Physics – Uspekhi **39** (9) 891 – 896 (1996)

TO THE 40TH ANNIVERSARY OF THE JOINT INSTITUTE FOR NUCLEAR RESEARCH

PACS numbers: 13.75.Cs, **25.40.–h**, **28.20.–v**

Coherent processes in nuclei and crystals †

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Abstract. **The history of the discovery of the nucleon – nucleon interaction is outlined with special reference to the contribution of the Frank Laboratory of Neutron Physics (FLNP) at JINR, to this field of research. The author lays down a programme of joint studies to be carried out by the Institute of Theoretical and Experimental Physics (ITEP), FLNP at JINR, the Russian Research Centre 'Kurchatov Institute' (KI) on the IBR-2 reactor, and Moscow Engineering-Physics Institute (MEPI).**

My purpose is to trace in brief the history of the discovery of weak nucleon – nucleon interaction in ITEP. Also, I am going to highlight the contribution of FLNP, JINR, to the development of this line of research and, finally, to tell about plans of our joint studies on the IBR-2 reactor. The present report is by no means an ordinary review. Therefore, I apologise to all the respected colleagues of mine both in this country and abroad as well as to groups of authors whose works I shall not be able to mention below. The scope of the report is restricted by its immediate objective.

The weak nucleon – nucleon interaction was first recorded in ITEP in 1964 [1 – 3]. We observed asymmetry of γ-quanta emission with respect to the direction of neutron beam polarisation in the process of the radiative capture of neutrons by cadmium nuclei

$$^{113}\mathrm{Cd}(n\gamma)^{114}\mathrm{Cd}\,.$$

We recorded γ-quanta with the energy of 9.04 MeV which suggested the $1^+ \to 0^+$ transition of the ^{114}Cd nucleus from the excited compound-nuclear state to the ground state. Evidently, that was a M1-transition. The experiment was proposed by I S Shapiro who had found an error in the calculation of the expected effect by our predecessors [4]. While undertaking this experiment, P A Krupchitsky and myself came to the conclusion that its design should be changed in such a way as to enable us to very often compare effects with polarised and depolarised neutron beams or very frequently (many times per second) reverse the direction of neutron beam polarisation to make up for the influence of instabilities of the neutron flux and measuring devices. The choice of the cadmium nucleus was not fortuitous. The capture cross-section for thermal neutrons in cadmium nuclei is almost wholly determined by resonance at the neutron energy $E = 0.17$ eV. This is the s-resonance with quantum numbers 1^+. It is known (the Wolfenstein theorem) that the s-neutron capture must lead to spherically symmetric emission of γ-quanta provided parity is conserved. The correlation $\mathbf{P}_\mathrm{n}\mathbf{k}_\gamma$ between polarisation directions $\mathbf{P}_\mathrm{n}$ of a neutron beam and γ-quanta momentum $\mathbf{k}_\gamma$ would suggest parity non-conservation since this correlation changes the sign on coordinate inversion. The best way to observe such a correlation is to arrange detectors of γ-quanta in or against the direction of neutron beam polarisation. Parity non-conservation in the above reaction would physically mean that the wave function of the nuclear state 1^+ actually contains an admixture of the 1^- state, i.e. that weak interaction in the nucleus mixes up the two states. In order this mixing be noticeable, it is necessary, in agreement with the theory of perturbations, that the 1^+ level in an excited cadmium nucleus ^{114}Cd had the 1^- level close by [4]. On the other hand, the presence of such a level must inevitably give rise to a P-even correlation of the form $P_\mathrm{n}(\mathbf{k}_\mathrm{n} \times \mathbf{k}_\gamma)$, where $\mathbf{k}_\mathrm{n}$ is the incoming radiation momentum, i.e. the momentum of neutrons incident upon the target. Such a correlation can be found if the neutron polarisation vector is normal to the reaction plane. Effect of the P-even correlation was excluded by the experimental design and its absence confirmed by special control measurements. It is easy to see that the ratio of weak to strong nucleon – nucleon interaction amplitudes in nuclei is of the order of $F \sim 10^{-7}$ [4]. If a P-odd effect is to be recorded, such reactions should be chosen in which P-odd effects are amplified by several orders of magnitude. A classification of amplification mechanisms for P-odd phenomena has been proposed in Ref. [4]. The physical sense of amplification mechanisms arising in the reaction in question can be explained in terms of the diagram technique (Fig. 1). The first diagram shows the radiative neutron capture by nuclei in the absence of weak interaction. If phase multipliers are omitted, the amplitude of this process may be written in the form [5]:

$$f_\mathrm{ss} \simeq \sqrt{\Gamma_\mathrm{n}^\mathrm{s}}\,\frac{1}{E - E_\mathrm{s} + (\mathrm{i}/2)\Gamma_\mathrm{s}}\,\langle \mathrm{M1}\rangle\,,$$

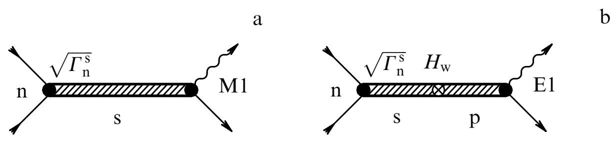

Figure 1. Diagrammatic representation of neutron capture in a s-wave: (a) in case of strong interaction in the absence of weak nucleon – nucleon interaction; (b) with weak interaction.

† Report presented at the JINR Scientific Council Session on the occasion of the 40th anniversary of the Institute

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Received 29 May 1996
Uspekhi Fizicheskikh Nauk **166** (9) 949 – 954 (1996)
Translated by Yu V Morozov, edited by L V Semenova

where Γ_n^s is the neutron s-width, E is the neutron energy, E_s is the resonance meaning of the neutron energy, Γ_s is the total s-width, $\langle M1 \rangle$ is the amplitude of the $1^+ \to 0^+$ M1-transition in the reaction $^{113}Cd(n\gamma)^{114}Cd$. The second graph (Fig. 1b) describes the same process involving weak interaction

$$f_{sp} \simeq \frac{\sqrt{\Gamma_n^s}\,\langle s|H_w|\,p\rangle}{\left[E - E_s + (i/2)\Gamma_s\right]\left[E - E_p + (i/2)\Gamma_p\right]}\,\langle E1 \rangle\,,$$

where $\langle s|H_w|\,p\rangle$ is the 'weak' matrix element responsible for an admixture of 1^- state to the 1^+ state of the ^{114}Cd nucleus caused by weak interaction. E_p, Γ_p are the energy and the width of the p-level respectively, $\langle E1 \rangle$ is the amplitude of E1-quantum emission during the $1^- \to 0^+$ transition. One and the same neutron simultaneously runs along two 'paths' or channels of the reaction: neither can be cancelled, and there is no sense to guess which one was used by the neutron to enter the nucleus. Otherwise, interference would be broken and the P-odd effect proportional to the squared weak matrix element.

This situation is reminiscent of the known conceivable experiment on electron diffraction at two gaps. Effect of interference is apparent if both gaps are open. In the case being examined, the two 'gaps' are open, and the amplitude of the process is the sum of amplitudes: $f_s = f_{ss} + f_{sp}$. Therefore, it is clear that any P-odd effect (asymmetry of γ-quanta emission with respect to polarisation direction and circular polarisation of γ-quanta if a neutron beam is not polarised) must be determined by the ratio of amplitudes f_{sp}/f_{ss}. Hence,

$$\left|\frac{f_{sp}}{f_{ss}}\right| \simeq \left|\frac{\langle H_w \rangle}{E - E_p + (i/2)\Gamma_p}\right| \frac{\langle E1 \rangle}{\langle M1 \rangle} \simeq \frac{\langle H_w \rangle}{D}\,\frac{\langle E1 \rangle}{\langle M1 \rangle} \equiv RF\,.$$

Here, $F \sim 10^{-7}$, R is the summarised amplification factor for the P-odd effect. The neutron energy being close to s-resonance, $E - E_p \simeq E_s - E_p \simeq D$ nearly equals the mean distance between compound-nucleus levels D. The former multiplier defines the so-called dynamic [4] amplification of the effect caused by the proximity of levels with opposite parity. Therefore, nuclei with high density of the excited states must be selected because in this case levels with similar spin and opposite parity may happen to occur close to each other. The ^{114}Cd nucleus meets this requirement. The second multiplier also describes amplification since $\langle E1 \rangle / \langle M1 \rangle \simeq c/v \sim 10$, where v is the nucleon velocity in the nucleus and c is the velocity of light. This amplification factor is referred to as kinematic one. Getting ahead of the story, it should be noted that the p-level 1^- in the ^{114}Cd nucleus was actually found in a study carried out in FLNP, JINR. It was reported to correspond to the neutron energy $E = 7$ eV [6]. If parity is violated during the radiative capture of neutrons, the angular distribution of secondary (outgoing) radiation (γ-quanta) must contain the pseudoscalar term $\mathbf{P}_n \mathbf{k}_\gamma$:

$$W(\theta) \simeq \text{const} \times \left(1 + a\,\mathbf{P}_n \frac{\mathbf{k}_\gamma}{|\mathbf{k}_\gamma|}\right) = \text{const} \times (1 + a\,P_n \cos\theta)\,,$$

where θ is the angle between directions of the neutron beam polarisation vector $\mathbf{P}_n$ and the γ-quanta momentum $\mathbf{k}_\gamma$ while a is the asymmetry coefficient. Let the momentum of γ-quanta be in or against the direction of neutron beam polarisation. N^+, N^- are the number of readings on a γ-quanta detector for the two orientations of neutron beam polarisation and the γ-quanta momentum. Then, the asymmetry coefficient can be inferred from the equality:

$$\frac{N^+ - N^-}{N^+ + N^-} = aP_n\,\overline{\cos\theta}\,.$$

The bar indicates averaging of the angular distribution of the emitted γ-radiation taking into account the real ('non-point') geometry of the experimental device. It can be shown that the asymmetry of γ-quanta emission to be found, which must be determined by the amplitude ratio $f_{sp}/f_{ss} \simeq RF$, has the form [5]:

$$a_{n\gamma} = \frac{\langle s|H_w|\,p\rangle}{(E - E_p)^2 + (1/4)\Gamma_p^2}\,\frac{E - E_p}{2}\,\frac{\langle E1 \rangle}{\langle M1 \rangle} \simeq \frac{\langle H_w \rangle}{E_s - E_p}\,\frac{\langle E1 \rangle}{\langle M1 \rangle} = RF\,,$$

that is, it is actually determined by the said ratio. The measured asymmetry is related to RF by the expression [3, 4]

$$a = 2ARF\,.$$

Coefficient A depends on the spins of the initial, intermediate, and final nuclear states and many-field nature of the transition. There is no need to reproduce here the explicit form of this factor [3, 4]. In the present case, this coefficient is unity for the transition of the ^{114}Cd nucleus to the ground state. Figure 2 shows the part of the nuclear fission scheme for ^{114}Cd which is of interest for our purpose. It is worthy of note that, besides the M1-transition $1^+ \to 0^+$ with the energy of 9.04 MeV, there is a nearby $1^+ \to 2^+$ transition with energy 8.5 MeV. Coefficient A for this M1-transition has the opposite sign. Therefore, we had to record γ-quanta with energy in excess of 8.5 MeV to separate the $1^+ \to 0^+$ transition which took much time to collect information.

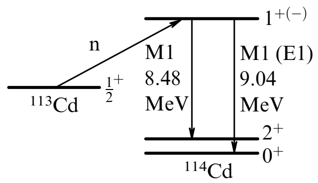

Figure 2. A scheme of $^{114}CD^*$ decay in the high-energy $1^+ \to 0^+$ and $1^+ \to 2^+$ transitions region.

The experimental set-up is shown in Fig 3. A polarised neutron beam was obtained by the complete reflection of neutrons off the system of magnetised cobalt mirrors that focused the beam on the target. The outgoing beam was polarised in the vertical direction normal to the reaction plane. A special electromagnet turned the polarisation vector by 90° in either side to maintain it in the horizontal plane. Moreover, a special device was used to rapidly reverse the direction of beam polarisation [7]. This device allowed the polarisation direction to be reversed with a frequency of 10 Hz. Depolarisation of the neutron beam was achieved by periodically introducing a non-magnetised iron plate, a shim, into the beam. γ-quanta outgoing from the target were recorded with two scintillation detectors with thallium-activated sodium iodide crystals. The detectors were placed in and against the direction of neutron beam polarisation, i.e.

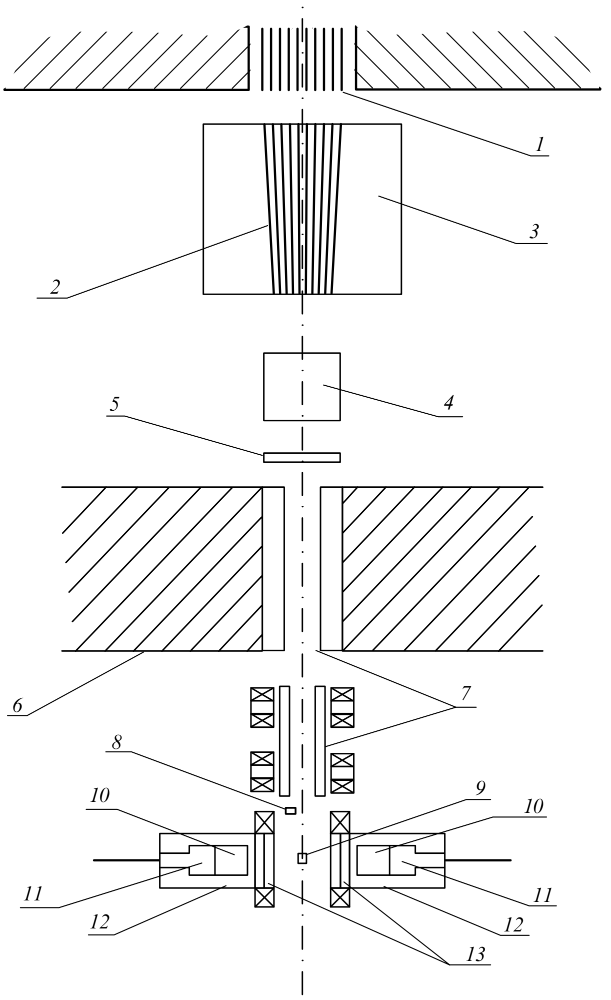

Figure 3. Experimental set-up: *1* — collimator in a reactor channel; *2* — cobalt mirrors of the polariser; *3* — electromagnet of the polariser; *4* — electromagnet turning neutron spin from the vertical to horizontal position; *5* — spin-flipper; *6* — concrete wall; *7* — magnetic neutron guide; *8* — a screen of lithium; *9* — target; *10* — sodium iodide crystals; *11* — photoelectronic multipliers (PEM); *12* — PEM magnetic shielding; *13* — coils generating fixed magnetic field on a specimen to prevent neutron beam depolarisation.

to the left and the right of the beam incident on the target. A combination of the two identical detectors arranged in this mode was intended to neutralise instrumental asymmetry.

The following result was obtained:

$$a = (-4.1 \pm 0.8) \times 10^{-4} .$$

The overall amplification being $R \sim 10^3$, the observed asymmetry was in good agreement with the expected one at the 10^{-4} level. Concurrently, asymmetry was measured in a wide energy range where the effect was suppressed due to the random distribution of the signs of coefficient A and also by virtue of the marked contribution of E1-transitions for which the kinematic factor played the role of a suppressor rather than an amplifier of the P-odd effect. One of the control experiments was designed to search for a P-even correlation which required vertical orientation of the polarisation vector. It was shown that such a correlation could not appreciably contribute to the observed P-odd effect. Beam depolarisation also eliminated the effect.

In the absence of neutron beam polarisation, interference between amplitudes shown in Fig. 1 must result in P-odd circular polarisation of γ-quanta. In the reaction being examined, this polarisation is

$$P_{\gamma} = 2RF ,$$

that is, the magnitude of the effect is independent of coefficient A, and there is no need to strictly resolve the $1^+ \to 0^+$ transition from the $1^+ \to 2^+$ one. Such an experiment was carried out by R Wilson and co-workers in the USA [8] who reported the value of

$$P_{\gamma} = (-6.0 \pm 1.5) \times 10^{-4} .$$

Now, let us turn to another process known to always accompany the radiative capture of neutrons, that is elastic neutron scattering. P-odd photoneutronic phenomena were first observed in Grenoble, France, in the Seventies. The authors described neutron-spin rotation in a plane normal to the neutron momentum for a cross-polarised beam passing through a specimen, an analog of double optical refraction. They also reported observation of P-odd dichroism, i.e. dependence of target transparency on neutron helicity. If neutrons exhibit weak interaction, the amplitude of neutron scattering on a nucleus must contain a pseudoscalar term the sign of which changes with coordinate inversion. Such a pseudoscalar quantity in the neutron scattering amplitude must be neutron helicity. If the scattering amplitude is a function of helicity, two refraction coefficients arise

$$n_{\pm} = 1 + \frac{2\pi\rho}{k^2} f_{\pm} ,$$

where ρ is the density of scatterers, k is the neutron wave number, and $f_{\pm}$ is the forward scattering amplitude for positive and negative helicities. The cross-polarised state is a coherent mixture of positive and negative helicity states. Different refraction coefficients for these states account for a phase shift which is apparent at the outlet from the target as a turn of the neutron beam polarisation vector in the plane normal to the neutron momentum. Moreover, helicity dependence of the amplitude is responsible for asymmetry of the total cross-section, i.e. target transparency for a beam:

$$A_{\mathrm{n}} = \frac{\sigma_{\mathrm{t}}^{+} - \sigma_{\mathrm{t}}^{-}}{\sigma_{\mathrm{t}}^{+} + \sigma_{\mathrm{t}}^{-}} ,$$

where $\sigma_{\mathrm{t}}^{\pm}$ are the total cross-sections of interaction between neutrons and nuclei for the two helicity states.

It turns out that, in both cases, there is one more amplification mechanism for P-odd phenomena which is readily apparent from the two diagrams shown in Fig 4. Let us assume that two resonances with opposite parity, rather than one s-level of the compound-nucleus as in the previous

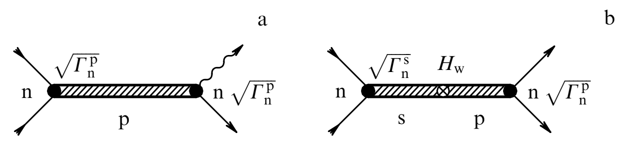

Figure 4. Diagrams of elastic neutron scattering and compound-nucleus formation: (a) in the absence of weak interaction; (b) with weak interaction.

case, contribute to the cross-section for neutron interaction with nuclei. This means that the same neutron can enter the nucleus either in a s-wave or in a p-wave. These levels are located in such a way and make such a contribution to the total cross-section that neither process may be neglected. Such a situation is likely to occur near the p-resonance. In the immediate vicinity of this resonance, the contribution of a p-wave to the scattering cross-section may prove sufficiently large not to be neglected, even if the s-wave is significantly stronger than the p-wave in the low-energy region. The diagram in Fig. 4a depicts neutron elastic scattering via p-resonance in the absence of weak interaction. In the adopted approximation (with phase factors being omitted)

$$f_{\rm pp} \simeq \sqrt{\varGamma_{\rm n}^{\rm p}}\,\frac{1}{E - E_{\rm p} + ({\rm i}/2)\varGamma_{\rm p}}\,\sqrt{\varGamma_{\rm n}^{\rm p}}\,.$$

Thus, there are both the capture and the emission of neutrons in the p-wave. E, $E_{\rm p}$ are the energy of the neutrons incident upon the target and its resonance value respectively, $\varGamma_{\rm n}^{\rm p}$ is the neutron width of p-resonance. The diagram in Fig. 4b describes the neutron capture and emission in s- and p-waves respectively. Weak interaction converts a s-wave into a p-one. In other words, the s-level contains an admixture of the opposite parity state:

$$f_{\rm sp} \simeq \sqrt{\varGamma_{\rm n}^{\rm s}}\,\frac{\langle {\rm s}|H_{\rm w}|\,{\rm p}\rangle}{\left[E - E_{\rm s} + ({\rm i}/2)\varGamma_{\rm s}\right]\left[E - E_{\rm p} + ({\rm i}/2)\varGamma_{\rm p}\right]}\,\sqrt{\varGamma_{\rm n}^{\rm p}}\,.$$

It is worthwhile to emphasise once again that the same neutron is simultaneously involved in both processes, and one can not be separated from the other as in the case of electron diffraction on two gaps. Only, the diagrams have different inlet channels rather than outlet ones. A neutron simultaneously ‘enters’ two resonances thus contributing to both s- and p-resonances. The amplitudes are summarised since the same neutron contributes to the two processes, and the P-odd effect is again defined by the amplitude ratio:

$$\left|\frac{f_{\rm sp}}{f_{\rm pp}}\right| \simeq \sqrt{\frac{\varGamma_{\rm n}^{\rm s}}{\varGamma_{\rm n}^{\rm p}}}\,\frac{\langle {\rm s}|H_{\rm w}|\,{\rm p}\rangle}{E - E_{\rm s} + ({\rm i}/2)\varGamma_{\rm s}} \simeq \sqrt{\frac{\varGamma_{\rm n}^{\rm s}}{\varGamma_{\rm n}^{\rm p}}}\,\frac{\langle H_{\rm w}\rangle}{D}\,.$$

The dynamic amplification mechanism arising from the proximity of s- and p-resonances is preserved while the kinematic factor disappears. Instead, another amplification mechanism appears which is referred to as the resonant one and is most probably of structural nature [5], in accordance with the classification proposed in Ref. [4]. The neutron s-width in the low-energy region is many orders of magnitude larger than the p-width; hence, $\sqrt{\varGamma_{\rm n}^{\rm s}/\varGamma_{\rm n}^{\rm p}} \sim 10^3$.

This amplification mechanism was theoretically predicted in ITEP [9, 10] for the nuclear radiative nucleon capture when the contribution of p, d, etc. waves can not be neglected. However, at that time, i.e. in the late Sixties, the resonance amplification factor was difficult to see in proper perspective for the lack of reliable data on neutron widths. Therefore, by way of precaution, the authors put too low the value of this amplification [9, 10]. As a result, those works did not attract attention of experimenters and passed unnoticed.

Later, the amplification mechanism for P-odd phenomena was rediscovered by O P Sushkov and V V Flambaum with reference to p-odd photoneutronic phenomena [11, 12]. These authors came to understand that both inelastic processes and reactions with an elastic channel are underlain with the same mechanism of spatial parity non-conservation, that is mixing opposite parity states in a compound-nucleus. They correctly estimated the magnitude of P-odd photoneutronic phenomena and showed that these effects must be especially pronounced near p-resonances.

This finding was used by the group of L B Pikel'ner and V P Alfimenkov, of FLNP, JINR, to observe, for the first time, marked P-odd effects that amounted to a few percent. Asymmetry of total cross-sections $A_{\rm n}$ was shown to be dependent on neutron helicity. In other words, target transparency for tin, lanthanum [13, 14], and some other elements depended on the reciprocal orientation of neutron spins and momenta. Also, this group discovered P-odd dichroism for a longitudinally polarised neutron beam passing through metallic cadmium [6], near the p-resonance at the neutron energy of $E = 7$ eV first observed by the same authors.

It follows from the above that the values of the weak matrix element obtained in the experiment must be similar for various P-odd phenomena (asymmetry of γ-quanta emission, circular polarisation, total cross-section asymmetry) if the same levels of a given nucleus are involved in the formation of these effects.

Reference [6] reports comparative analysis of the weak matrix element values deduced from experimental findings in ITEP (asymmetry of γ-quanta emission), Harvard University (circular polarisation), and FLNP, JINR, (total cross-section asymmetry). These results are presented in Table 1. Here,

$$x = \sqrt{\frac{\varGamma_{\rm n}^{\rm p}(1/2)}{\varGamma_{\rm n}^{\rm p}}}$$

is the square root of the ratio of the p-resonance neutron width with the total momentum 1/2 to the total neutron p-width. It is clear that $x > 0$; otherwise, a P-odd effect would be impossible to observe although x can not exceed unity. Roughly speaking, $x \approx 1/2$. Such a fair agreement between the results of totally different experiments is really surprising. Evidently, the nature of the phenomena examined is well understood.

So far, we have not been interested in the aggregate state of the target when considering P-odd photoneutronic effects if only the condition of optical homogeneity of the medium were met. Let us now assume that a perfect monocrystal is used as the target. Furthermore, let a neutron beam fall on this crystal and the Bragg diffraction conditions be strictly fulfilled. Also, let the crystal be positioned in such a way as to have the reflecting crystallographic planes (h, k, l) normal to the surface upon which the neutron beam falls. The neutrons escape from the opposite side of the crystal plate. Half intensity of the incident beam passing through the crystal will further spread in the same direction whereas the other half at an angle $2\theta_{\rm B}$ to the initial direction, where $\theta_{\rm B}$ is the Bragg angle. Such a position of the crystal corresponds to the

Table 1. Values of the matrix element $\langle {\rm s}|H_{\rm w}|\,{\rm p}\rangle$ for mixing up cadmium 1^+ and 1^- states in weak nucleon – nucleon interaction (from Ref. [6])

Matrix element	ITEP	Harvard	LNP, JINR
$\langle {\rm s}|H_{\rm w}|\,{\rm p}\rangle$	$(3.6 \pm 0.8) \times 10^{-4}$ eV	$(8.4 \pm 2.3) \times 10^{-4}$ eV	$(3.1 \pm 1.0)(1/x) \times 10^{-4}$ eV

so-called symmetrical Laue diffraction. In the case of the Laue diffraction in a sufficiently thick crystal, neutrons are many times redistributed between the direct and reverse directions (passing and diffraction waves respectively) whereas the beam intensity is equally partitioned between these two rays. Nuclei in a crystal may be considered as emitters or resonators tuned up to the same frequency, the way they are in X-ray physics [15]. When the Bragg conditions are strictly fulfilled, there is a self-consistent field of emitters in a crystal.

Let the Ewald sphere have only two sites of the inverse lattice. Then, owing to the diffraction (self-consistency) conditions, as many as two waves with slightly different wave vectors propagate in each direction inside the crystal, i.e. in the directions of passing and diffraction waves (schematically shown in Fig. 5). This gives rise to four partial waves with the wave vectors $\mathbf{k}_{01}$, $\mathbf{k}_{02}$ (passing wave) and $\mathbf{k}_{h1}$, $\mathbf{k}_{h2}$ (diffraction wave). In case of symmetric diffraction, when the Bragg conditions are satisfied, these pairs are of equal value: $|\mathbf{k}_{01}| = |\mathbf{k}_{h1}|$; $|\mathbf{k}_{02}| = |\mathbf{k}_{h2}|$. The difference between wave vectors of incoming radiation $\mathbf{k}_0$ and that produced in the crystal $\mathbf{k}_{01}$, $\mathbf{k}_{02}$ or $\mathbf{k}_{h1}$, $\mathbf{k}_{h2}$ is insignificant. Finally, propagation directions for pairs $\mathbf{k}_{01}$, $\mathbf{k}_{02}$ and $\mathbf{k}_{h1}$, $\mathbf{k}_{h2}$ are virtually coincident. For all that, there is some difference.

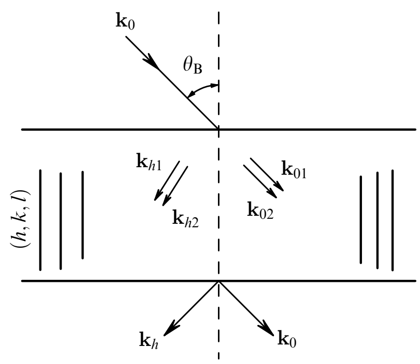

Figure 5. Neutron diffraction in the Laue geometry. Two waves with wave vectors $\mathbf{k}_{01}$, $\mathbf{k}_{02}$ propagate in the direction of the incident neutron beam inside the crystal; waves with vectors $\mathbf{k}_{h1}$, $\mathbf{k}_{h2}$ propagate in the direction of diffraction. There are two beams with wave vectors $\mathbf{k}_0$, $\mathbf{k}_h$; $|\mathbf{k}_0| = |\mathbf{k}_h|$ at the outlet from the crystal.

It is noteworthy that one and the same neutron 'carries' four wave vectors at once. The neutron 'spreads' inside the crystal due to its simultaneous interaction with the whole macroscopic nuclear ensemble of the crystal. It may be assumed that scattering near the resonance occurs via compound-state formation channel. Under diffraction conditions, it appears impossible to identify a nucleus on which the scattering occurs, and nuclear levels undergo 'collectivisation', and the total nuclear ensemble of the crystal turns into a macroscopic resonator.

Following Ewald [15], let us expand each vector ($\mathbf{k}_{01}$, $\mathbf{k}_{02}$, $\mathbf{k}_{h1}$, $\mathbf{k}_{h2}$) into two components: parallel and normal to planes (h, k, l), as shown in Fig. 6a. In this case, normal components are directed along (against) the inverse lattice vector whereas components parallel to the reflecting planes are summed into pairs and form two running waves. Their normal components of equal size but opposite direction form standing waves (Fig. 6b). Distances between nodes (antinodes) of these standing waves are practically the same as distances between the planes of the reflecting surfaces (up to the deviation of the refraction coefficient from unity, i.e. to the order $10^{-6} - 10^{-5}$). Nodes of the first standing wave are located on atomic planes and antinodes between them, while the second standing wave displays the inverse nodes – antinodes pattern (Fig. 6c). Given strong absorption by a crystal, the second component is intensely absorbed as the distance from the inlet surface of the crystal increases; conversely, absorption of the first component is decreasing.

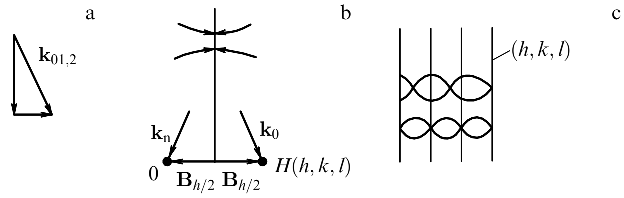

Figure 6. Formation of standing waves in conventionally dynamical Laue diffraction [15]: (a) the wave vector expansion into two components — parallel and normal to the reflecting planes; (b) standing waves formation; (c) nodes and antinodes pattern.

This effect, an analog of the Borman effect of anomalous X-ray transmission, has been theoretically described by Yu M Kagan and A M Afanas'ev [16, 17] for the case of neutron optics and experimentally confirmed by S Sh Shil'shtein, V A Somenkov, et al. [18, 19] in KI. Effects of the anomalous neutron passage through a cadmium sulfite monocrystal in the Laue geometry has been examined near the resonance but not in the resonance itself because it is very difficult to avoid the influence of higher reflection orders in a stationary reactor; moreover, beam intensity rapidly decreases with increasing neutron energy. This difficulty was obviated using the IBR-2 reactor at JINR by virtue of high neutron intensity in the resonant region and separation of higher reflection orders in terms of transit time. This provides the possibility to study the effect of anomalous neutron passage straight in the resonance where the lifetime of the intermediate state is especially long. The presence of the effect would indicate conservation of the coherence of incident and reflected waves despite a long lifetime of the compound-state.

We can not go here into all details of the forthcoming studies to be carried out jointly by FLNP (JINR), ITEP, and KI. Briefly, the work will be done on two reactors: the IBR-2 in FLNP, JINR, and the IRT in MEPI. Our purpose is to find out the effect of multifrequency neutron-spin precession during dynamic diffraction in a diamagnetic crystal placed in an uniform magnetic field which was long ago predicted by V G Baryshevskiĭ [20]. We are also planning an in-depth study of spin precession in a pseudomagnetic field [20]. Turning back to P-odd photoneutronic phenomena, it is worthwhile to emphasise that investigations carried out in FLNP, JINR, have shown that the inelastic reaction channel, i.e. the radiative capture of neutrons by nuclei, makes the major contribution to the total cross-section asymmetry, that is asymmetry of transparency with respect to neutron helicity. It is easy to see that, in case of neutron diffraction in the Laue geometry, asymmetry of a diffraction beam relative to neutron helicity, if any, is determined by the neutron elastic scattering cross-section rather than the total cross-section. That is why such measurements are of special interest. It may be expected that the degree of asymmetry will decrease;

moreover, suppression of elastic scattering asymmetry versus total cross-section asymmetry under conditions of kinematical diffraction (single scattering) must be very strong. However, it has been predicted independently by two groups of theorists [21, 22] that, in dynamical diffraction, there must be a new, so far unknown, amplification mechanism for P-odd photoneutronic phenomena based on the coherent action of nuclei responsible for the transformation of the crystal to the like of a single resonator. Amplification in the centre of the Bragg reflex must be great, but separation of this centre entails the loss of intensity. Incidentally, Shull, the first I M Frank prize winner, has demonstrated that the same can be achieved without the catastrophic loss of intensity using a crystal collimator (Otie collimator). However, even the integrated effect averaged over the full reflex turns out to be markedly amplified by one or two orders of magnitude relative to asymmetry without diffraction. It is natural to ask whether the IBR-2 reactor can be used in neutron diffraction studies under dynamical diffraction conditions. Stationary reactors in MEPI and KI have for a long time been employed for this purpose. However, anomalous passage of neutrons through a crystal in the immediate vicinity of neutron resonance or elastic neutron scattering asymmetry near p-resonance is better to observe with a fast reactor, such as the IBR-2 one, using the time-of-flight technique to totally exclude the influence of higher reflection orders. Is the intensity of neutron beams in the IBR-2 reactor sufficient for the purpose? Preliminary studies on dynamic effects of neutron diffraction in perfect silicon crystals were carried out by Yu A Aleksandrov, R Mikhal'ts, and co-workers using channel No. 1 of the IBR-2 reactor as early as in 1988 [23]. Specifically, these authors observed the pendulum effect in different reflection orders: (220), (440), (660). The accuracy of the measurements was sufficient to steadily observe the effect.

At present, this channel is being modified to enhance intensity of neutron beams. We shall have to obtain a polarised neutron beam and set up a new diffractometer. There is plenty of work to be done especially in methodology, but it is hoped, based on the previous experience, that future studies will be able to throw new light on the problem.

Acknowledgements. I would like to take this opportunity and thank the JINR Administration and Scientific Council for doing me the honour of presenting this report at the Jubilee Session of the Scientific Council.

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