INTERNATIONAL SESSION-CONFERENCE
"Physics of fundamental interactions"
dedicated to 50th anniversary of Baksan Neutrino Observatory

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ИССЛЕДОВАНИЕ ФОТОЯДЕРНЫХ РЕАКЦИЙ С ИСПОЛЬЗОВАНИЕМ КВАЗИМОНОЭНЕРГЕТИЧЕСКОГО ПУЧКА ФОТОНОВ УСКОРИТЕЛЯ LUE-8-5

STUDY OF PHOTONUCLEAR REACTIONS USING A QUASI-MONOENERGETIC PHOTON BEAM OF LUE-8-5 ACCELERATOR

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Why study photonuclear reactions at low energies?

- **Study reactions near the threshold of the one-neutron separation.**
- **Study the structure of the giant dipole resonance.**
- **New giant resonance modes.**
- **Scissors Mode.**
- **Pygmy Dipole Resonances.**

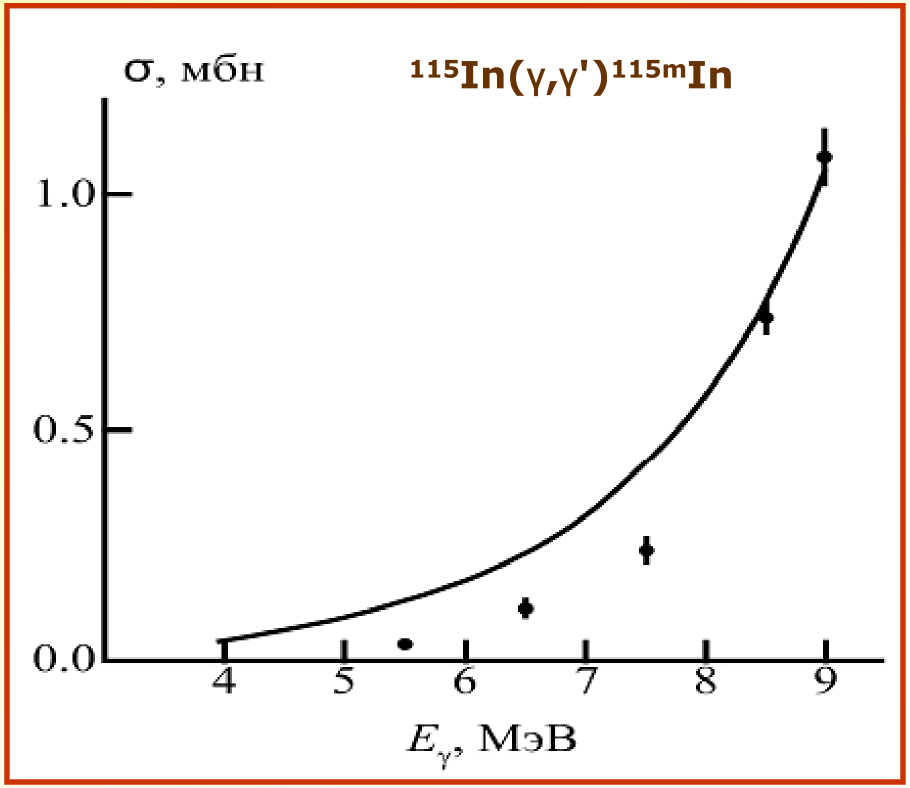
It is of interest to study isomeric states in the (γ,γ') reactions on medium-heavy nuclei, since the probability of population of the isomer can be related to the multipolarity of the initial stage of the interaction of the photon with the nucleus.

Study reactions near the threshold of the one-neutron separation

Comparison of the low-energy part of the total photoabsorption cross-section in the region of small E_γ reactions with $E_\gamma \leq (E_\gamma)_{(\gamma,\ n)\text{-thr}}$ with the Lorentz fitting curve.

The calculated cross section decreases with decreasing E_γ less steeply than the experimental cross section.

One can consider the measurements of $\sigma(\gamma, \gamma')^m$ as a method of studying the σ_{total} in this energy range E_γ.



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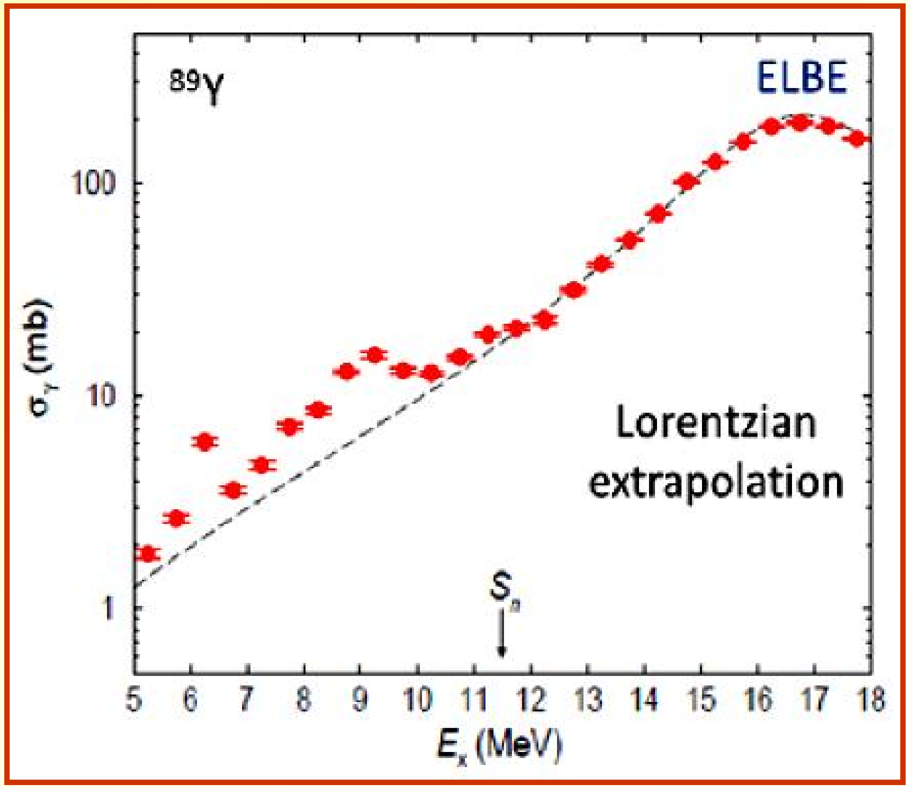
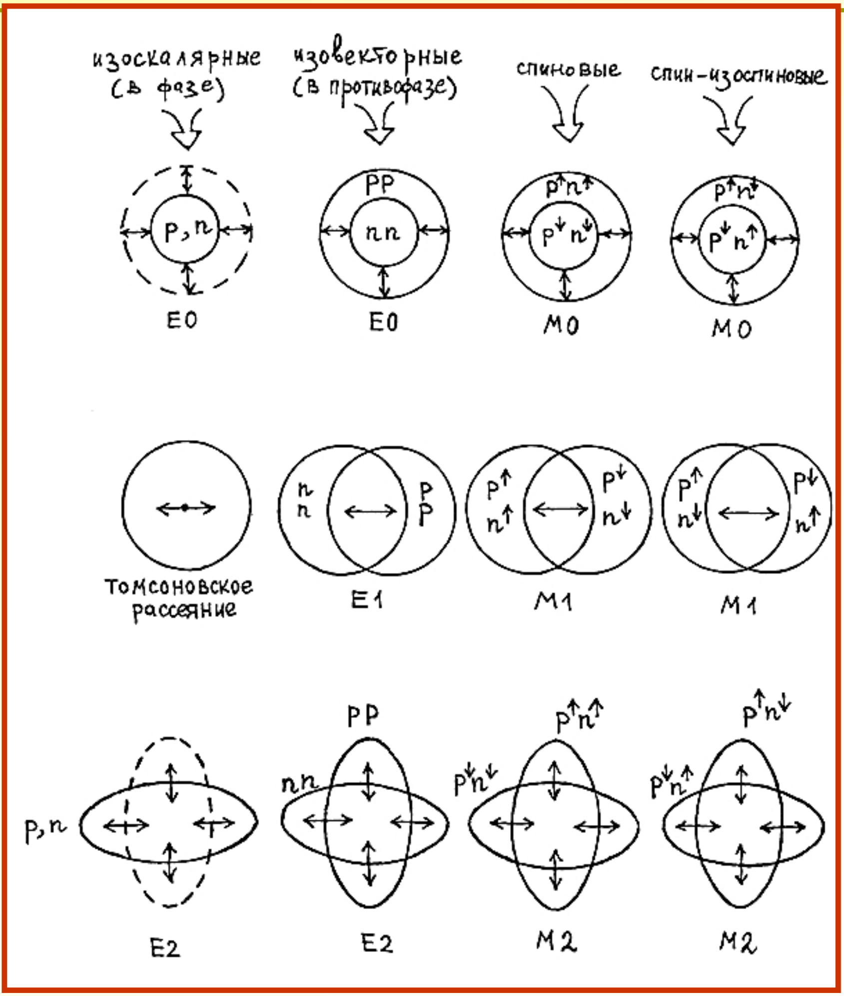


A.Zilgesand D.Savran. EPJ Web of Conferences. 93,0102(2015)

Types of giant resonances smallest multipolarity

Giant resonances are distinguished by the type of collective motion of nucleons inside the nucleus.



Classification of giant resonances is based on the fundamental characteristics of electromagnetic radiation (photons) - their total angular momentum J = 1 (dipole, 2 (quadrupole), 3 (octupole), ...

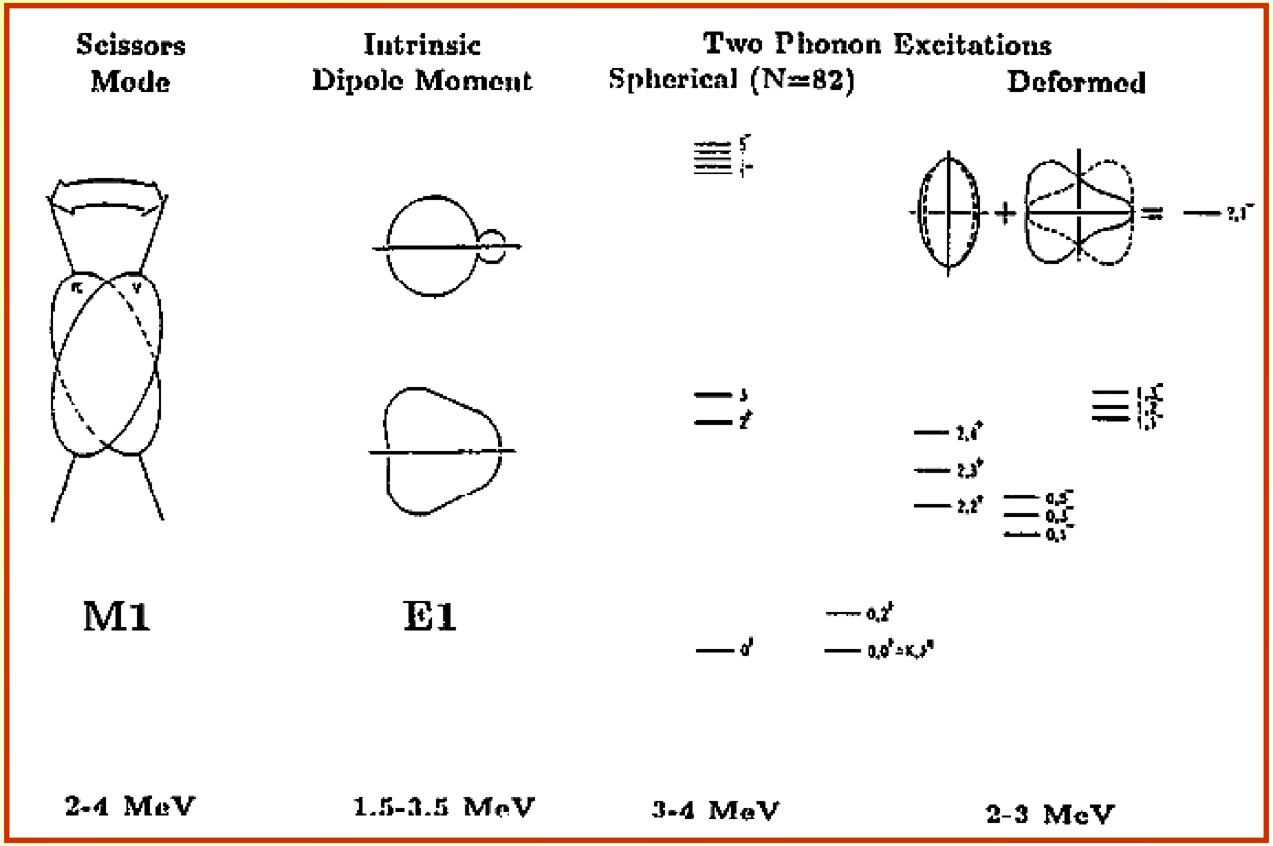
Absorption by the core of E1-, M1-, E2-, etc. photons excites in them, respectively, electric dipole (E1), magnetic dipole (M1), electric quadrupole (E2), etc. oscillations.

Thus, knowledge of the type and multipolarity of the photon absorbed by the nucleus provides us with an understanding of the nature of intranuclear excitation.

Ишханов Б.С., Капитонов И.М.
Гигантский дипольный резонанс атомных ядер

Ножничные моды ГДР
(Scissors Modes GDR)

Schematic representation of possible low-lying dipole excitations of an heavy even-even nucleus



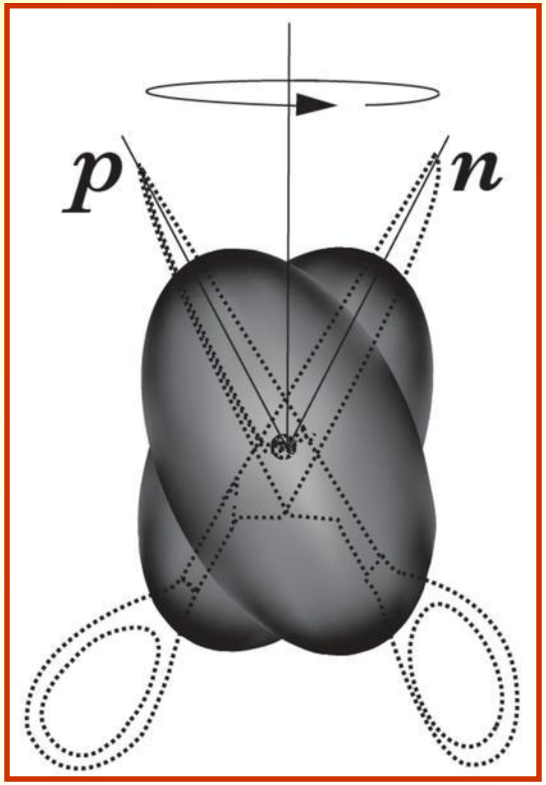
U. Kneissl et al. , Progr. Part. Nucl. Phys. 37(1996)349

Ножничные моды ГДР
(Scissors Modes GDR)

Scissors Modes are collective excitations in which two particle systems move with respect to each other conserving their shape. For the first time they were predicted to occur in deformed atomic nuclei by N. Loludice and F. Palumbo, who used a semiclassical Two Rotor Model.

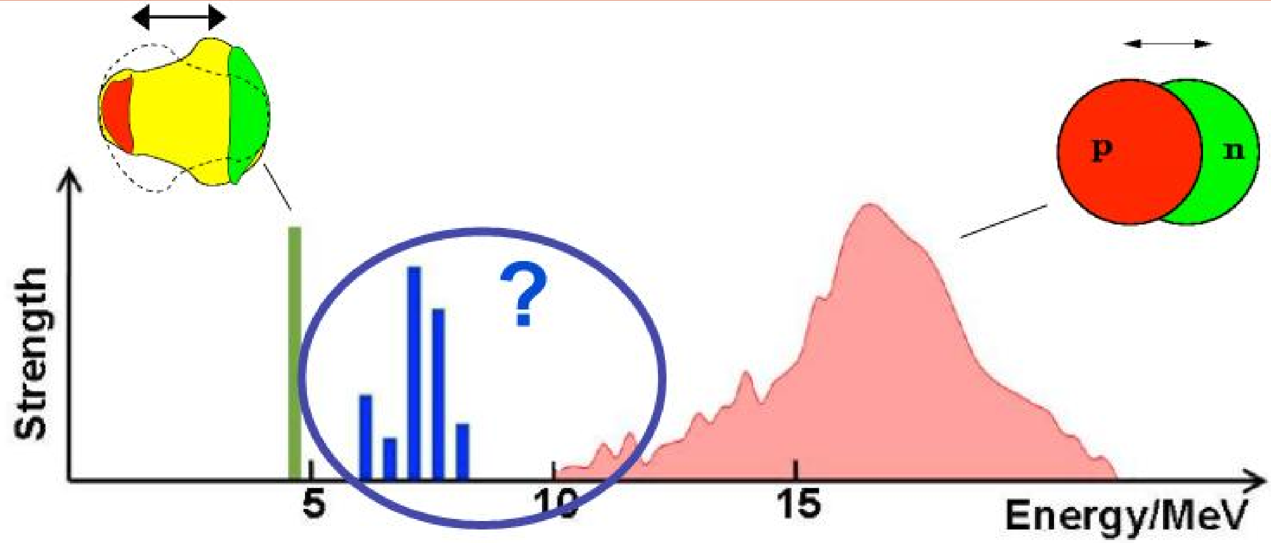
In this model protons and neutrons were assumed to form two interacting rotors to be identified with the blades of scissors. Their relative motion generates a magnetic dipole moment whose coupling with the electromagnetic field provides the signature of the mode.

Such states have been experimentally observed for the first time by A. Richter and collaborators in a rare earth nucleus, ^{156}Gd.



Ножничные моды **(Scissors Modes)- Wikipedia**

Electric dipole strength in (spherical) atomic nuclei

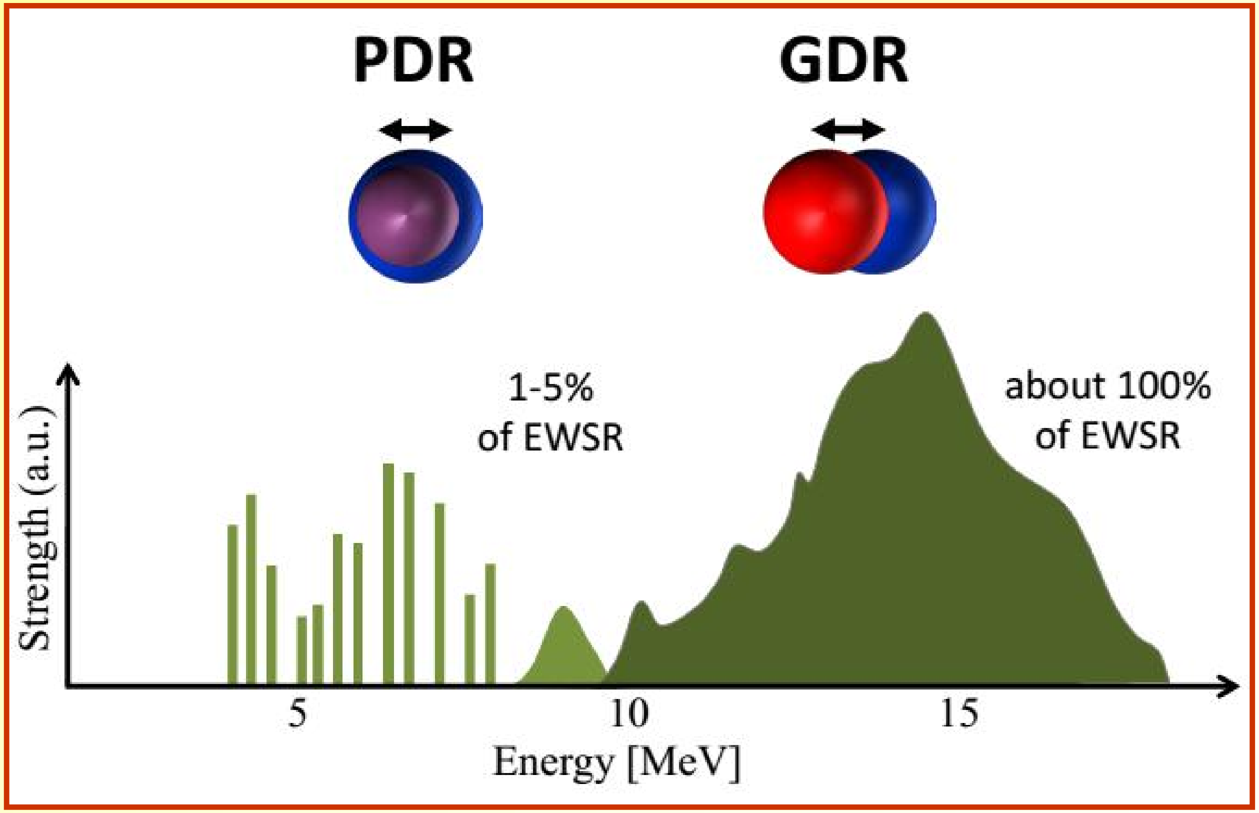


- Two-Phonon excitation ($2^+ \otimes 3^-$)
- Giant Dipole Resonance (GDR)
- Pygmy Dipole Resonance (PDR)

Such states have been experimentally observed for the first time by A. Richter and collaborators in a rare earth nucleus, ^{156}Gd.

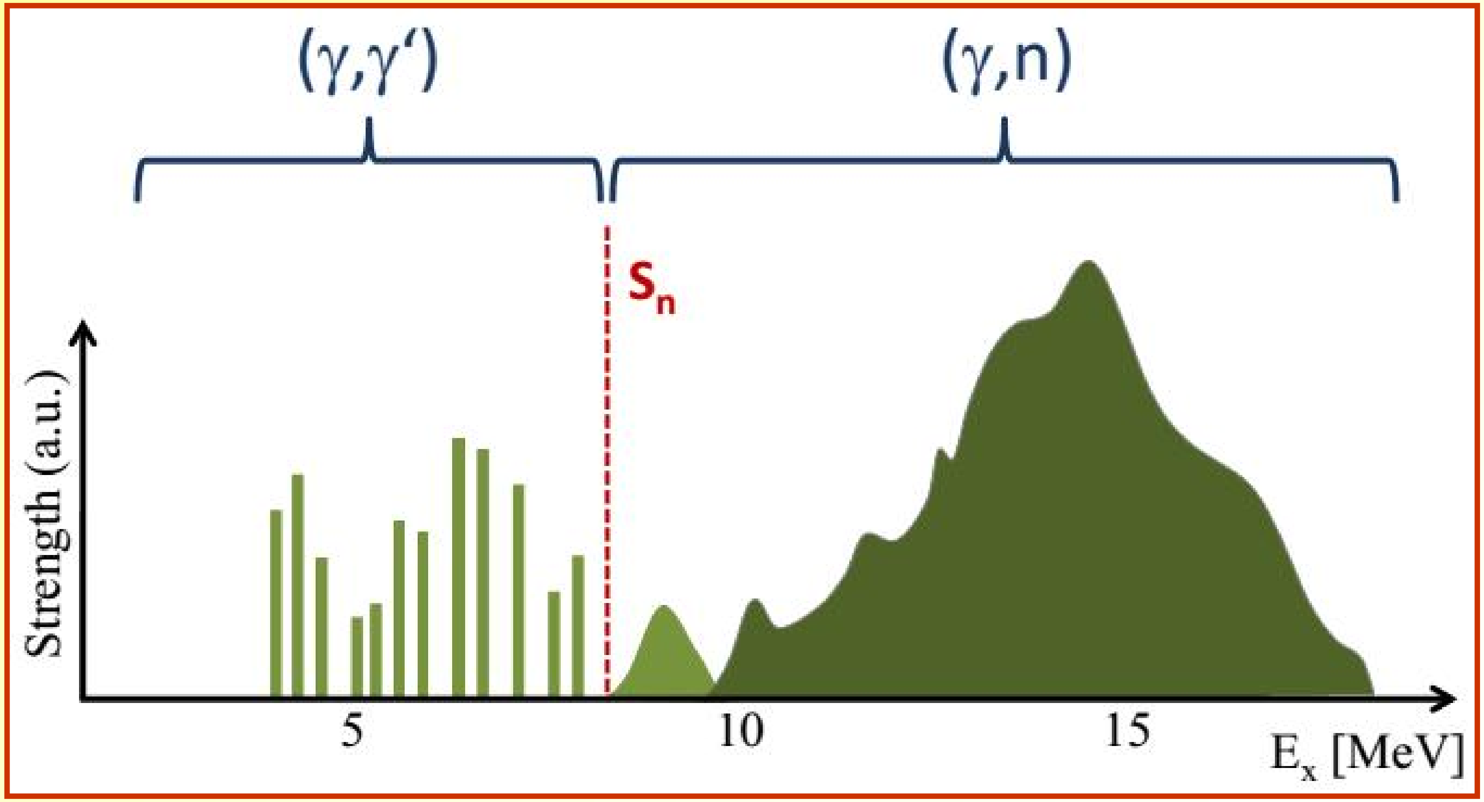
D. Savran at al. Investigation of the PDR in (γ,γ′) and (α,α′γ) experiments

Пигми (карликовые) Дипольные Резонансы (Pygmy Dipole Resonances)



From giants to pygmies

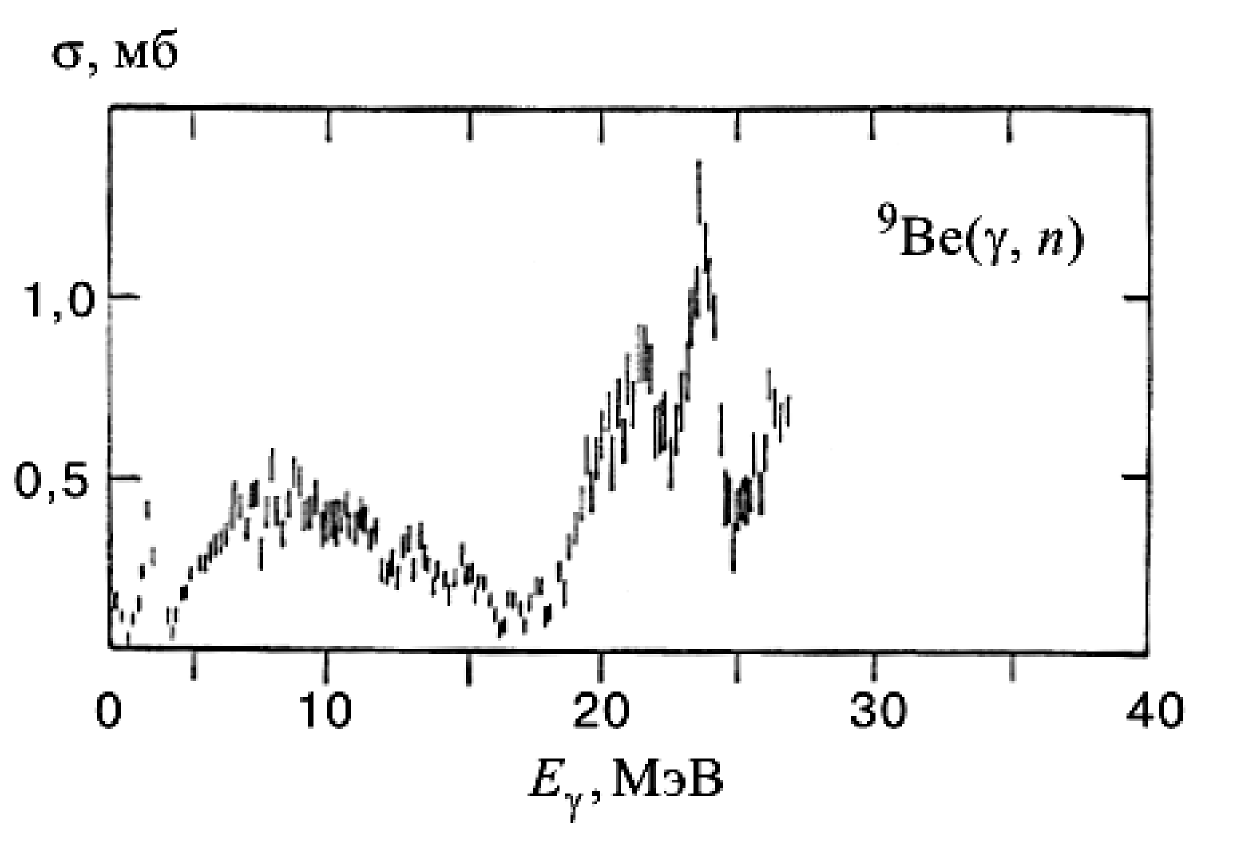
Пигми (карликовые) Дипольные Резонансы
(Pygmy Dipole Resonances)



Study of the E1 strength distribution via electromagnetic interaction

Пигми (карликовые) Дипольные Резонансы
(Pygmy Dipole Resonances)

The cross section for the reaction $^9Be(\gamma,n)$

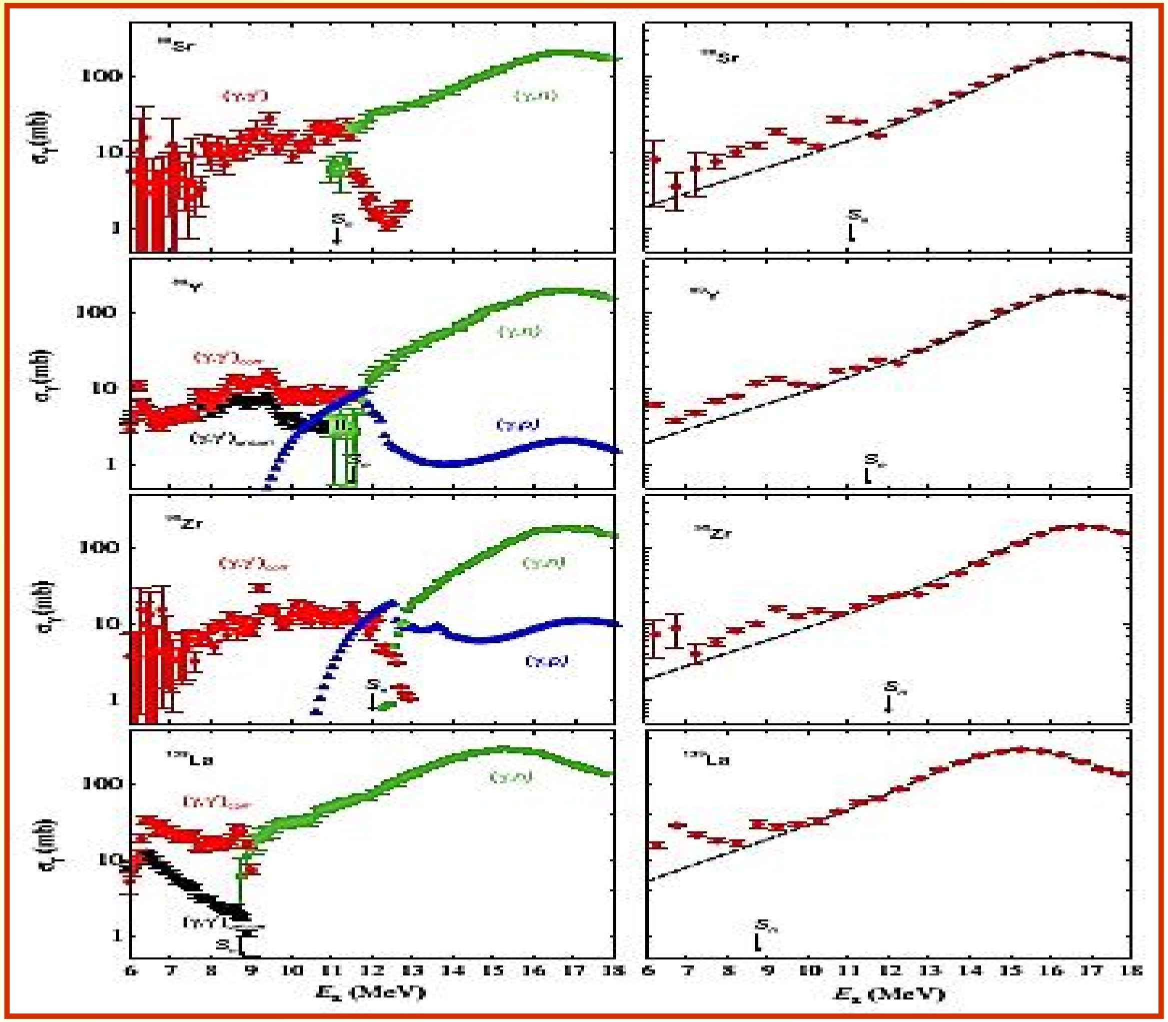


Ahrens J. et al. Nucl. Phys., 1975, v.A251, p.479

Пигми (карликовые) Дипольные Резонансы
(Pygmy Dipole Resonances)

Extracted photo-absorption (γ, γ’) cross sections on selected isotopes ^{88}Sr, ^{89}Y, ^{90}Zn, ^{139}La together with data above the particle separation energy obtained in (γ, n) experiments (left part).

The right panel shows the total photo-absorption cross section combining the results of all reactions.



D. Savran et al. Progr. Part. Nucl. Phys. 70(2013)210

Methods for studying photonuclear reactions

- The "tagged" photon method.
- Inverse Compton scattering of high-power laser radiation on a moving electron.
- Annihilation on the fly of relativistic positrons.
- Bremsstrahlung γ-radiation of electron accelerators.

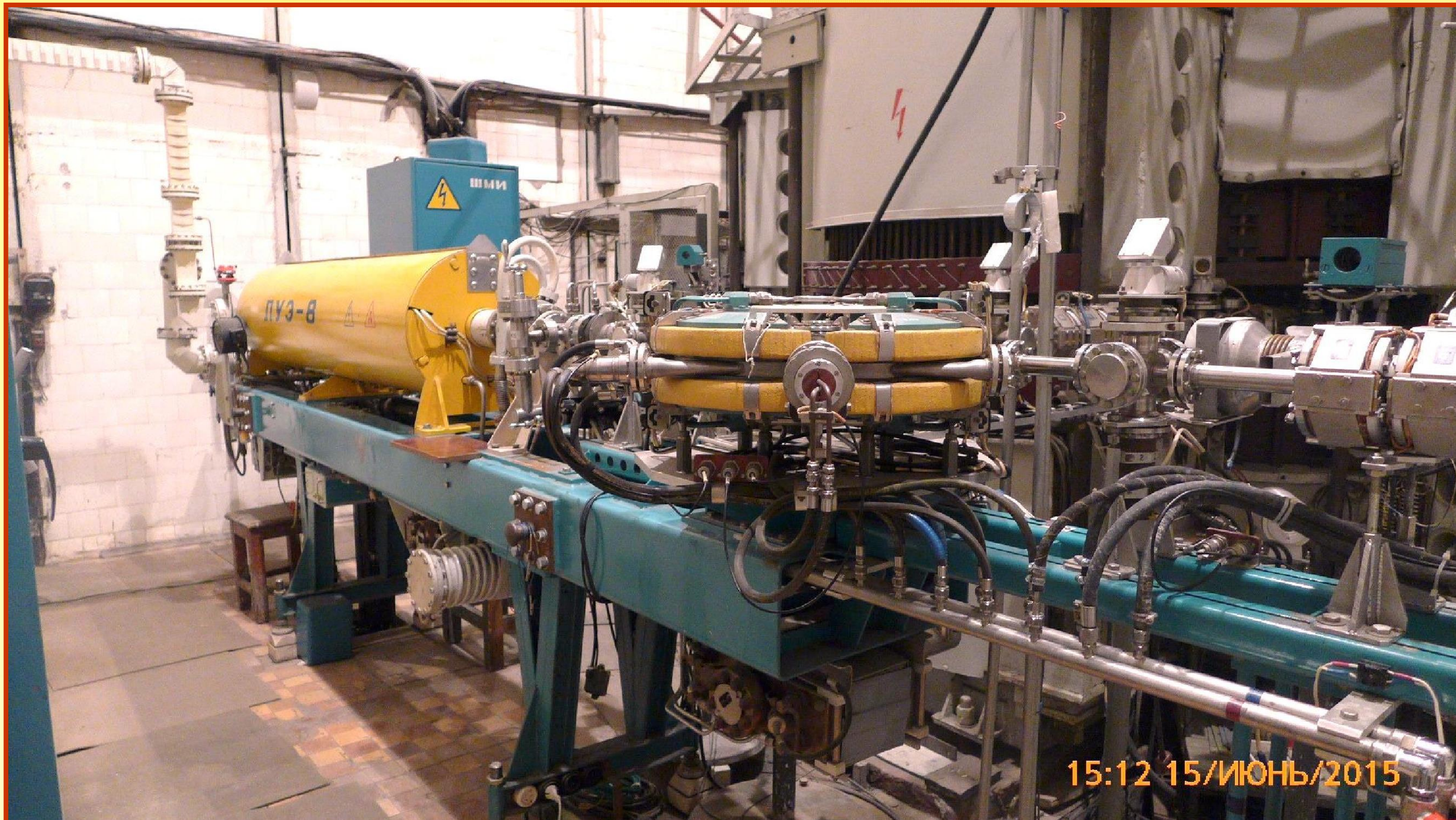
The most widely used and still used beams of bremsstrahlung γ-quanta at electron energies up to 10 MeV.

Use this method is possible and on our LUE-8 accelerator.

The remaining methods are mainly used at high electron energies.

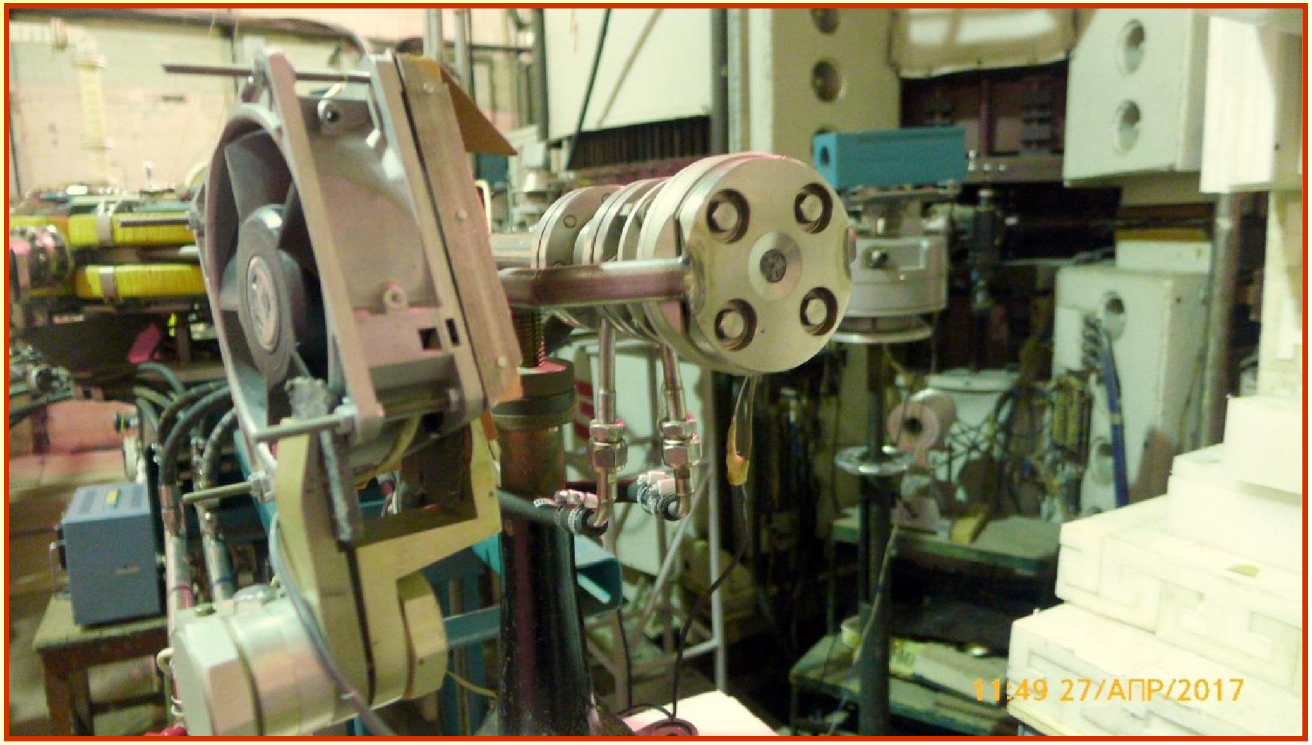
LUE with photoneutron source

Electron Linac LUE-8-5 INR RAS



The energy of accelerated electrons	**4 – 9.5 MeV**
Frequency of repetitions	**to 600 Hz**
Pulse width	**3 μs**
The average electron current at a frequency of 50 Hz	**40-50 μA**

W - e-γ - Conversion Target



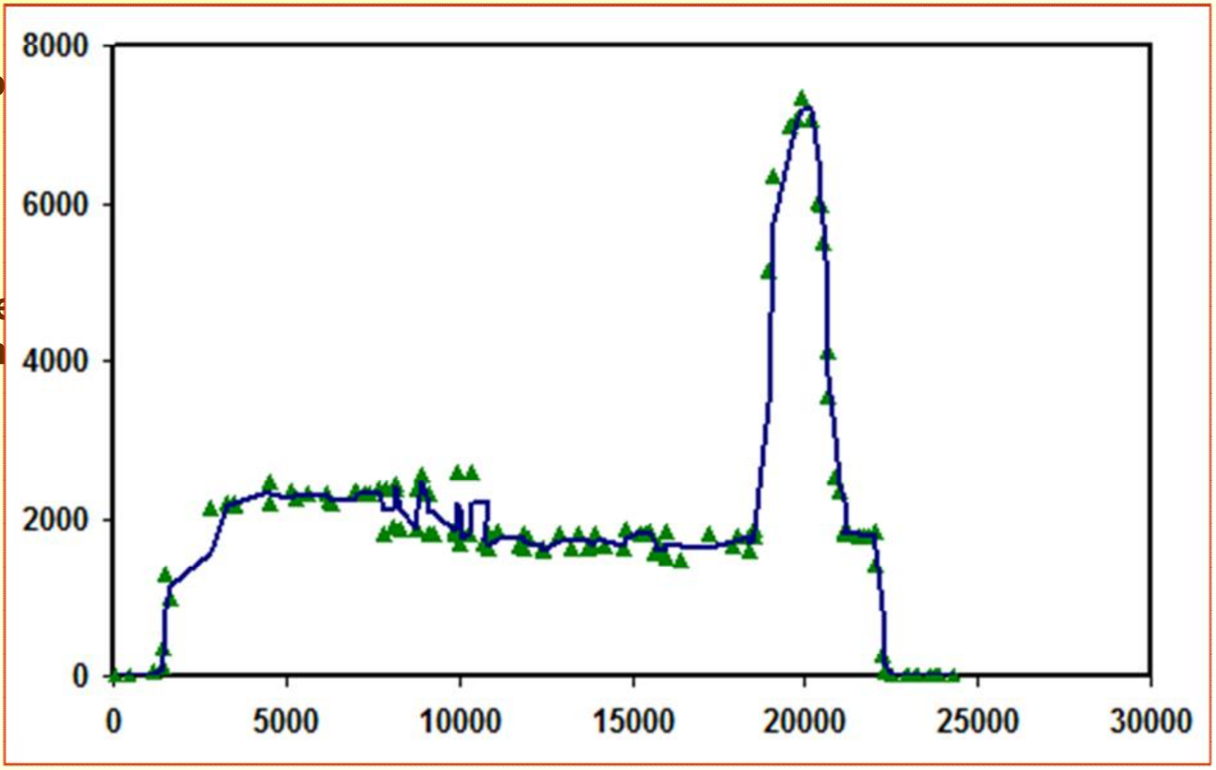
Conversion W target - 0.4 mm thick

Method of measurements - Beam energy profile

The energy distribution of the electrons in the beam was determined using a magnetic spectrometer consisting of two 135-degree magnets, which made it possible to rotate the beam 270 degrees.

The spectrometer was calibrate with a magnetometer based on Hall sensor.

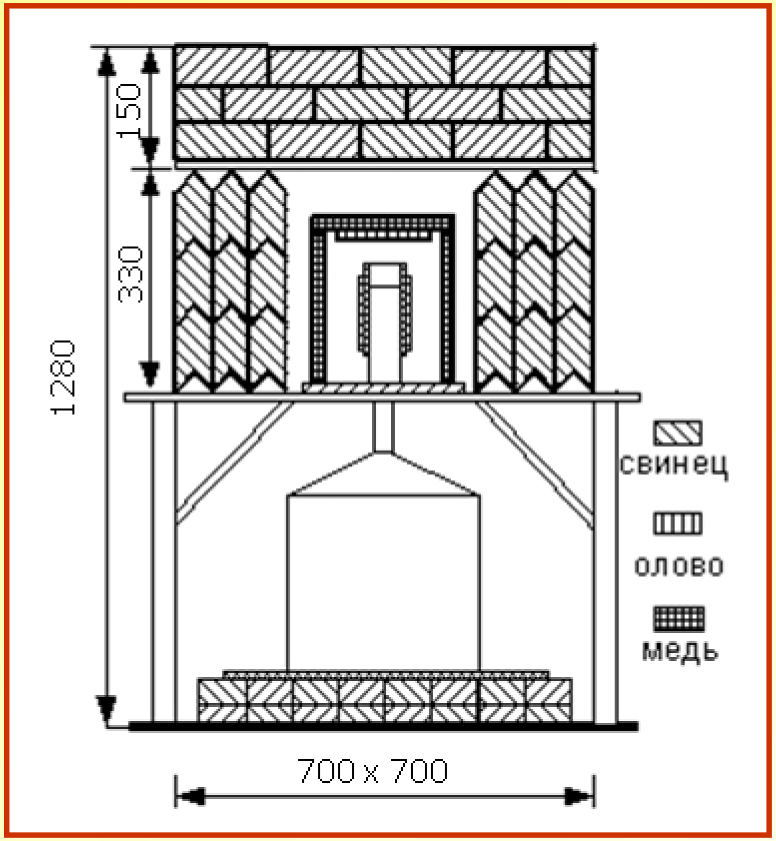
Current of the beam, arb.

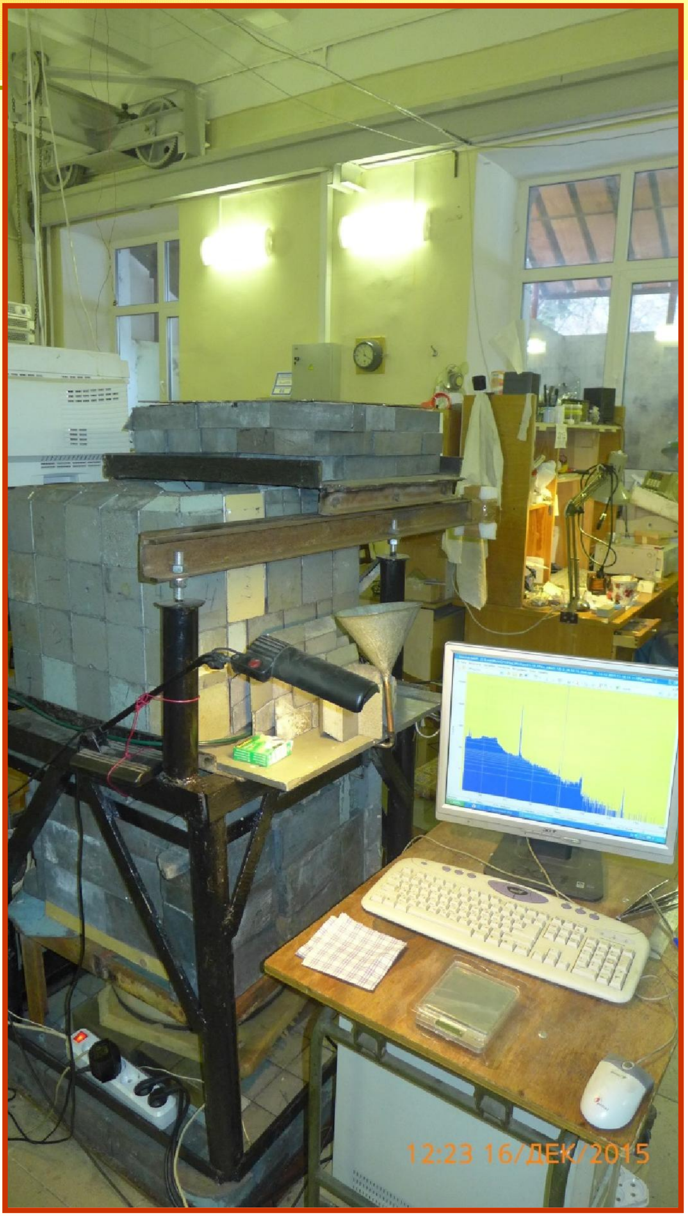


Magnet current, arb.

The instantaneous values of the beam current and the control magnet current were digitized with visualization in the form of a two-dimensional "beam current-magnet current" diagram on the computer screen. This allows on-line fine-tuning and operational control of the beam energy of the accelerator

Low-background γ-spectrometer chamber





Low-background camera of a gamma spectrometer based on a detector of High Purity Germanium with "passive" protection (protective upper part is shifted to set the sample)

Method of measurements - Activation method

The peak area of the i-th radionuclide in the gamma spectrum of the activated sample is represented as S_i:

$$S_i = \frac{m_i g_i N_A p_i a_i}{M_i \lambda_i} J_i E(t_{\text{а}}, t_{\text{в}}, t_{\text{и}}),$$

где J_i — скорость реакции:

$$J_i = \int_0^{\infty} \sigma_i(E)\Phi(E)\,dE,$$

$$E(t_{\text{а}}, t_{\text{в}}, t_{\text{и}}) = (1 - e^{-\lambda_i t_{\text{а}}})e^{-\lambda_i t_{\text{в}}}(1 - e^{-\lambda_i t_{\text{и}}}),$$

$\sigma_i(E)$ – cross-section of the nuclear reaction as a function of the energy of the incident photon E;

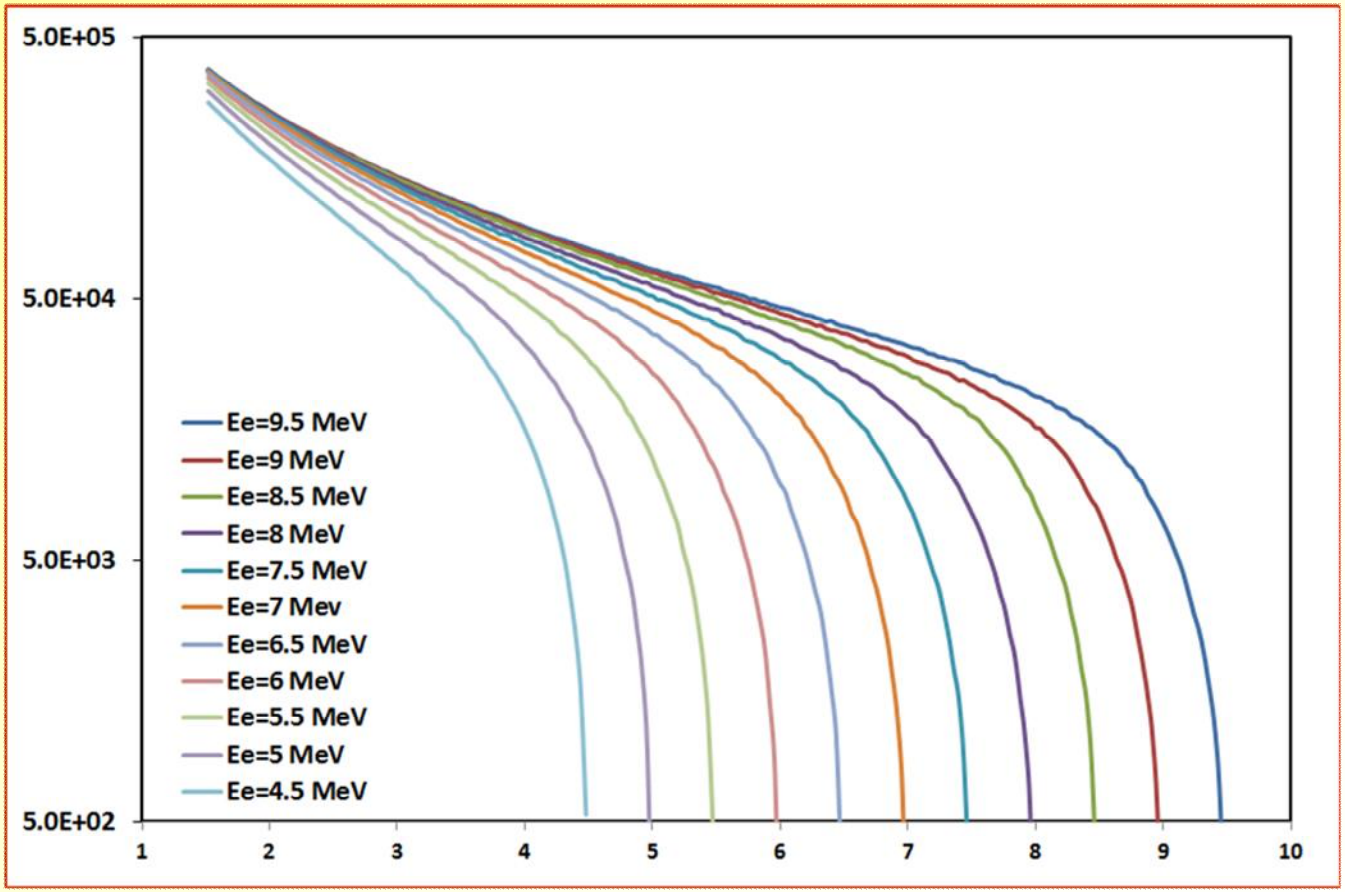
$\Phi(E)$ – gamma radiation flux spectral density;

$t_{\text{а}}$ – activation time;
$t_{\text{в}}$ – delay time after irradiation;
$t_{\text{и}}$ – measuring time;
λ_i – radioactive decay constant

Quasi-monochromatization of the photon spectrum

- **The distributions of the bremsstrahlung photon spectra were obtained using the GEANT program for a number of electron energies.**
- **Distributions for intermediate energy values are obtained by interpolation.**
- **Construction of difference combinations of bremsstrahlung photon spectra.**
- **Extracting cross-sections, using the same combination of experimental data difference.**

Quasi-monochromatization of the photon spectrum

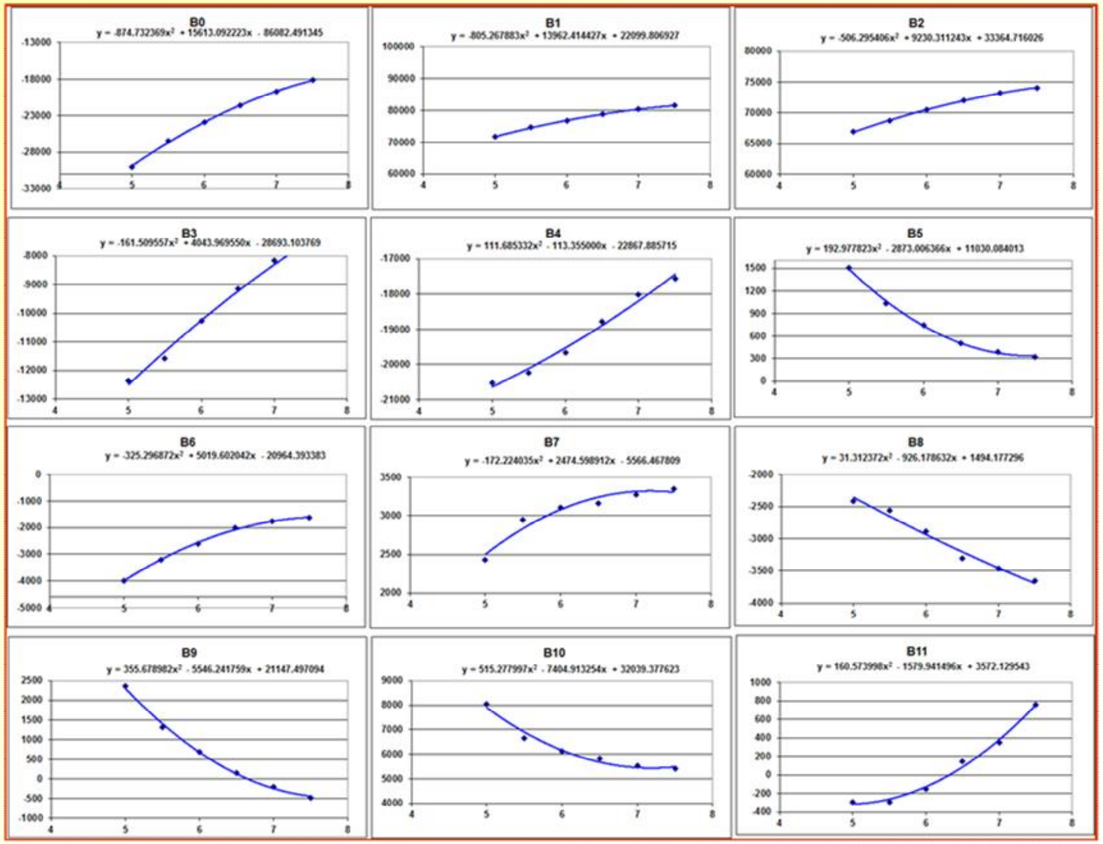


The distributions were obtained using the GEANT program for several electron energies. Distributions for intermediate points were obtained using interpolated values.

Quasi-monochromatization of the photon spectrum

Distributions for intermediate points can be obtained using interpolated values.

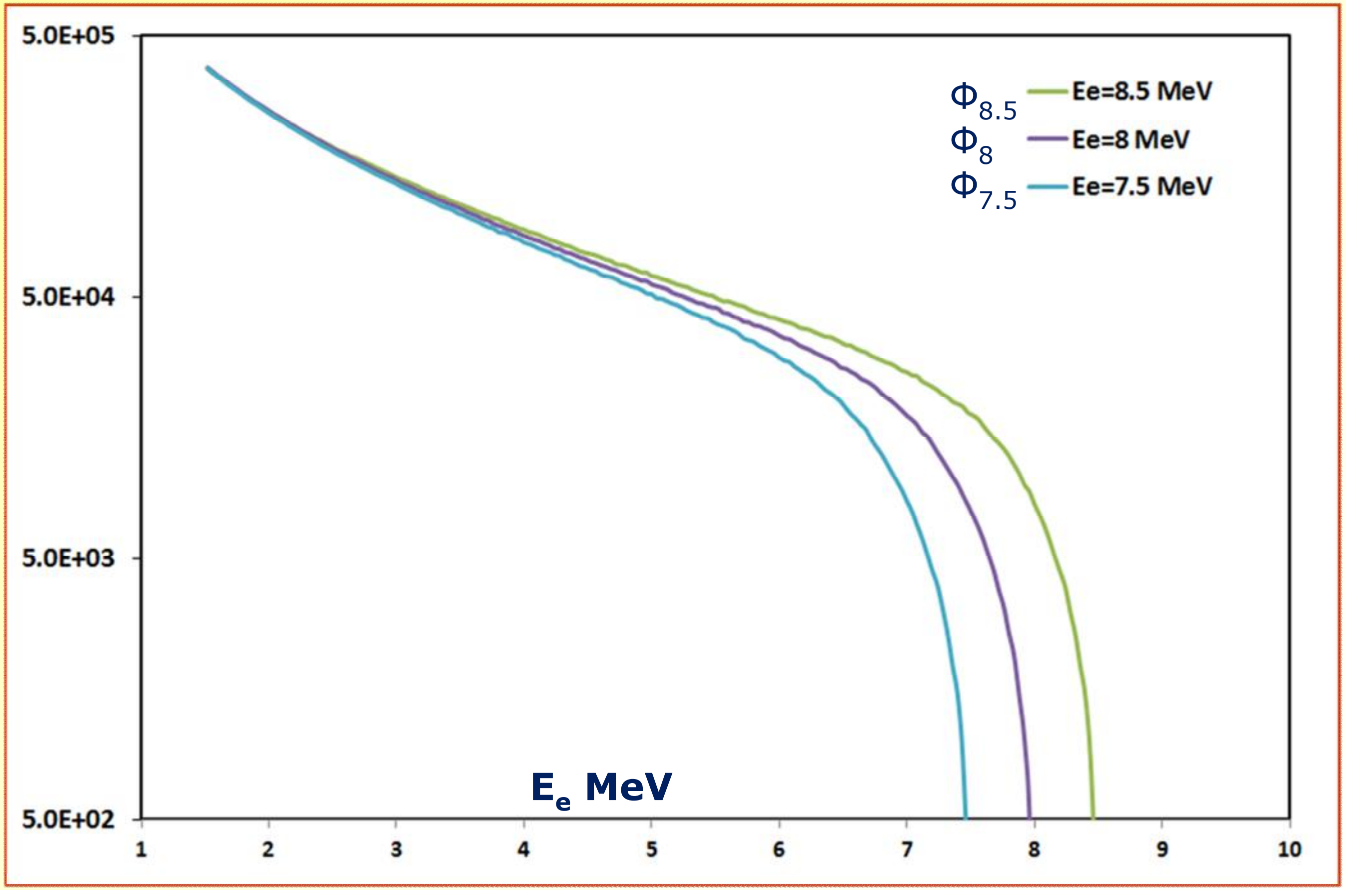
At the same time, the GEANT-modeled distributions were approximated by a set of mathematical functions fitted according to the χ^2 method, and the dependences of the expansion coefficients on the electron energy were used to calculate with arbitrary energy.



E_e MeV

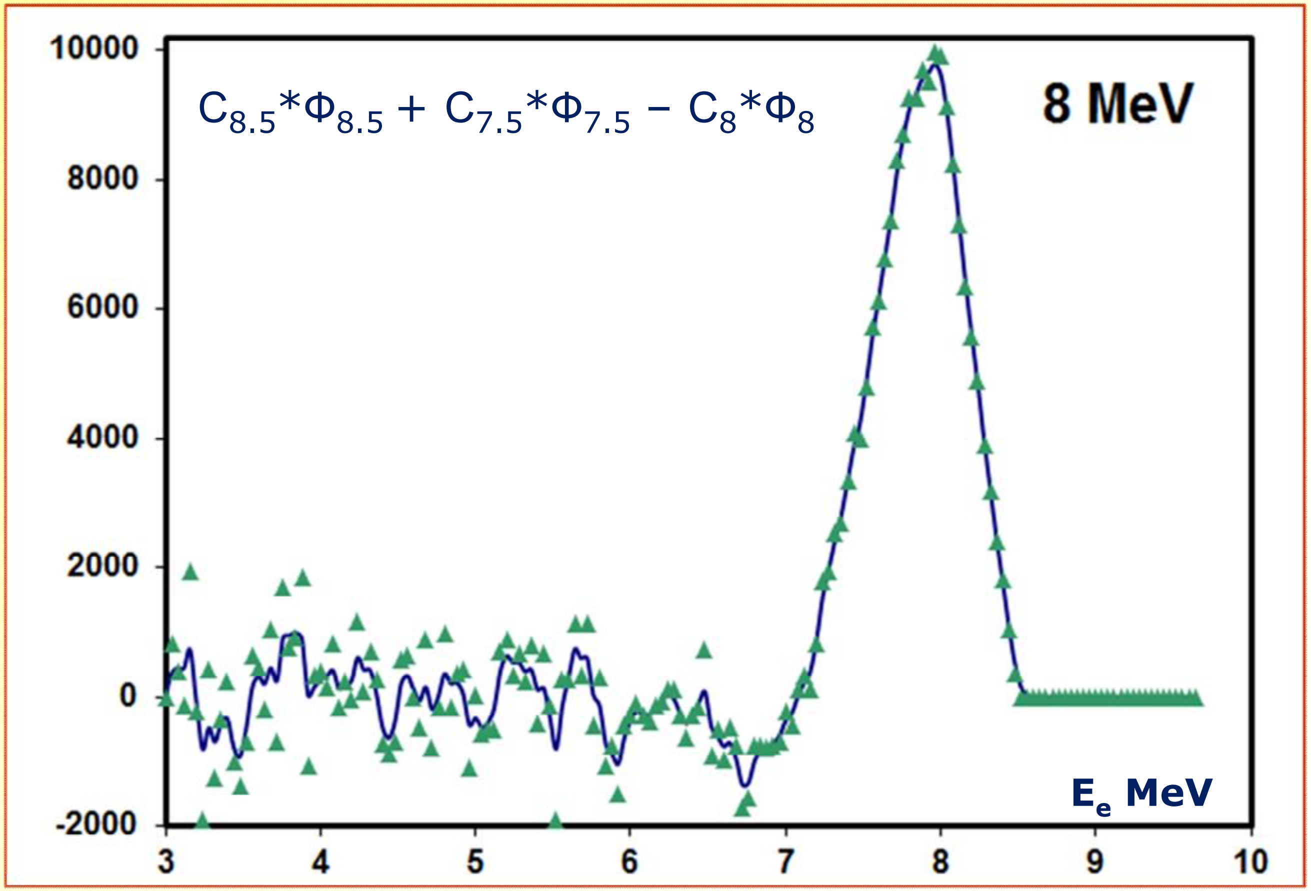
The figure shows the dependence of some parameters on the energy of electrons. It can be seen that the dependences on the energy are smooth, which allows us to hope for sufficient accuracy of obtaining photon spectra during interpolation.

Quasi-monochromatization of the photon spectrum



Suppose that the three fluxes $\Phi_{8.5}$, Φ_8 and $\Phi_{7.5}$ are calculated for the same integral of the electron beam. It was found that such coefficients, for example $C_{8.5}$, C_8 and $C_{7.5}$, can be obtained, that for all energies less than 7 MeV the combination $C_{8.5} * \Phi_{8.5} + C_{7.5} * \Phi_{7.5} - C_8 * \Phi_8$ was close to 0.

Quasi-monochromatization of the photon spectrum

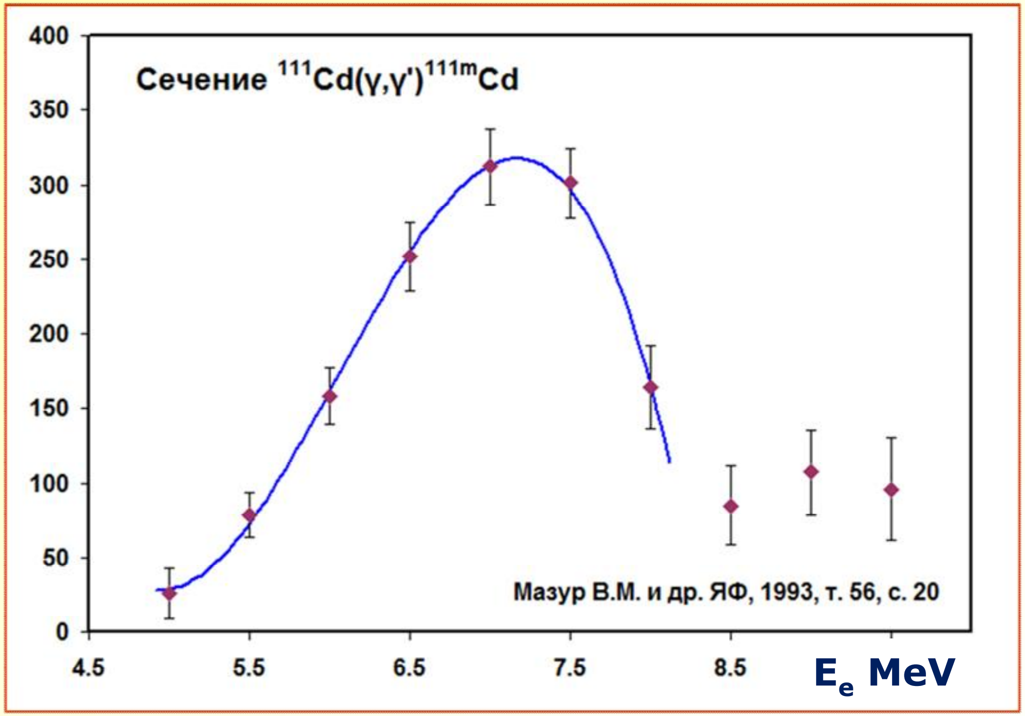


Thus, for three electron beam energies, a combination of fluxes equivalent to a beam of quasimonoenergetic photons with an average energy of 8 MeV can be obtained.

Extracting - example of modeling

If the excitation function is known, i.e. The dependence of the photonuclear cross section, for example (γ, γ ') of the photon energy, it is possible to verify the method.
To do this, we calculate the convolution of the experimental cross section and the calculated photon spectra.

Knowing the convolution integral, it is possible to obtain the measured areas of the peaks in the activation spectra for different values of the electron beam energy.



Further using the peak areas as input data, it is possible to extract the "original" excitation function using the quasi-monoenergetisation method.

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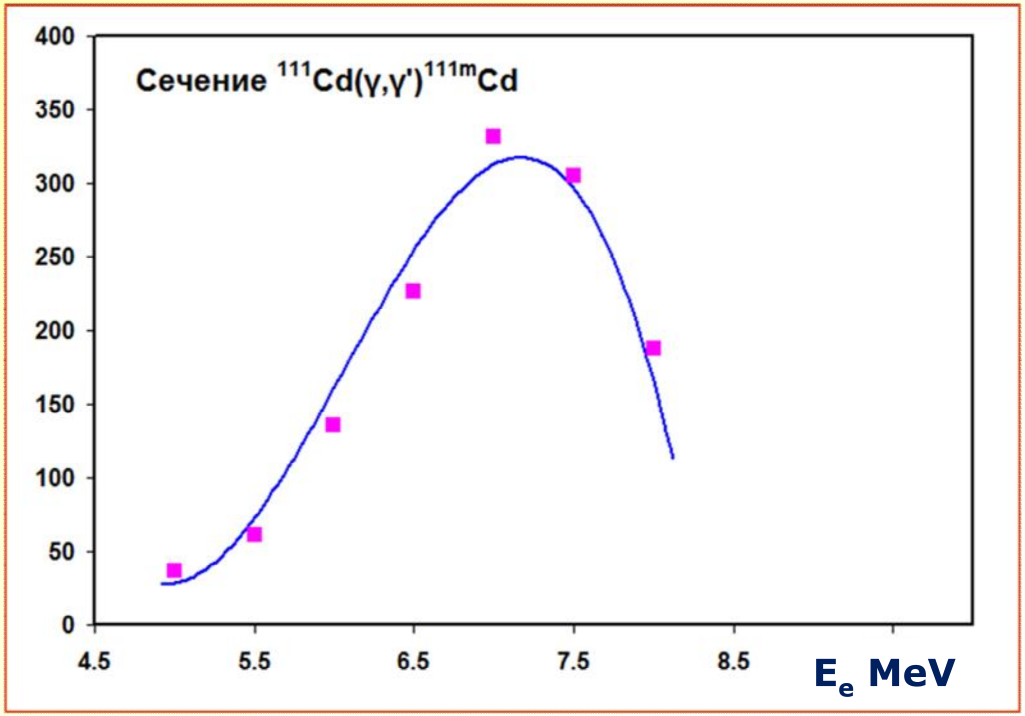

Further using the peak areas as input data, it is possible to extract the "original" excitation function using the quasi-monoenergetisation method.

Summary and conclusions

- The study of photo-nuclear reactions at low energies is an actual problem.
- In the low-energy region, new modes of giant resonances can be studied.
- Accelerators of low-energy electrons can solve such problems.
- The use of quasimonoenergetic photons makes it possible to extract data on the energy dependence of photonuclear reactions.
- Работа поддержана Российским научным фондом, грант РНФ 16-12-10039.