdot \left[1 + \frac{1}{\sqrt{2}} P_{zz} T_{20} \right]$$

Cross-section for unpolarized target

Deuteron spin = 1 $\Rightarrow$ vector and tensor polarization.

Vector polarization: $P_z = n_+ - n_-$.

Tensor polarization: $P_{zz} = 1 - 3n_0$.

n_+ , n_- , n_0 – relative number of atoms with nuclear spin projection +1, -1, 0 onto the direction of magnetic field.

Tensor polarization: $P_{zz}^+ = +1$, $P_{zz}^- = -2$.

Degree of tensor polarization in the experiment $\approx 40\%$.

$$N^{\pm} = \mathcal{L} \cdot \sigma_0 \cdot \left[1 + \frac{1}{\sqrt{2}} P_{zz}^{\pm} T_{20} \right]$$

Integrated luminosity is identical for both polarization states.
Switching between polarization states every 30 seconds.

Resulting formula for T_{20} extraction:
$$T_{20} = \sqrt{2} \cdot \frac{N^+ - N^-}{P_{zz}^+ N^- - P_{zz}^- N^+}$$

Experimental results

Criteria for identifying true deuteron **photodisintegration**:

1. **coincidence** detection of **proton** and **neutron** in different arms + detection of **electron** in the Photon Tagging System;
2. **correlation** between **azimuthal emission angles** of proton and neutron:
$$\Delta\Phi = |\Phi_p - \Phi_n| \approx 180^\circ$$

Signal process was measured and simulated: $\gamma d \rightarrow pn$

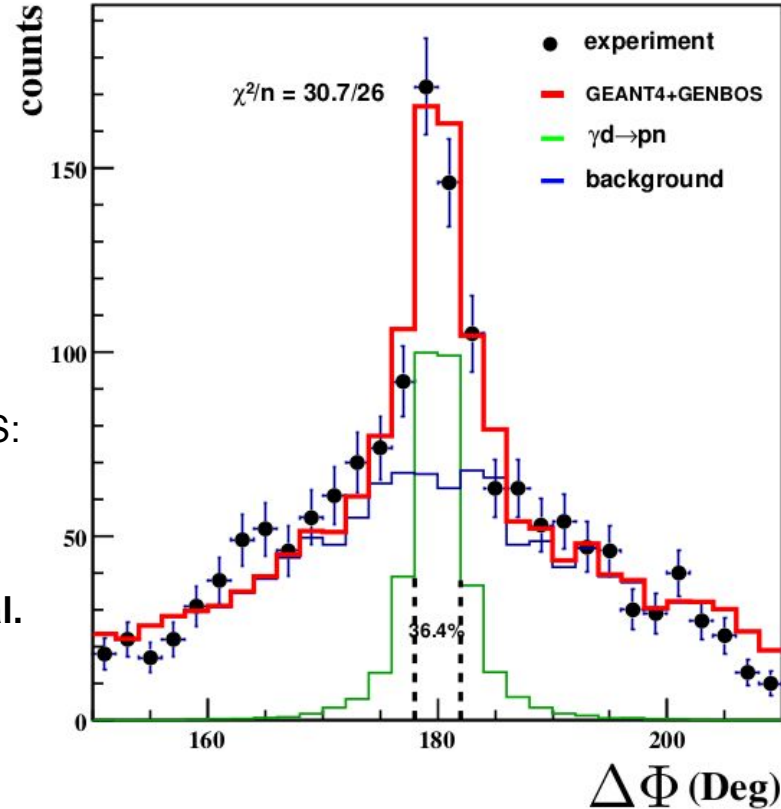
Background processes were simulated with GEANT4+GENBOS:

$$\gamma d \rightarrow \pi^0 pn \quad \gamma d \rightarrow \pi^0 \pi^0 pn \quad \gamma d \rightarrow \pi^+ \pi^- pn$$

Simulated background was subtracted from measured signal.

Polar (Θ_p) and **azimuthal** (Φ_p) emission angles of protons were measured by **drift chambers** with **resolution** $\sim 0.6^\circ$.

Azimuthal emission angle of neutrons (Φ_n) was measured using **scintillators** with **resolution** $\sim 7^\circ$.



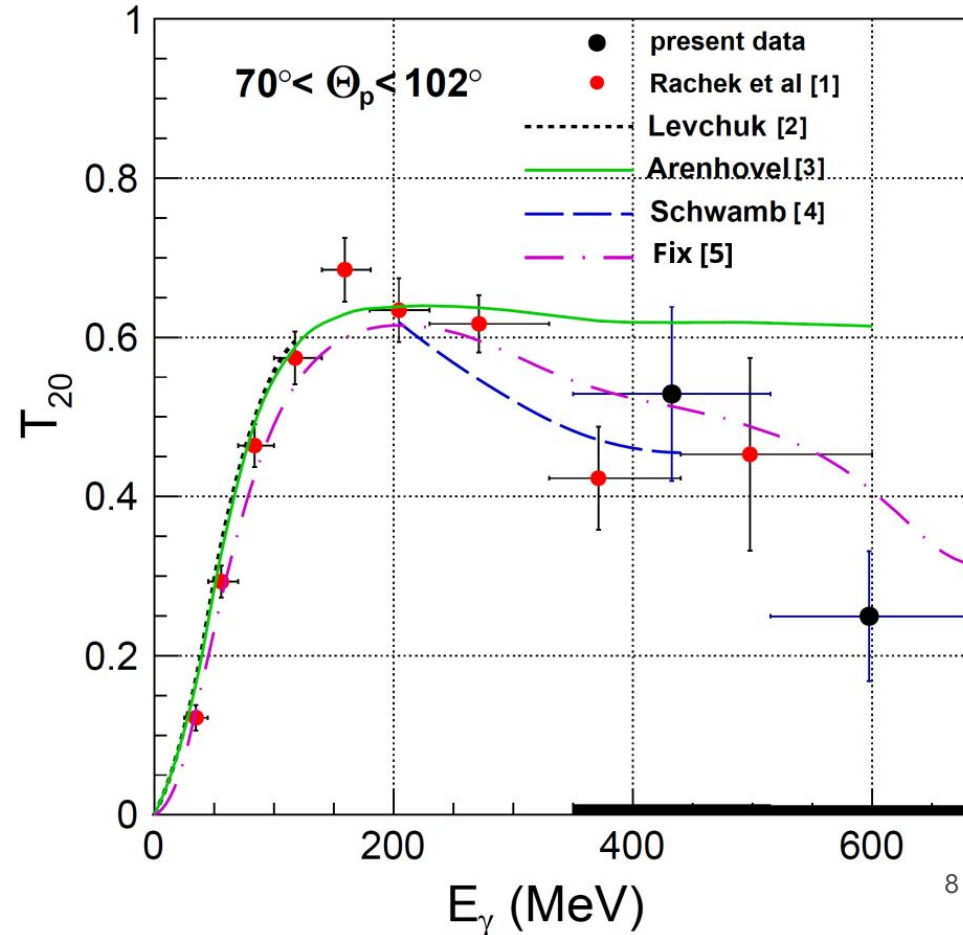
Distribution of **azimuthal angle difference** between **proton** and **neutron**

Results for T_{20}

The measured **tensor analyzing power** T_{20} remains **positive** across the entire energy range and it demonstrates a **gradual decrease** from $T_{20} \approx 0.65$ at $E_\gamma = 150 - 200$ MeV to $T_{20} \approx 0.35$ at $E_\gamma = 500 - 600$ MeV.

For energy region $E_\gamma < 150$ MeV, **theoretical models** are in a **good agreement** with the experiment. With **increasing energy**, the **calculations** become more **complex** due to opening of π NN-channel.

Meson-baryon theoretical **approach** adequately **describes data** within experimental uncertainties.



[1] I. A. Rachek et al., Phys. Rev. Lett. 98, 182303 (2007).

[2] M. I. Levchuk, Few-Body Syst. 19, 77 (1995).

[3] K.-M. Schmitt and H. Arenhövel, Few-Body Syst. 7, 95 (1989).

[4] M. Schwamb, Phys. Rep. 485, 109 (2010).

[5] A. I. Fix, <https://arxiv.org/abs/2608.09169v1>.

Conclusions

Tensor analyzing power T_{20} was measured in **photodisintegration process** ($\gamma d \rightarrow p n$) at **photon energies $E_\gamma = 350 - 680$ MeV** with DEUTERON facility at VEPP-3 storage ring.

The obtained **results** are generally **consistent** with **previously published** data [I. A. Rachek et al., Phys. Rev. Lett. 98, 182303 (2007)] at **$E_\gamma < 600$ MeV**.

Measured T_{20} is **positive** and is qualitatively **described by the meson-baryon model**, which is dominated by **meson-exchange currents and Δ -isobar excitations**.

Perspectives

Increase accumulated **statistics** and **extend photon energy range up to 1 GeV**.

Measure T_{21} and T_{22} components for **comprehensive test of theoretical models**.

1. Yu. V. Shestakov et al., Photodisintegration of tensor polarized deuteron: Status of the experiment at the VEPP-3 storage ring, International Journal of Modern Physics E (2024) 2441023.

2. A. I. Fix, Tensor analyzing power T_{20} in the reaction $\gamma d^{\uparrow} \rightarrow pn$ at photon energies 350–680 MeV, <https://arxiv.org/abs/2608.09169v1>.

Thank you for attention!

Backup

Physical introduction

The noncentral (tensor) components of the nuclear interaction are known to play a crucial role in electro- and photonuclear reactions, particularly at short internucleon distances. However, detailed experimental investigations of these effects have emerged only in recent years. For a long time, the main obstacle was the lack of tensor-polarized targets with a high degree of polarization suitable for use with storage rings or extracted beams. Without such targets, isolating tensor effects, measuring analyzing powers, and separating spin amplitudes were practically impossible.

The shift from unpolarized cross sections to spin observables in the 1980s opened the way for direct tests of the deuteron structure, particularly its connection to the tensor component of the NN forces. One of the key technological breakthroughs was the development of internal polarized gas targets for charged-particle storage rings, first implemented at the Budker Institute of Nuclear Physics (Novosibirsk).

The main feature of our experiments is to get data with electrons scattered at very small angles ($< 1^\circ$). In this case, the square of the 4-momentum transfer is close to zero and we can consider the reaction of an electrodisintegration $e\vec{d} \rightarrow e'pn$ as the reaction of photodisintegration $\gamma\vec{d} \rightarrow pn$ (a virtual photon is similar to a real one).

The differential cross-section for a tensor polarized deuteron and an unpolarized photon can be expressed in terms of the tensor analyzing power components T_{20} , T_{21} and T_{22} as

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \left\{ 1 + \frac{1}{\sqrt{2}} P_{zz} \left[\frac{1}{2} (3\cos^2(\theta_H) - 1)T_{20} - \sqrt{\frac{3}{8}} \sin(2\theta_H) \cos(\phi_H)T_{21} + \sqrt{\frac{3}{8}} \sin^2(\theta_H) \cos(2\phi_H)T_{22} \right] \right\}, \quad (1)$$

where $\frac{d\sigma_0}{d\Omega}$ is the unpolarized cross-section, P_{zz} is the degree of deuteron tensor polarization (vector polarization is equal to zero, see the next section of the paper for details), and the angles θ_H and ϕ_H determine the orientation of the magnetic field in the coordinate system with the z -axis along the photon momentum. Each of the components of the tensor analyzing power depends on two kinematic parameters — the incident photon energy in the lab frame and the proton emission angle in the center-of-mass frame.

In the experiment the magnetic field was directed along the z -axis, therefore the expression (1) is reduced to

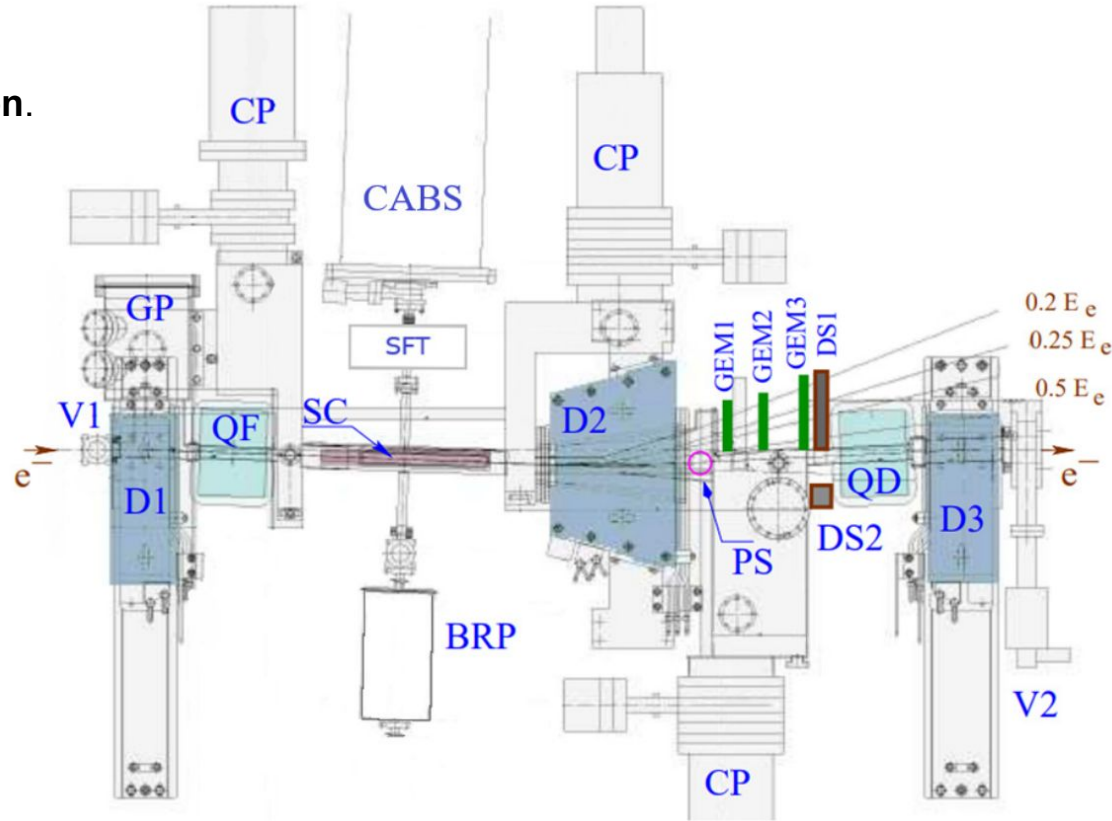
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \left\{ 1 + \frac{1}{\sqrt{2}} P_{zz}T_{20} \right\}. \quad (2)$$

As can be seen from (2), the value of T_{20} can be extracted by measuring the asymmetry in the count rate when changing the degree of tensor polarization P_{zz} . To suppress systematic error the tensor polarization was changed every 30 s during the experimental run.

Tagging System (TS) of quasi-real photons

Top view of the **experimental straight section**.

D1, D2, D3 – dipole magnets;
GEM1, GEM2, GEM3 – tracking detectors;
QF, QD – quadrupole lenses;
CABS – Cryogenic Atomic Beam Source;
SC – storage cell;
BRP – Breit-Rabi polarimeter;
CP – cryogenic pump;
DS1, DS2 – trigger sandwiches;
V1, V2 – gate valves.



Cryogenic Atomic Beam Source (CABS) produces jet of nuclear polarized atoms of deuterium

CABS consists of:

- 1) **dissociator** – gas discharge tube where **molecular deuterium** is **dissociated** into **atoms** in a high-frequency **discharge**;
- 2) **five superconducting sextupole magnets**;
- 3) **two Radio Frequency (RF) transition units**.

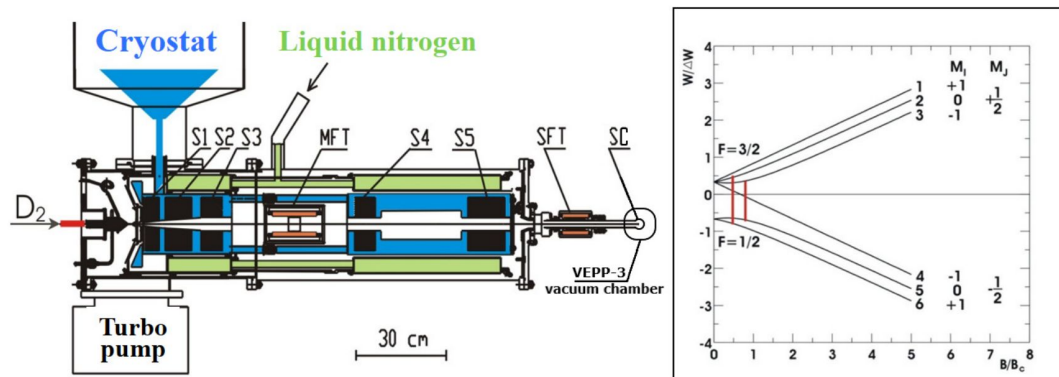
Unpolarized atoms enter into the first group of magnets as a **directed beam**. **Energy levels** of atomic deuterium are **split** in the strong magnetic field.

There are **six energy states** for atomic deuterium. Each of them corresponds to an **electron spin projection M_j** and a **nuclear spin projection M_i** .

Atoms with electron spin projection $M_j = +1/2$ are **directed** by the nonuniform magnetic field **toward** the magnet axis. **Atoms with $M_j = -1/2$** are **deflected from the axis** and **pumped out** by cryogenic surfaces.

After passing the **first three magnets** (S1, S2, S3), the beam contains **atoms in states 1, 2, 3** in practically equal ratios.

Deuteron nuclear spin = 1.



Schematic view of the CABS. S1–S5 — superconducting sextupole magnets; MFT — medium field transition unit; SFT — strong field transition unit; SC — storage cell. Right graph shows a Zeeman splitting of energy levels of atomic deuterium in a magnetic field (M_j and M_i are the projections of electron and nuclear spins, respectively, F is the total angular momentum of the atom).

The high-frequency transition unit MFT (**Medium Field Transition**) is located **between** the magnets **S3 and S4** to produce the transition of atoms **from the state 1 to 4**.

Then the **atoms in the energy state 4 are removed from the beam using the last two magnets** (S4 and S5). As a result, the **atoms are in the states 2 and 3 at the output** of the magnetic system of CABS. The SFT (**Strong Field Transition**) unit can induce **transitions** between the atomic substates **3 and 5** or **2 and 6**. Finally, the nuclear polarized atoms with **tensor polarization $P_{zz} = -2$ or $P_{zz} = +1$** (depending on the selected transition) can be obtained. The **vector polarization is close to zero**. The measured **intensity** of the polarized deuterium **gas jet reaches $8 \cdot 10^{16}$ atoms/s** with a very **high degree of tensor polarization (more than 98% of maximum values +2 or -1)** while vector polarization is less than 2%.

Tensor polarized deuterium gas target

Polarized atoms produced by CABS are **injected** into the **storage cell** that is placed in the electron orbit of the VEPP-3.

Storage cell is a thin-wall **T-shaped tube** with one **port** for **polarized atoms** and **other two ports** for **electron** movement.

Storage cell was built to **increase** the **target density** due to multiple **intersection** of the **electron beam** with **atoms reflected** from the **inner surface** of the cell.

The **cell** is **cooled** with **liquid nitrogen** in order to **reduce** the **speed** of the **atoms** and to **increase** the **target thickness**.

A tiny **hole** is made **in the cell** through which a small fraction of the atomic beam is directed to the **Breit–Rabi polarimeter** to **control** the **polarization**.

To **reduce** the **depolarization** of atoms due to wall **collisions**, the storage **cell** is **coated** with **drifilm**.

