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ЯДРА

A METHOD TO MEASURE NEUTRON POLARIZATION USING P-EVEN ASYMMETRY OF γ-QUANTUM EMISSION IN THE NEUTRON–NUCLEAR INTERACTION

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A new method to measure polarization of cold/thermal neutrons using P-even asymmetry in nuclear reactions induced by polarized neutrons is proposed. A scheme profiting from a large correlation of the neutron spin and the circular γ-quantum polarization in the reaction (n, γ) of polarized neutrons with nuclei is analyzed. This method could be used, for instance, to measure the neutron-beam polarization in experiments with frequently varying configuration. We show that high accuracy and reliability of measurements could be expected.

INTRODUCTION

Neutron polarization analysis is a powerful tool in neutron scattering (see, for instance, [1]) and an important component in precision measurements in particle physics [2]. Numerous methods for the neutron polarization analysis have been developed, for instance, using polarizing supermirrors [3–5] or polarized ^{3}He [6–9]. We propose a new complementary method based on P-even asymmetry in reactions of polarized neutrons with nuclei. In particular, we analyze a measurement scheme profiting from a large correlation of the neutron spin $\boldsymbol{\sigma}_n$ and the circular γ-quantum polarization in the reaction (n, γ) of polarized neutrons with nuclei. In contrast to standard methods using measurements of neutron fluxes, we use asymmetries in emission of products of nuclear reactions induced by polarized neutrons. Advantageous of this method include: short measuring time, small size needed along the neutron beam, and no need for time-consuming scans over positions, angles, and wavelength. We propose to use the integral current method to measure the polarization of intense neutron beams instead of the commonly used the method of counting single events; no attenuation and/or collimation of neutron beam is needed in our case. Potential applications include measurement/monitoring of the neutron beam polarization in experiments with frequently varying configuration, which are typical, for instance, for neutron instruments devoted to fundamental particle physics [10]: to give examples: [11–26]; applicability of this method to experiments demanding the highest precision in the neutron polarization analysis, like to precision studies of the neutron β decay [27] has to be studied.

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A METHOD TO MEASURE THE NEUTRON POLARIZATION USING P-EVEN ASYMMETRY IN THE NEUTRON–NUCLEAR INTERACTION

Angular and polarization correlations involving the neutron spin $\boldsymbol{\sigma}_n$ and momentum $\mathbf{p}_n$, the γ-quantum momentum $\mathbf{p}_\gamma$ and circular polarization λ in (n, γ) reactions have been measured in many experiments primarily for studies of the weak interaction [28–30]. Possible correlations are studied theoretically, for instance, in [31] containing an expression for the cross section of (n, γ) reaction with polarized neutrons; the expression includes 17 P-even and P-odd correlations. As we are interested only in correlations involving the γ-quantum circular polarization, we write this expression ignoring other correlations:

$$\frac{d\sigma(\mathbf{p}_\gamma, \lambda)}{d\Omega} = \frac{1}{2}\Big\{a_0 + \ldots + a_5\lambda\,(\boldsymbol{\sigma}_n\cdot\mathbf{p}_\gamma) + \\ + a_6\lambda(\boldsymbol{\sigma}_n\cdot\mathbf{p}_n) + \\ + a_7\lambda\left[(\boldsymbol{\sigma}_n\cdot\mathbf{p}_\gamma)(\mathbf{p}_\gamma\cdot\mathbf{p}_n) - \frac{1}{3}(\boldsymbol{\sigma}_n\cdot\mathbf{p}_n)\right] + \\ + a_8\lambda\left[(\boldsymbol{\sigma}_n\cdot\mathbf{p}_n)(\mathbf{p}_n\cdot\mathbf{p}_\gamma) - \frac{1}{3}(\boldsymbol{\sigma}_n\cdot\mathbf{p}_\gamma)\right] + \ldots\Big\}. \quad (1)$$

Expressions for these coefficients are rather bulky in their general form; therefore the authors of [31] illustrate the ratios between values of the coefficients considering the reaction $^{117}\mathrm{Sn}(n,\gamma)^{118}\mathrm{Sn}$, for which most complete experimental data are available. The normalized values of the coefficients $A_i = a_i/a_0$ for the considered dipole transitions are: $A_5 \sim 1$, $A_6 \sim \sim 10^{-2}$, $A_7 \sim 1.5\times10^{-2}$, $A_8 \sim 4\times10^{-5}$ for thermal neutrons with energy of ~0.01 eV (far from p resonances). The largest correlation is $a_5\lambda(\boldsymbol{\sigma}_n\cdot\mathbf{p}_\gamma)$. Thus if a polarized neutron is absorbed, then a fully circularly polarized prompt γ quantum is emitted from a compound state (dipole transition), provided the angles between the neutron spin and the γ-quantum momentum are chosen properly. Reverse of the neutron spin reverses the γ-quantum circular polarization. This observation allows us to measure the neutron polarization P_n by measuring the polarization of emitted γ quanta.

Usually the multipolarity of primary transitions from compound states in (n,γ) reactions is $M1$ ($E1$). If a polarized neutron hits a target consisting of nuclei emitting γ quanta via $M1$ ($E1$) transitions, the neutron polarization will be fully transmitted to the circularly polarized γ quanta. Noncorrected γ quantum polarization is equal to

$$\delta_{\mathrm{exp}} = 2\frac{N_\gamma^+ - N_\gamma^-}{N_\gamma^+ + N_\gamma^-}. \quad (2)$$

Here, N_γ^+ and N_γ^- are the intensities of γ quanta passed through a polarimeter for opposite neutron polarizations. The circular polarization of γ quanta P_γ corrected to the polarimeter efficiency ε equals

$$P_\gamma = P_n = \frac{\delta_{\mathrm{exp}}}{\varepsilon}, \quad (3)$$

if the γ-quantum momentum is parallel to the neutron spin.

For mixture of different transitions, sometimes with the circular polarization of both signs, the resulting value of the circular polarization might be averaged. In the counting method one could select a photo-peak, thus one can use an isotope emitting many prompt γ quanta. In contrast, in the integral method we cannot select a single γ transition; therefore the resulting value of the circular polarization would range from 0 to some δ_{max}.

In fact, the efficiency of realistic ferromagnetic γ polarimeters (magnetized iron, permendur, etc.) [32] is much smaller than unity. The probability of scattering of γ quanta in magnetized ferromagnetic materials depends on their polarization and on the ferromagnetic magnetization. For example, in iron: as γ quanta could be scattered anisotropically only on 2 polarized free electrons in the conducting band, also the total number of electrons is 28, the maximum polarimeter analyzing power cannot exceed $2/28 \approx 0.07$

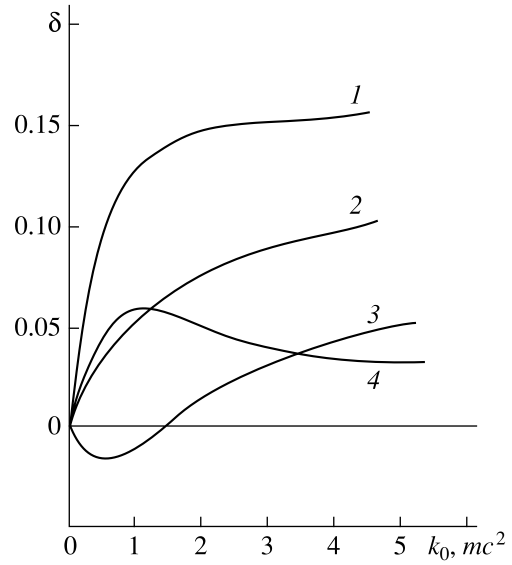

Fig. 1. Analyzing power of various polarimeters as a function of the γ-quantum energy: (*1*) a backward scattering method; (*2*) a forward scattering method (for the optimum scattering angle); (*3*) a transmission method (for the optimum polarimeter length L); (*4*) the Bird–Rouse method (for complete magnetization of a ferromagnetic material).

[32]. The analyzing power depends on a ferromagnetic material and its magnetization; therefore it has to be measured.

Consider two main methods used to measure the anisotropic scattering of γ quanta:

1. In the transmission method, one measures the intensity of the γ-quantum flux transmitted through a ferromagnetic material (containing polarized electrons) as a function of the neutron or electron polarization.

2. In the scattering method, one measures the intensity of the γ quanta scattered (forward or backward) in a ferromagnetic material as a function of its polarization.

Figure 1 is copied from [32]; it illustrates the calculated optimum analyzing powers of various polarimeters as a function of the γ-quantum energy.

One could see in Fig. 1 that the analyzing power in the transmission method is lower than that in the scattering method; also the intensity of a transmitted beam is lower than the intensity of scattered γ quanta. The best signal/background ratio is provided for the optimum sample thickness $L_{\mathrm{opt}} = = 2/(n\tau)$, where n is the number of iron atoms per volume unit, and $\tau = \tau_0 + \tau_p + \tau_c$; here, τ_0, τ_p, τ_c are polarization-independent absorption coefficients for Compton scattering, photo-effects, and pair production, respectively. For totally magnetized iron,

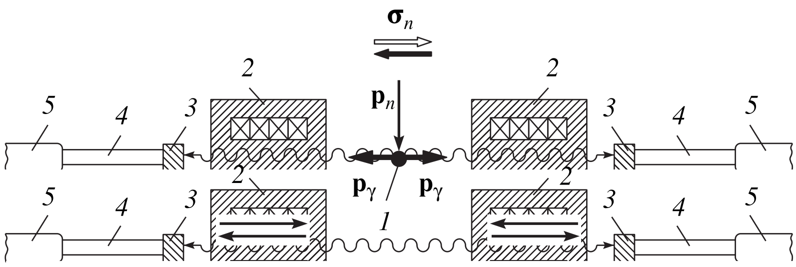

Fig. 2. A scheme to measure the neutron polarization: (*1*)—target; (*2*)—polarimeter; (*3*)—scintillation crystal; (*4*)—light guide; (*5*)—photomultiplier. Arrows below indicate directions of magnetization of the polarimeters.

the optimum thickness equals $L_{\rm opt} \sim 4{-}7$ cm for γ quanta with the energy of 2–7 MeV.

In the transmission method, the energy of transmitted γ quanta is equal to the initial γ-quantum energy, in contrast to the scattering method. Therefore we could select a narrow γ line, thus highly improving the signal/background ratio. That is why we chose the transmission method for further analysis. Keeping in mind the energy dependence of the polarimeter analyzing power in the transmission method, see *3* in Fig. 1, one favors large γ-quantum energy. In order to increase the correlation $\lambda(\boldsymbol{\sigma}_n \cdot \mathbf{p}_\gamma)$ (see Eq. (1)), we have to set the neutron spin parallel to the γ-quantum momentum.

Evidently, in order to get the maximum correlation $\lambda(\boldsymbol{\sigma}_n \cdot \mathbf{p}_\gamma)$ we should set the angle between the ferromagnetic polarization axis and the γ-quantum momentum equal to 0° (180°); the angle between the neutron spin and the γ-quantum momentum should be equal to 0° (180°). The correlation for the angle 0° is opposite in sign to that for the angles 180°. We do not consider reverse of the polarimeter magnetization axis, as it might strongly influence the γ detectors. We will reverse the neutron spin, using, for instance, radio-frequency spin-flippers.

A corresponding scheme to measure the neutron polarization is shown in Fig. 2. A magnet in Fig. 2 is magnetized parallel or anti-parallel to the γ-quantum momentum; change in the count rate due to reverse of the neutron spin is proportional to the γ-quantum polarization. The γ quanta could be measured in germanium semiconductor detectors or using NaI(Tl), CsI(Tl) crystals with high γ-quanta efficiency in integral or counting modes. Light-guides allow transporting light out of strong magnetic fields of the polarimeters.

Let us estimate the accuracy of such a measurement. The whole setup should be rigidly assembled together (including neutron and γ shielding); in this case precision of setting the ferromagnetic magnetization axis relative to the γ-quantum momentum is not relevant. Mechanical precision of setting the target relative to the neutron beam is not relevant as well. Displacement of the setup by 1 cm perpendicular to the neutron momentum changes the solid angle by ~0.02; therefore it could produce a sizeable false effect in one detector. However, as the measuring scheme presented in Fig. 2 is complemented by a symmetric (mirror) setup on the other side of the neutron beam, the corresponding false effects in opposite detectors would be of opposite sign and therefore they could be subtracted. In order to avoid uncertainty concerning the angle between the neutron spin and the polarimeter magnetization axis, one has to find experimentally the angle corresponding to the maximum γ-count rate. To summarize: systematic uncertainties caused by geometric effects are expected to be at least smaller than 10^{-2}. Statistical uncertainty would be negligible.

Concerning eventual target in a neutron beam: For the counting method, the choice of a target material is not very constrained as one could select a photopeak, provided it corresponds to a prompt $M1$ ($E1$) γ transition emitted from a state with the spin $J > 1/2$ (as values of all even correlations for $J = 1/2$ are equal to zero in first approximation). For the integral method, assuming measurement of all γ quanta, one favors a (n, γ) reaction with a single γ transition. The optimum target would be that consisting of natural lead although it consists of several isotopes.

The circular polarization of γ quanta in the reaction $^{207}{\rm Pb}(n, \gamma)^{208}{\rm Pb}$ has been measured in [29]. The compound state spin is $J = 1$; it transfers to the ground state $J = 0$ via the dipole transition with the energy $E_\gamma = 7.37$ MeV. The authors of [29] used a transmition polarimeter made of permendur with a thickness of 90 mm; the magnetic induction was equal to 20.5 kG. The γ detectors were crystals NaI(Tl) with a diameter of 150 mm and a height of 100 mm, operated in the counting mode. The asymmetry in the total absorption line was equal to $|\delta| = (4.18 \pm 0.04) \times 10^{-2}$ [29]; the neutron polarization was higher than 96%. The asymmetry in the same installation using the integral method and complete γ-quantum spectrum was equal to $|\delta| = (2.3 \pm 0.1) \times \times 10^{-2}$ [30]. Thus for complete spectrum of γ quanta emitted from a target of natural lead, the asymmetry decreases only twice compared to that measured using the counting method. Therefore one could use both the integral method and the counting method to measure the circular polarization of γ quanta emitted from a target of natural lead.

As any absolute measurements including measurements of the polarimeter material magnetization are not quite precise, such a device should be "calibrated" in advance using standard precision methods, for instance, with polarized ^{3}He. Ultimate precision and stability of such a polarimeter should be studied in dedicated experiments.

CONCLUSIONS

We have described a new method to measure the polarization of cold and thermal neutrons using P-even asymmetry in the reactions of polarized neutrons with nuclei. We analyze a scheme using large correlation of the neutron spin and the circular γ-quantum polarization in the reaction (n, γ) of neutrons with nuclei; in particular, we consider targets of natural lead. We show that high accuracy and reliability of measurements is expected.

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МЕТОД ИЗМЕРЕНИЯ ПОЛЯРИЗАЦИИ НЕЙТРОНОВ С ИСПОЛЬЗОВАНИЕМ P-ЧЕТНОЙ АСИММЕТРИИ ВЫЛЕТА γ-КВАНТОВ В НЕЙТРОН-ЯДЕРНОМ ВЗАИМОДЕЙСТВИИ

Ю. М. Гледенов, В. В. Несвижевский, П. В. Седышев, Е. В. Шульгина, В. А. Весна

Предлагается новый метод измерения поляризации холодных/тепловых нейтронов, использующий P-четную асимметрию в ядерных реакциях, вызванных поляризованными нейтронами. Анализируется схема, основанная на большой корреляции между спином нейтрона и циркулярной поляризацией γ-кванта в (n, γ)-реакции поляризованных нейтронов с ядрами. Этот метод может быть использован, например, для измерения поляризации нейтронного пучка в экспериментах с часто меняющейся конфигурацией. Показано, что можно ожидать высокую точность и надежность измерений.