Investigation of properties of low-lying p-wave neutron resonances at the IREN facility
FLNP, JINR, Dubna

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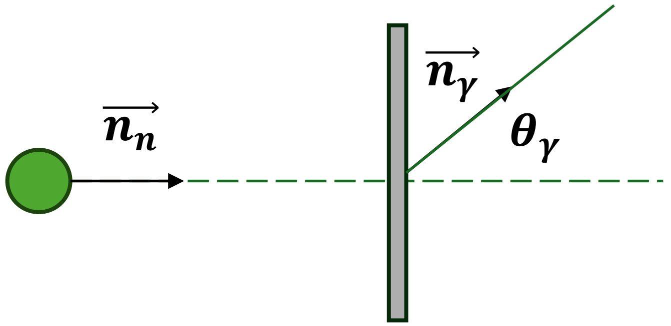
Determination of partial neutron widths, $\Gamma^{n}_{p,1/2}$ and $\Gamma^{n}_{p,3/2}$, in two-component neutron resonance from angular distributions of gamma quanta emitted in radiative neutron capture process

The $\Gamma^{n}_{p,1/2}$ value supports an important role in P-odd asymmetry in transmission of neutrons. In this connection, in FLNP, JINR experimental investigations of forward-backward asymmetry and right-left asymmetry of gammas from (n, γ) reaction were started to discover P-even $(\vec{n}_n\vec{n}_\gamma)$ and $(\vec{s}_n[\vec{n}_n\vec{n}_\gamma])$ correlations.



Nuclide	p-resonance	$\Gamma^{p}_{n\,1/2}/\,\Gamma^{p}_{n}$ F-B	$\Gamma^{p}_{n\,1/2}/\,\Gamma^{p}_{n}$ R-L	$\Gamma^{p}_{n\,1/2}/\Gamma^{p}_{n}$ anisotropy
^{117}Sn	1.33 эВ	0.33 ± 0.02 Dubna	0.27 ± 0.03 Dubna	0.18 ± 0.08 Dubna
^{113}Cd	7 эВ	0.951 Dubna		0.84 ± 0.07 Dubna
^{111}Cd	4.56 эВ			0.33 ± 0.07 Dubna
^{93}Nb	35.8 эВ			0.70 ± 0.08 BNL
	42.2 эВ			0.27 ± 0.17 BNL
	94.3 эВ			0.84 ± 0.13 BNL

Differential cross section of (n, γ) reaction for a flux of unpolarized neutrons can be presented as [1]:

$$\frac{d\,\sigma(\vec{n_\gamma},\lambda)}{d\,\Omega} = \frac{1}{2}\left\{a_0 + a_1(\vec{n_n}\,\vec{n_\gamma}) + a_3\left[(\vec{n_n}\,\vec{n_\gamma})^2 - \frac{1}{3}\right]\right\} =$$
$$= \frac{1}{2}\left\{a_0 + a_1\cos\theta_\gamma + a_3\left(\cos^2\theta_\gamma - \frac{1}{3}\right)\right\}$$

The coefficients for the correlations, a_0, a_1, a_3 are as follows:

$$a_0 = |U_1|^2 + |U_2|^2;\ a_1 = Re(U_1U_2^*)(-2x + 1.414y);\ a_3 = |U_2|^2(-1.061\cdot 2\cdot x\cdot y - 0.75y^2),$$

where $x = \sqrt{\frac{\Gamma^{n}_{p,j=1/2}}{\Gamma^{n}_{p}}}$, $y = \sqrt{\frac{\Gamma^{n}_{p,j=3/2}}{\Gamma^{n}_{p}}}$, $x^2 + y^2 = 1$.

The quantities U1 and U2 depend on the neutron energy and include the parameters of the s- and p-wave resonances.

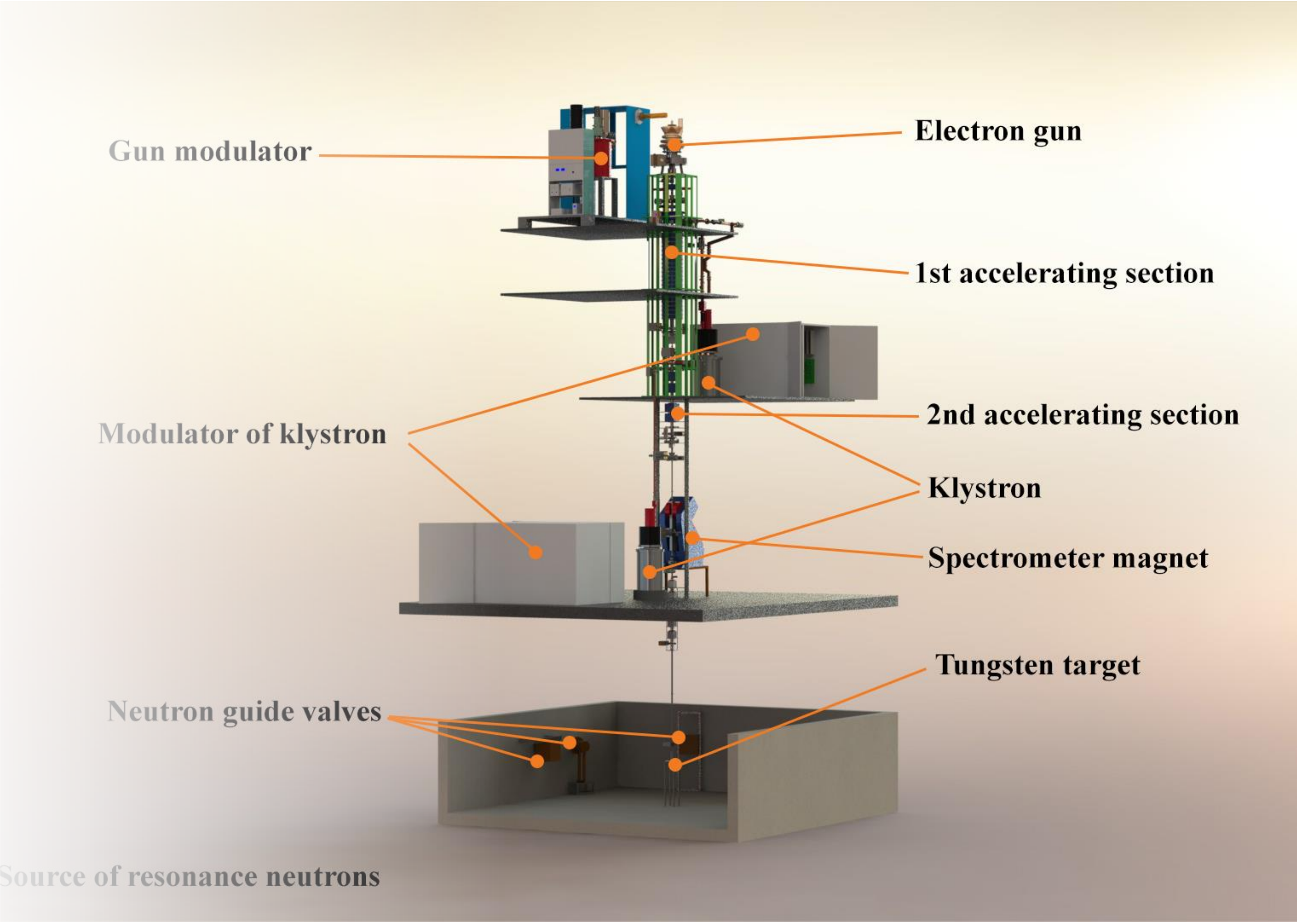
1. Flambaum V. V., Sushkov O. P., Nucl. Phys., A435, 1985, 352.
2. Barabanov A. L., Sharapov E. I., Skoy V. R., Frankle C. M., Testing T-odd, P-even interactions with gamma rays from neutron p-wave resonances. Phys. Rev. Lett., 1993, v. 70, iss. 9, p. 1216.

IREN Facility is resonance neutron source of the Frank Laboratory of Neutron Physics of JINR

Basic parameters

Maximum emission current (A)	1.8
Repetition rate (Hz)	25, 50
Electronic pulse duration (ns)	100
Electron energy (MeV)	110
Beam power (kW)	1.2
Neutron yield (n/s)	$2 \cdot 10^{12}$

Target Material W: 90%, Ni: 7%, Fe: 1.5%, Co: 1%



picture is from website FLNP

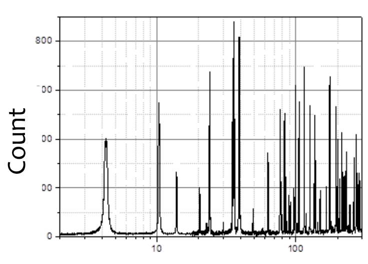
Determinations of resonance and thermal neutron fluxes, energy resolution function and dependence of flux on neutron energy for 11-meter flight pass (4^{th} channel) of the IREN facility

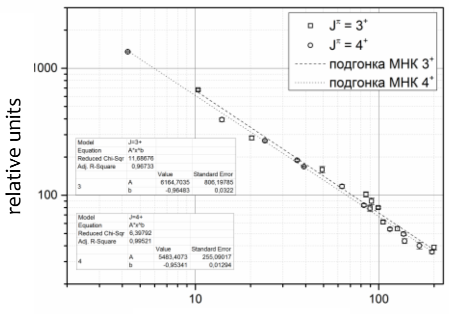
The thermal and resonance neutron fluxes, an energy dependence of the neutron flux and the resolution function are experimentally obtained. The experimental characteristics of the IREN facility are confirmed by Monte Carlo calculations.

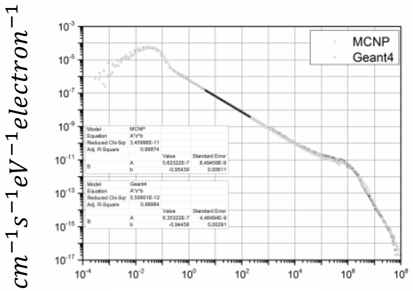
Thermal and resonance neutron fluxes measured by gold foil activation at channels No. 4. The resonance neutron flux is given at 1 eV.

Channel №4	
$\Phi_{th}, \frac{\mathrm{n}}{\mathrm{cm}^2 \cdot \mathrm{s}}$	$\Phi_{res}, \frac{\mathrm{n}}{\mathrm{cm}^2 \cdot \mathrm{s} \cdot \mathrm{eV}}$ c
(2.78±0.06) ·10^4	(1.58±0.05) ·10^4

The energy dependence of the neutron flux was determined by γ-quanta yield in neutron radiation capture in ^{181}Ta.







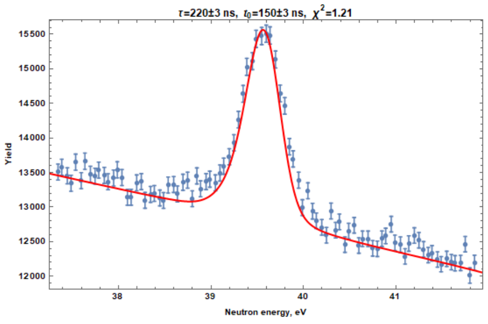
$$f(E_n) \sim \frac{1}{E_n^{1-\alpha}}$$ α=0.0453±0.0042

The parameters of the energy resolution function, t_0 and τ, were extracted from the experimental yield of γ-quanta in neutron radiation capture.

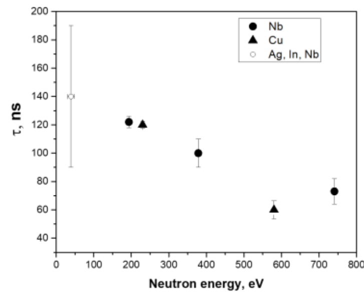
$$Y_{\gamma exp} = \int R(E,E')Y_\gamma(E')dE'$$

The resolution function of the setup according to [1] is

$$R(E,E') = \begin{cases} 0, & E' < E - \varepsilon_0; \\ \frac{1}{\varepsilon_0}\left(1 - e^{-t_0/\tau} \cdot e^{-\frac{E'-E}{\tau \cdot W}}\right), & E - \varepsilon_0 \le E' \le E; \\ \frac{1}{\varepsilon_0}\left(1 - e^{-t_0/\tau}\right) \cdot e^{-\frac{E'-E}{\tau \cdot W}}, E' > E, \text{где } \varepsilon_0 = \frac{2 \cdot t_0 \cdot E^{3/2}}{72.3 \cdot L}, W = \frac{2 \cdot E^{3/2}}{72.3 \cdot L}, & \end{cases}$$



Yield of γ-quanta in $^{115}In(n,\gamma)$ reaction, resonance 39.6 eV.

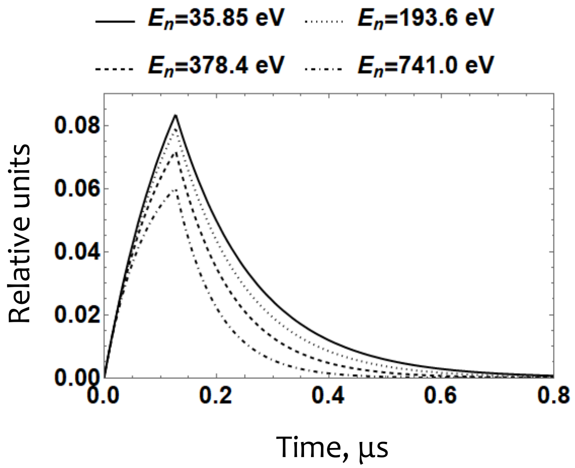


Dependence of τ parameter on neutron energy

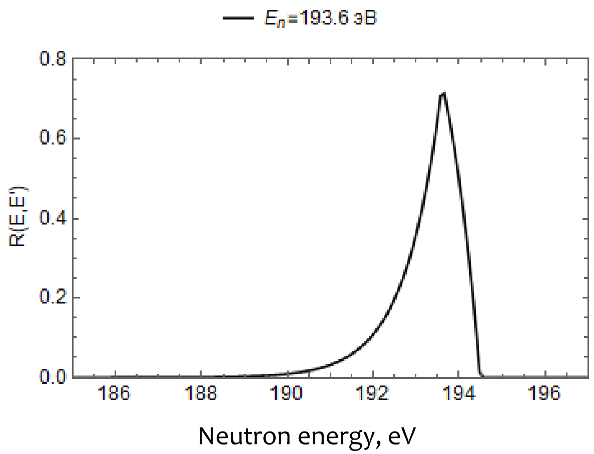
[1] A. B. Popov, I. I. Shelontsev, N. Yu. Shirikova, Calculation of neutron resonance parameters. JINR Communication 3–9742, Dubna, 1976.

Determinations of resonance and thermal neutron fluxes, energy resolution function and dependence of flux on neutron energy for 11-meter flight pass (4^{th} channel) of the IREN facility

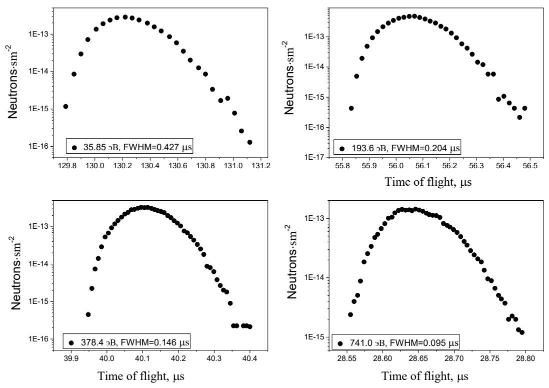
Neutron pulses of the IREN facility of different energies, constructed using , t_0 and τ, obtained from niobium resonances.

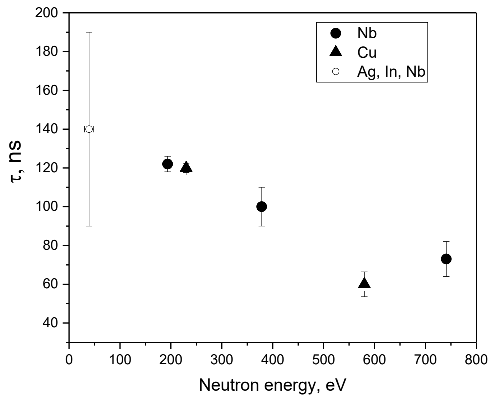


Energy resolution function of the installation located on the 11-meter flight pass of the IREN for neutrons with an energy of 193.6 eV, calculated with experimental parameters.



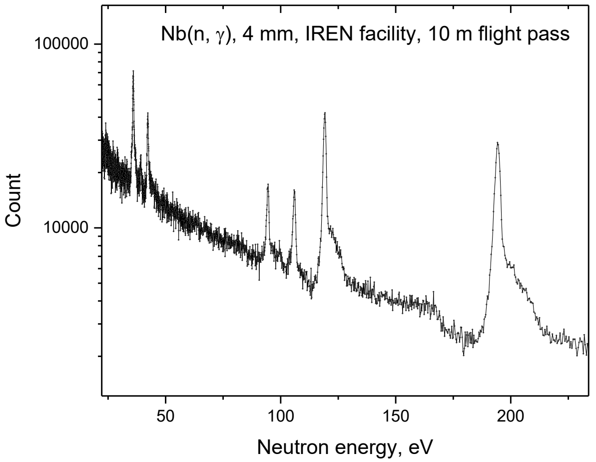
Calculated time distribution of neutrons of a certain energy. From left to right, resonances are 35.85 eV, 193.6 eV, 378.4 eV, 741.0 eV.



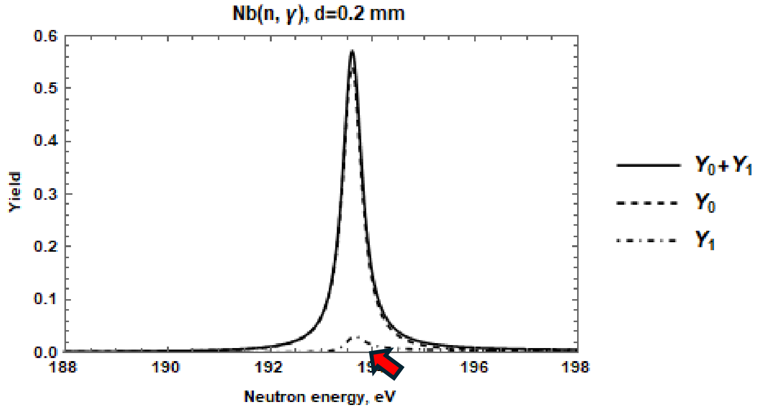


Systematic errors in measuring of angular correlations in (n, γ) reactions. Contribution from scattered neutrons.

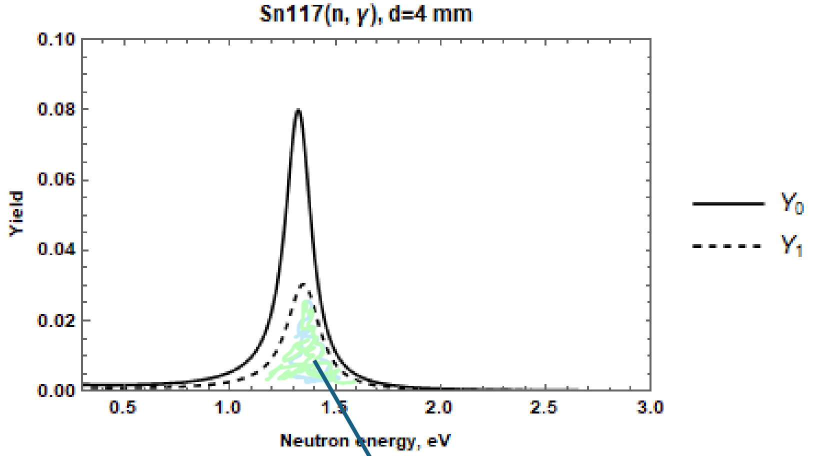
Scattering (single, multiple) of neutrons before capture in the investigated target always distorts the shape of neutron-capture resonances measured with the time-of-flight technique. There are difficulties for a choice of the sample thickness to minimize an undesirable distortion of the desired anisotropy effect.



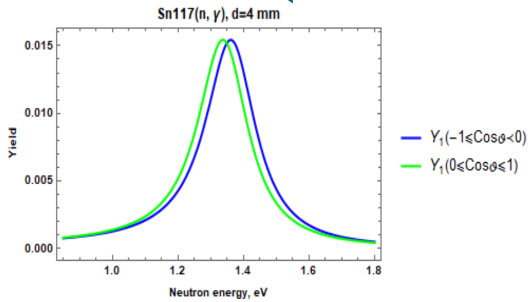
Experimental spectrum of $Nb(n,\gamma)$ reaction.



γ-quanta yield in resonance neutron capture in niobium considering single neutron scattering.



γ-quanta yield in resonance neutron capture in tin considering single neutron scattering.



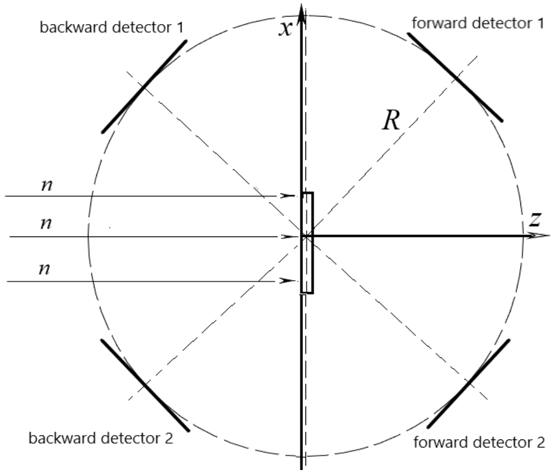
$$E' = E \cdot \frac{m^2}{(M+m)^2}\left(\cos\theta + \sqrt{\left(\frac{M}{m}\right)^2 - \sin^2\theta}\right)^2$$

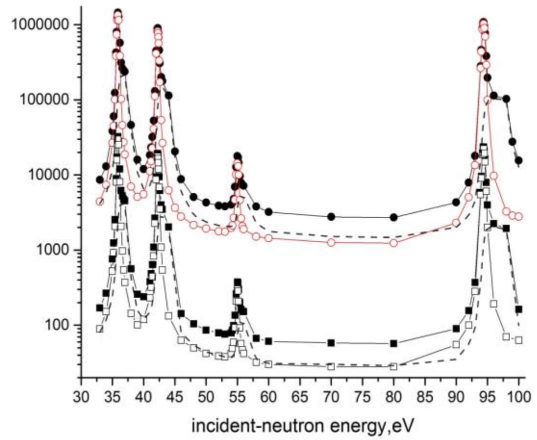
The position of the peak of γ-quanta emitted in the capture of a neutron after scattering depends on the ratio of the mass of the target nucleus M and neutron m, the energy of the incident neutron E, neutron scattering angle θ.

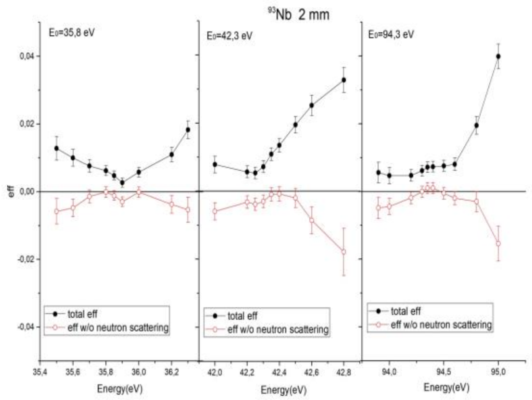
Monte-Carlo evaluations of low-energy neutron radiative capture in Nb targets and γ-quanta forward-backward asymmetry caused by geometry and kinematics

For a correct analysis of the experimental forward-backward anisotropy of gammas to obtain the statistically significant value, it is need to establish and consider the asymmetries which distort counts of the detectors and inevitably contribute to the required spatial anisotropy.

The forward-backward asymmetry of detected gammas $\boldsymbol{\varepsilon(E)} = \frac{N_{1f}(E)+N_{2f}(E)-N_{1b}(E)-N_{2b}(E)}{N_{1f}(E)+N_{2f}(E)+N_{1b}(E)+N_{2b}(E)} = \frac{N_{forw}(E)-N_{bacw}(E)}{N_{forw}(E)+N_{bacw}(E)}$







- γ-quanta are recorded by 4 detectors placed at R=20 cm distance from the center of the target at the angles 45°, 135°, 225° and 315°;
- the entry windows of the detectors: 6.5 cm in width and 7.6 cm in height.

The target must be thick enough for desirable high yield of gammas (for a high statistical accuracy).

The target may be as thin as possible for minimization of an undesirable distortion of the required forward-backward γ-asymmetry.

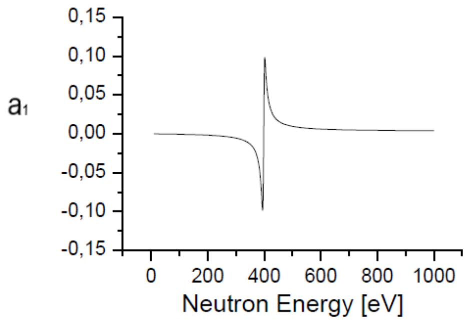
An optimum alternative must be found

Investigation of low-energy p-wave resonances of ^{93}Nb and 397.8 eV p-wave resonance of ^{35}Cl nucleus at the IREN facility, FLNP, JINR

The property of resonances that allows us to extract partial neutron widths is forward-backward asymmetry of γ-quanta angular distribution $a_1(E) = \frac{\sigma(\theta,E)-\sigma(\pi-\theta,E)}{\sigma(\theta,E)+\sigma(\pi-\theta,E)} \sim \frac{N(\theta)-N(\pi-\theta)}{N(\theta)+N(\pi-\theta)}$

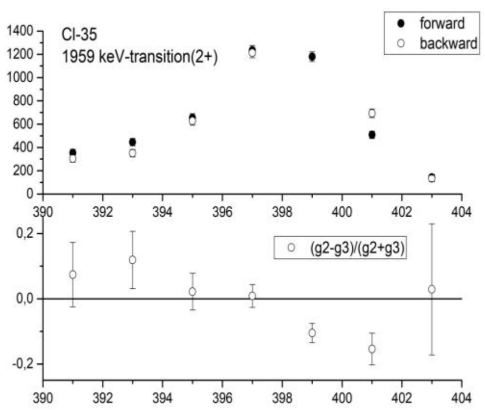
$Cl_{17}^{35} + n \rightarrow Cl_{17}^{36*} \rightarrow Cl_{17}^{36} + \gamma$ transition 2 -> 2

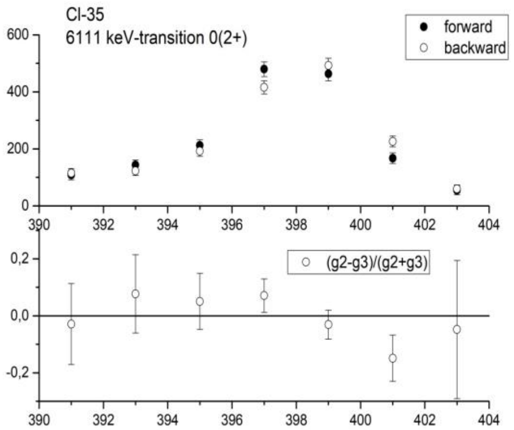
$J_S^{\Pi} = 2^+; I = \frac{3}{2}^+; I' = 2^+; l_n = 0,1; j_n = \frac{1}{2}, \frac{3}{2}; j_\gamma = 1; l_\gamma^S = 1,2; l_\gamma^P = 1,2$



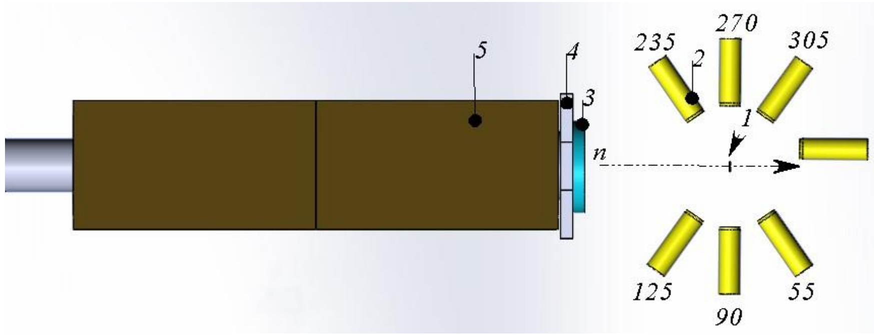
A. Yergashov, S. B. Borzakov, C. Hramco, Yu. N. Kopatch, V. L. Kuznetsov, S. T. Mazhen, L. V. Mitsyna, A. I. Oprea, C. Oprea, N. V. Rebrova, P. V. Sedyshev, N. V. Simbirtseva, Investigation of Low-Energy p-Wave Resonances in ^{93}Nb (n, γ) Reaction at the IREN Facility, JINR, ISINN-30.

Experimental forward-backward asymmetry of γ-quanta angular distribution for a $CaCl_2$ target, Ø = 8 cm, thickness 3 cm thick, region of 398 eV p-wave resonance of ^{35}Cl(n, γ)





Prototype of installation for the measurement of the angular distribution of γ-quanta from (n, γ) – reaction: 1-sample, 2-BGO detectors, 3-Pb collimator, 4-Pb shielding, 5-shielding of neutron guide.



The upper figures show the counts of the "forward" and "backward" detectors for 7 energy intervals, and the lower figures show the count ratio $\frac{N_{forward}(E)-N_{backward}(E)}{N_{forward}(E)+N_{backward}(E)}$. Statistical errors calculated considering the subtracted backgrounds.

Thank you for your attention!

1. Okudaira T., Takada S., Hirota K. et al., Angular distribution of gamma-rays from neutron-induced compound states of ^{140}La. - Phys. Rev. C, 2018, v. 97, 034622, 15 pp.
2. Okudaira T., Shimizu H.M., Kitaguchi M., Hirota K., Haddock C.C. et al., Measurement of the angular distribution of γ-rays after neutron capture by ^{139}La for a T-violation search. - EPJ Web Conf., 2019, v. 219, 09001.
3. Endo S., Shimizu H.M., Kitaguchi M., Katsuya H., Yamamoto T. et al., Measurement of the angular distribution of γ-rays emitted from the compound state after neutron capture by ^{81}Br for a search of T-violation. - EPJ Web Conf., 2019, v. 219, 09003.
4. Koga J., Takada S., Yoshioka T., Shimizu H.M., Hirota K. et al., Measurement of the angular distribution of prompt gamma-rays emitted in the $^{117}Sn(n,\gamma)$ reaction for a T-violation search. - EPJ Web Conf., 2019, v. 219, 09004.
5. Yamamotto T., Okudaira T., Endo S. et al., Transverse asymmetry of γ rays from neutron-induced compound states of ^{140}La. Phys. Rev. C 101, 064624 (2020).
6. Okudaira T., Endo S., Fujioka H. et al., Energy-dependent angular distribution of individual γ- rays in the $^{139}La(n,\gamma)^{140}La^*$ reaction. Phys. Rev. C 104, 014601 (2021).
7. Okudaira T., Nakabe R., Auton C.J. et al., Spin dependence in the p-wave resonance of $^{139}La + n$, Phys. Rev. C 109, 044606 (2024).