26

ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
СО АН СССР

V.V.Flambaum and O.P.Sushkov

NEUTRON SPIN ROTATION AND THE OTHER EFFECTS OF PARITY NONCONSERVATION IN Sn

ПРЕПРИНТ 81-37

Новосибирск

NEUTRON SPIN ROTATION AND THE OTHER EFFECTS OF PARITY NONCONSERVATION IN Sn

V.V.Flambaum and O.P.Sushkov
Institute of Nuclear Physics,
630090, Novosibirsk, USSR

A b s t r a c t

We discuss the results of the first measurements of a parity-nonconserving (PNC) spin rotation for thermal neutrons in ^{117}Sn. The comparison with the theoretical estimations is carried out. The magnitudes of the PNC effects for resonance neutrons are calculated. Parity nonconservation in the reaction $^{117}Sn(n,\gamma)$ is also considered.

The present paper has been written in connection with the publication of the results of first weak spin rotation measurement for thermal neutrons passing through the tin /1/. It has been shown in our paper /2/ that the main contribution to this effect comes from the mechanism associated with the virtual excitation of the nucleus into a compound state. The results obtained in /1/ are in good agreement with the estimation given in /2/. In the present paper the calculations for ^{117}Sn are compared in detail with experimental data. Using these data, the magnitudes of the PNC effects for the other possible experiments are calculated.

In principle, the PNC effects in neutron optics are similar to those observed in conventional optics /3/ (see also the review /4/). The first suggestions concerning the observations of parity violation in neutron optics was made by C.Michel /5/ and later by L.Stodolsky /6/. They suggested to measure a spin rotation about the momentum for neutrons passing through the matter. Also, the other effect was discussed - the longitudinal polarization in the initially unpolarized neutron beam. The expected angle of rotation ψ and the longitudinal polarization degree a per the attenuation length of a neutron were $\psi \sim 10^{-6}-10^{-8}$ rad and $a \sim 10^{-8}\sqrt{E\ eV}$. In 1976 M.Forte pointed out that the PNC effect was enhanced near a single-particle p-wave resonance /7/. He suggested to measure the neutron spin rotation in ^{124}Sn, where at an energy of 62 eV the p-wave resonance with a relatively large single-particle component lies. According to /8/, near the resonance $\psi \sim 10^{-3}-10^{-4}$ rad and $a \sim 10^{-5}-10^{-6}$ per the attenuation length. For thermal neutrons $\psi_t \lesssim 5\cdot 10^{-6}$ rad/cm /8/.

In the mentioned refs./5-8/ and in a number of the papers of other authors /9-15/ the spin rotation induced by neutron scattering on the P-odd potential of the nucleus is discussed. In other words, the nucleus is regarded as a particle without the internal degrees of freedom. As shown in /2/, in medium and heavy nuclei the other mechanism associated with the virtual excitation of the nucleus into a compound state gives a much larger contribution to the PNC effects. The possibility of such an interpretation of the effect discovered in /1/ was pointed out in /16/, too.

For the sake of completeness, the results of the paper /2/ are also presented.

a) Resonance effects

Let us consider the capture of a neutron with energy E into the p-wave resonance. After the capture the nucleus is excited into the compound state with angular moment $\mathcal{J}$ and parity η. As a matter of fact, this state is a superposition of different-parity states because of the nucleon-nucleon weak interaction.

$$\Psi(E) = |\mathcal{J}^{\eta}\rangle + i\sum_{\nu} \varepsilon_{\nu}(E)\, |\mathcal{J}^{\bar{\eta}},\nu\rangle \tag{1}$$
$$i\,\varepsilon_{\nu}(E) = \frac{\langle \mathcal{J}^{\bar{\eta}},\nu\,|H_w|\,\mathcal{J}^{\eta}\rangle}{E - E_{\nu} + i\Gamma_{\nu}/2}$$

The imaginary unit is separated in the mixing coefficient, since in the conventional definition of angular wave functions the matrix element of H_w is purely imaginary. Due to dynamical enhancement, the mixing between the nearest levels of the compound nucleus $\varepsilon \sim G m_{\pi}^{2}\sqrt{\frac{\omega}{\mathcal{D}}} \sim 10^{-4}\text{-}10^{-5}$. Here $\omega \sim 1$ MeV is the interval between the single-particle levels of opposite parity; $\mathcal{D} \sim 10$ eV is the interval between the compound-nucleus levels (see Appendix).

The neutron is captured into the state (1) both from the p - and s -waves. Let us expand the wave function of a slow neutron with momentum $\vec{K}$ and helicity $\pm 1/2$ in a series of states with a definite angular momentum, $|l\, j\, j_z\rangle$ (the axis z is directed along $\vec{K}$):

$$e^{i\vec{K}\vec{r}}\chi_{\pm} \approx (1 + i\vec{K}\vec{r})\chi_{\pm} = \sqrt{4\pi}\left(Y_{00}(\vec{n}) + \frac{iKr}{\sqrt{3}}Y_{10}(\vec{n})\right)\chi_{\pm} =$$
$$= \sqrt{4\pi}\left\{|0,\tfrac{1}{2},\pm\tfrac{1}{2}\rangle \mp i\frac{Kr}{3}|1,\tfrac{1}{2},\pm\tfrac{1}{2}\rangle + \frac{iKr\sqrt{2}}{3}|1,\tfrac{3}{2},\pm\tfrac{1}{2}\rangle\right\} \tag{2}$$

Here $\chi_{\pm}$ is the spin function. The amplitude of neutron capture from the state (2) into the compound-nucleus state (1) is as follows:

$$T = \left[\pm T_p(j=\tfrac{1}{2}) + \sum_{\nu}\varepsilon_{\nu}T_{s\nu}\right] C^{\mathcal{J}\mathcal{J}_z}_{I I_z \frac{1}{2},\pm\frac{1}{2}} + T_p(j=\tfrac{3}{2})\, C^{\mathcal{J}\mathcal{J}_z}_{I I_z \frac{3}{2},\pm\frac{1}{2}} \tag{3}$$

Here I and $\mathcal{J}$ are the nuclear angular moments before and after the capture; T_s and $T_p(j)$ are the scalar capture amplitudes from s - and p -waves. Note, that the imaginary unit in (1) is compensated by the difference in the free motion phases of s- and p-waves. For an unpolarized target the capture amplitudes at different j do not interfere, while interference of the different-parity amplitudes with $j = 1/2$ leads to the difference in the absorption cross sections for neutrons with $\pm 1/2$ helicities.

$$\sigma^{a}_{\pm} = \sigma^{a}\cdot(1 \pm P(K)), \qquad P(K) = \frac{P_0(K)\,\Gamma_n^{(p\frac{1}{2})}}{\Gamma_n^{(p\frac{1}{2})} + \Gamma_n^{(p\frac{3}{2})}}$$
$$P_0(K) = 2\,\mathrm{Re}\left\{\sum_{\nu}\varepsilon_{\nu}(E)\frac{T_{s\nu}}{T_p(j=\frac{1}{2})}\right\} = 2\sum_{\nu}\varepsilon_{\nu}(E)\sqrt{\frac{\Gamma_n^{(s\nu)}(K)}{\Gamma_n^{(p\frac{1}{2})}(K)}}\cos(\varphi^{(s\nu)} - \varphi^{(p\frac{1}{2})}) \tag{4}$$

Here $\Gamma_n^{(p)}(K) = \Gamma_n^{(p\frac{1}{2})}(K) + \Gamma_n^{(p\frac{3}{2})}(K)$ and $\Gamma_n^{(s\nu)}(K)$ are the neutron widths of the states $|\mathcal{J}^{\eta}\rangle$ and $|\mathcal{J}^{\bar{\eta}},\nu\rangle$ reduced to the energy of the incident neutron:

$$\Gamma_n^{(p)}(K) = \Gamma_n^{(p)} \left(\frac{K}{K_p}\right)^3, \qquad \Gamma_n^{(s)}(K) = \Gamma_n^{(s)} \frac{K}{K_s} \tag{5}$$

K_p and K_s are the momenta corresponding to the resonances; φ_p and φ_s are the capture phases. It is clear that in the case under consideration, $KR \ll 1$ (R is the nuclear radius), $\cos(\varphi_s - \varphi_p) = \pm 1$. We will be interested in the case when the distance to a p-wave resonance is much shorter than that to the nearest s-wave resonances. In this situation the dependence of $P_0(K)$ and $P(K)$ is easy to write down explicitly:

$$P_0(K) = P_0 \frac{K_p}{K}, \qquad P(K) = P \frac{K_p}{K} \tag{6}$$

For low-lying resonances with E_p = 1-10 eV $\sqrt{\Gamma_n^{(s)}(K_p)/\Gamma_n^{(p)}(K_p)} \sim 1/K_pR \sim 10^2\text{-}10^3$ and $P \lesssim P_0 \sim 10^{-1}\text{-}10^{-2}$.

Taking into account that σ^a in eq.(4) is of the usual Breit-Wigner form, it is not difficult to proceed from the absorption cross section to the index of refraction:

$$n_\pm = n_0 - \frac{\pi N g \Gamma_n^{(p)}}{K_p^3} \left(1 \pm P \frac{K_p}{K}\right) \frac{1}{E - E_p + i\Gamma/2} \tag{7}$$

$$g = \frac{2J+1}{2(2I+1)}$$

N is the density of the atoms in the target, n_0 the non-resonant part of the index of refraction, Γ the total width of the p-resonance. We ignore the Doppler line broadening $\Delta \sim 2\sqrt{\frac{m}{M_N} T E}$. At room temperature $\Delta \sim 0.03\sqrt{E\,(\text{eV})}$. At $\Delta > \Gamma \sim$ 0.03-0.1 eV the effect is suppressed approximately by a factor of Δ/Γ.

Let us consider now the neutron spin rotation about the momentum. Let the neutron move along z, and at $z = 0$ its

spin is directed along X. At $z = \ell$ the spinor components acquire different phases:

$$\frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix} \longrightarrow \frac{1}{\sqrt{2}}\begin{pmatrix}\exp(iKn_+\ell)\\ \exp(iKn_-\ell)\end{pmatrix} = \frac{1}{\sqrt{2}}\exp(iKn_+\ell)\begin{pmatrix}1\\ e^{-i\psi}\end{pmatrix}. \tag{8}$$

$$\psi = K\ell\,\mathrm{Re}(n_+ - n_-) = -\frac{2\pi N g \Gamma_n^{(p)}}{K_p^3} P\ell \frac{E - E_p}{(E-E_p^2) + \Gamma^2/4}$$

The resulting spinor corresponds to a spin rotated by the angle $-\psi$ about z-axis. It is easy to see also that the longitudinal polarization emerges for the initially unpolarized beam:

$$\alpha = -K\ell\,\mathrm{Im}(n_+ - n_-) = -\frac{2\pi N g \Gamma_n^{(p)}}{K_p^2} P\ell \frac{\Gamma/2}{(E-E_p)^2 + \Gamma^2/4} \tag{9}$$

Although ψ and α are proportional to the path length ℓ, it is clear that ℓ cannot exceed significantly the attenuation length, $\ell_0 = 1/(K\,\mathrm{Im}(n_+ + n_-)) \sim$ 1-5 cm.

For the experiments under discussion the nuclei are suitable in which, on the one hand, there are low-lying isolated p-wave resonances and, on the other hand, there is a dense enough spectrum of compound resonances. For example, ^{113}In, ^{117}Sn, ^{119}Sn, ^{139}La, ^{232}Th, ^{238}U. Near p-wave resonances the orders of magnitude of the PNC effects are as follows:

1) The relative difference in the capture cross sections of the right- and left-polarized neutrons is

$$P = \frac{\sigma_+^a - \sigma_-^a}{\sigma_+^a + \sigma_+^a} \sim 10^{-2} \tag{10}$$

2) The neutron spin rotation is

$$\psi(E_p - \Gamma/2) - \psi(E_p + \Gamma/2) \sim (10^{-2} \div 10^{-3})\,\ell/\ell_0 \text{ rad} \tag{11}$$

3) The longitudinal neutron polarization (or the relative difference between the attenuation lengths for the right- and left-polarized neutrons) is

$$a(E_p) \sim (10^{-2} \div 10^{-3})\, l/l_c \qquad (12)$$

The quantities ψ and a are several times less than P because of the potential neutron scattering ($\sigma_c \sim$ 5-10 b), which shortens the attenuation length. For the resonances under consideration the factor $\sigma_c/(\sigma^a+\sigma_c) \sim 0.2-0.5$.

The resonance effects under study are strongly dependent on neutron energy. The scale of this dependence $\sim \Gamma \sim$ 0.03-0.1 eV, determines the required monochromaticity of a neutron beam.

It is worth stressing that a large magnitude of the effects considered here is accounted for by two circumstances: first, by kinematic enhancement due to that the admixture S-amplitude is $1/KR$ times higher than the basic p-amplitude; second, by dynamical enhancement of the P-odd mixing in the compound nucleus.

b) A magnitude of the effects for thermal neutrons. Comparison with the experiment

For thermal neutrons the p-wave and S-wave resonances give, generally speaking, a comparable contribution to the spin rotation angle ψ_t/cm. However, if the S-wave resonance is close to the thermal region, then the absorption is large, and therefore the effect per attenuation length is small. In view of this, we will consider the case when a single p-resonance is near the thermal region.

There is no difficulty in estimating the effect in the thermal region (E = 0), using equations (8) and (9). At $\Gamma \sim$ 0.1-0.03 eV, $E_r \sim$ 1-10 eV, $\psi_t \sim 10^{-4}-10^{-5}\, l/l_c$ rad, $a_t \sim 10^{-6}-10^{-8}\, l/l_c$

The results of first measurements of ψ_t and a_t in Sn /1/ have been recently published. The group who obtained these results searched for the effect which is due to a single-particle p-wave resonance in ^{124}Sn. The natural Sn was used as a reference. The effect in ^{124}Sn was not found:[1]

$$\varphi_t\,(^{124}Sn) = (0.48 \pm 1.49)\cdot 10^{-6}\ rad/cm \qquad (13)$$

But the measurements showed a rotation in the natural Sn:

$$\varphi_t\,(natural\ Sn) = (4.95 \pm 0.93)\cdot 10^{-6}\ rad/cm \qquad (14)$$

In a detailed study the effect was found to be connected with ^{117}Sn:

$$\varphi_t\,(^{117}Sn) = (36.7 \pm 2.7)\cdot 10^{-6}\ rad/cm \qquad (15)$$

which had a p-wave compound-resonance at 1.32 eV. The measured quantity of $\varphi_t(^{117}Sn)$ is in good agreement with the above estimates /2/. The possibility of explaining a large magnitude of the effect in ^{117}Sn by the closeness to the thermal region of a p-wave compound-resonance was also pointed out in Ref./16/.

It should note that a somewhat smaller effect, in comparison with ^{117}Sn, can be expected in ^{119}Sn, which has a p-wave resonance at 6.2 eV (if, of course, its spin $J < 2$). It seems that just this explains the residual effect found in the natural Sn after subtraction of ^{117}Sn contribution /1/.

In Ref./1/ the value of a_t has been measured, too:

$$a_t\,(^{117}Sn) = (-1.63 \pm 0.67)\cdot 10^{-6}\ cm^{-1} \qquad (16)$$

The sign of the ratio ψ_t/a_t is opposite to that of the energy of the p-resonance, which gives the main contribution to the effect ($\psi_t/a_t = -2E_p/\Gamma$). Unfortunately, there is some

---

1) In eqs. (13)–(15) we use the notation φ_t instead of ψ_t because of some indeterminacy in the sign of φ_t (see below).

ambiguity in definition of φ_t in Ref./1/. (The sign of φ in eq.(3) of Ref./1/ differs from that defined in the text immediately above eq.(3).) If the definition of φ_t differs in sign from that of Ψ_t, then the main contribution to the effect comes from the resonance, which lies below the neutron threshold. Using as a reference the known total widths of the above-threshold resonances ($\Gamma = 0.08$ eV), we find that $E_p = -1$ eV. The existence of two resonances close to the thermal point is hardly probable (but not excluded), because the mean interval between the resonances in ^{117}Sn is $\gtrsim 20$ eV. In this situation we suppose that the main contribution to the effect is given by the 1.32 eV resonance, i.e.

$$\Psi_t(^{117}Sn) = \varphi_t = (36.7 \pm 2.7) \cdot 10^{-6}\ rad/cm \qquad (15a)$$

Using the quantity Ψ_t, let us estimate more precisely the effects under discussion near the resonance. According to /17/, for the resonance, $E_p = 1.32$ eV, the neutron width $g\Gamma_n^{(p)} = (1 \pm 0.5)\,10^{-7}$ eV. Therefore, it follows from (4) and (8) that

$$P = \frac{\sigma_+^a - \sigma_-^a}{\sigma_+^a + \sigma_-^a} = (1.3 \pm 0.7) \cdot 10^{-2} \qquad (17)$$

Unfortunately, the total width Γ for the 1.32 eV resonance is unknown. Using as a reference the widths of the higher resonances /17/, we put $\Gamma = 0.08$ eV. The elastic cross section in ^{117}Sn is $\sigma_c \approx 5$ b. The total cross section σ_{tot} in the thermal region and in the p-resonance are approximately equal, and they are 7-8 b. Hence the attenuation length l_0 is about 4 cm. And, finally, we find the following values:

$$a_t = -\Psi_t \cdot \Gamma/2E_p = -1.1 \cdot 10^{-6}\,cm^{-1} \quad or \quad -4 \cdot 10^{-6}\, l/l_0$$

$$\Psi(E_p - \Gamma/2) - \Psi(E_p + \Gamma/2) = 1.2 \cdot 10^{-3}\ rad/cm \quad or \quad 5 \cdot 10^{-3}\, l/l_0\ rad \qquad (18)$$

$$a(E_p) = -1.2 \cdot 10^{-3}\,cm^{-1} \quad or \quad -5 \cdot 10^{-3}\ l/l_0$$

In calculating these quantities we have assumed only that the main contribution to Ψ_t is given by the 1.32 eV resonance. If one supposes, in addition, that the S-resonance nearest to the thermal region has the same angular moment J as the 1.32 eV p-resonance, one can find the coefficient of mixing for these states. In ^{117}Sn the (n,γ)-reaction cross section for thermal neutrons is 2.6 b. It is easy justify that the known resonances with the positive energy contribute $\lesssim 0.2$ b to this cross section. This means that the cross section at a thermal point is determined by the resonance with the negative energy. Using the mean resonance widths $\Gamma_n^{(s)}$ and Γ, we find:

$$E_s \approx -10\,ev, \qquad |\langle s|H_w|p\rangle| = 0.5 \cdot 10^{-3}\,ev$$

$$|\varepsilon| = \left|\frac{\langle s|H_w|p\rangle}{E_s}\right| \approx 0.5 \cdot 10^{-4} \approx 2 \cdot 10^{2}\, G m_\pi^2 \qquad (19)$$

c) Enhancement of the PNC effects in the (n,γ) reaction

Let us start with the effect already discussed in point "a": the difference in the cross sections when the right- and left-polarized neutrons are captured into a p-resonance. It seems that this effect is convenient to search for in the (n,γ) reaction by the counting difference of the number of γ-quanta, since no suppression arises due to the elastic neutron scattering. According to (10), the relative effect is about 10^{-2}.

Let us consider now a circular polarization of γ-quanta in the (n,γ) reaction when capturing the unpolarized neutrons into a p-wave compound-resonance. Because of the difference in the cross sections σ_+^a and σ_-^a, the intermediate compound nucleus turns out to be longitudinally polarized. After decay this polarization is tranferred to the γ-quantum. Thus, the correlation $(\vec{s}_\gamma \vec{p}_\gamma)(\vec{p}_\gamma \vec{p}_n)$ arises, i.e. the degree of circular polarization is $\tilde{P}_\gamma \sim \cos\theta$ (θ is the angle between the photon and neutron moments). The order of magnitude of the circular polarization is $\tilde{P}_\gamma \sim P \sim 10^{-2}$. For example, if the 1.32 eV resonance in ^{117}Sn is assumed to have $J^P = 1^-$, then for transition from it to the ground state ^{118}Sn $|0^+\rangle$

$$\tilde{P}_\gamma = P \cdot \cos\theta = (1.3 \pm 0.7) \cdot 10^{-2} \cos\theta \tag{20}$$

Let us proceed now to a discussion of the "classic" PNC effects in the (n,γ) reaction - the angular asymmetry of γ-quanta (correlation $\vec{s}_n \vec{p}_\gamma$) and the circular polarization of γ-quanta (correlation $\vec{s}_\gamma \vec{p}_\gamma$). These correlations can also be enhanced near a p-wave resonance. We would not like to write down cumbersome formulas for an arbitrary case and therefore we consider a concrete example for which experimental data are available /18,19/: the $^{117}Sn(n,\gamma)$ reaction with transition to the ground state 0^+ of ^{118}Sn. The γ-transition can go from the compound levels 1^+ and 1^-. With the weak interaction taken into account, the reaction amplitude has the form:

$$\frac{\langle 0^+|M1|1^+\rangle\langle 1^+|T_s|n\rangle}{E - E_+ + i\Gamma_+/2} + \frac{\langle 0^+|E1|1^-\rangle\langle 1^-|T_p|n\rangle}{E - E_- + i\Gamma_-/2} +$$

$$+ \frac{\langle 0^+|E1|1^-\rangle\langle 1^-|H_w|1^+\rangle\langle 1^+|T_s|n\rangle}{(E - E_- + i\Gamma_-/2)(E - E_+ + i\Gamma_+/2)} + \tag{21}$$

$$+ \frac{\langle 0^+|M1|1^+\rangle\langle 1^+|H_w|1^-\rangle\langle 1^-|T_p|n\rangle}{(E - E_- + i\Gamma_-/2)(E - E_+ + i\Gamma_+/2)}$$

The fourth term in this formula always is much smaller than the third, and therefore it is unessential. Interference of the second term with the third leads to the correlation $(\vec{s}_\gamma \vec{p}_\gamma)(\vec{p}_\gamma \vec{p}_n)$ already considered. Interference of the first term with the third is responsible for the P-odd correlations $(\vec{s}_\gamma \vec{p}_\gamma)$ and $(\vec{s}_n \vec{p}_\gamma)$. If we are not too close to the p-wave resonance, the second term can be neglected. For the degree of circular polarization and the asymmetry coefficient in the angular distribution of γ-quanta ($W(\theta) = 1 + a\cos\theta$) we obtain:

$$P_\gamma = a = 2\,\mathrm{Re}\left\{\frac{\langle 1^-|H_w|1^+\rangle}{E - E_-}\ \frac{\langle 0^+|E1|1^-\rangle}{\langle 0^+|M1|1^+\rangle}\right\} \tag{22}$$

We would like to attract attention to that the energy denominator in this formula is $E - E_-$ rather than $E_+ - E_-$. This means that at $|E - E_-| << |E_+ - E_-|$ the mixing coefficient is additionally enhanced by the resonance factor $(E_+ - E_-)/(E - E_-)$ in comparison with the standard estimation.

The asymmetry in the angular distribution of γ-quanta in the $^{117}Sn(n,\gamma)$ reaction for thermal neutrons is known from experiment: $a = (8.9 \pm 1.5) \cdot 10^{-4}$ /18/ and $a = (4.4 \pm 0.6) \cdot 10^{-4}$ /19/. Let us make an attempt to compare this value with the results obtained in neutron optics. Unfortunately, the spin of the 1.32 eV resonance is unknown. The possibility of $J = 2$ was excluded when we assumed that this resonance contributes to the neutron spin rotation. If $J = 0$, then this resonance does not contribute to the angular asymmetry of γ-quanta, and there is no direct connection between these effects. It is possible only, taking into account the quantity ε in (19), to write down the standard estimation $|a| \sim |2\varepsilon\, E1/M1| \approx 10^{-4}|E1/M1|$. If $J = 1$, the effects are connected with each other. Using (22) and (19), we find:

$$|a| \approx \left| 2\varepsilon \frac{E_s}{E_p} \frac{E1}{M1} \right| \approx 8\cdot 10^{-4} \left| \frac{E1}{M1} \right| \qquad (23)$$

It is assumed above that only two nearest resonances contribute to the electromagnetic amplitudes ($|S_0\rangle = |1^+, E_s \approx -10\,ev\rangle$ and $|P_0\rangle = |1^-, E_p = 1.32\,ev\rangle$). Taking into account all the resonances, the following should be written:

$$a = -2\,\mathrm{Re} \left\{ \frac{\sum\limits_{p,s} \dfrac{\langle 0^+|E1|p\rangle\langle p|H_W|s\rangle\langle s|T_s|n\rangle}{E_p E_s}}{\sum\limits_{s} \dfrac{\langle 0^+|M1|s\rangle\langle s|T_s|n\rangle}{E_s}} \right\} \qquad (24)$$

One can present the arguments in favour of that the main contribution to the numerator really comes from the nearest resonances. As far as the denominator is concerned, the large number of terms (up to $|E_s| \sim 1$ MeV) is essential here. It means that eq.(23) holds but instead of $M1 = \langle 0^+|M1|S_0\rangle$ the effective amplitude should be used:

$$\widetilde{M1} = \langle 0^+|M1|S_0\rangle + \sum_{s \neq s_0} \frac{E_{s_0}}{E_s} \langle 0^+|M1|s\rangle \frac{\langle s|T_s|n\rangle}{\langle s_0|T_s|n\rangle} \qquad (25)$$

The rough estimation shows that the sum in eq.(25) is of the same order of magnitude as the first term or 2-3 times larger.[2] Therefore, the ratio $|E1 / \widetilde{M1}| \sim 1$ following from the comparison of (23) with experimental data, seems to be reasonable.

To avoid confusion, let us point out that a comparatively large contribution of distant resonances to the M1-amplitude

2) Note, for comparison, that in case of the $^{113}Cd(n,\gamma)^{114}Cd(0^+)$ reaction the sum is significantly smaller than the first term.

arises when we consider the transition to the ground state. Of course, the total cross section of the $^{117}Sn(n,\gamma)$ reaction is mainly determined by the nearest S-resonance.

We are indebted to I.B.Khriplovich for numerous useful discussions.

APPENDIX

A range of parity-nonconservation in nuclear forces. Dynamical enhancement

The parity-nonconserving nucleon weak interaction in the nucleus is approximately described by the effective Hamiltonian:

$$H_w \sim G \frac{\vec{\sigma}\vec{p}}{2m}\rho \qquad (A.1)$$

where $G = 10^{-5}/m_p^2$ is the Fermi constant; $\vec{\sigma}$, $\vec{p}$, m are the nucleon spin, momentum and mass, respectively; ρ is the nuclear density. The mixing coefficient for the single-particle levels of opposite parity is determined by the ratio H_w/ω, where $\omega \sim p^2/2m$ is the typical nucleon energy. In the nucleus $p \sim m_\pi$, $\rho \sim 1/m_\pi^3$, so that

$$F \sim H_w/\omega \sim G m_\pi^2 \approx 2\cdot 10^{-7} \qquad (A.2)$$

Strictly speaking, in this formula ω should be taken as an interval between the single-particle opposite-parity levels, which is usually less than $p^2/2m$. However, the matrix element $\langle H_w \rangle$ is somewhat smaller, as compared to the rough estimate, because of a partial overlap of the wave functions. In view of this, the estimate $F \sim G m_\pi^2 = 2\cdot 10^{-7}$ is likely to be reasonable.

Parity nonconservation in nuclei has been observed in the $^{113}Cd(n,\gamma)$ reaction for the first time (see the review /20/). The asymmetry discovered in the angular distribution of γ-quanta was equal to $-(4.1\pm 0.8)\cdot 10^{-4}$, that is much larger than F. Such an enhancement is mainly connected with a high density of the levels in the compound nucleus /21-23/. Following /23/, this enhancement is referred to as a dynamical one. Remind how this

enhancement arises. The wave function of any state in the compound nucleus can be expanded in the products of the single-particle functions:

$$\Psi = \sum_{i=1}^{N} a_i \varphi_i , \qquad (A.3)$$

where φ_i are the products of the wave functions of the excited particles and the holes. The typical number of the terms in the sum is determined by the intensity of the residual nucleon-nucleon interaction. If ΔE is the range of this interaction and $\mathcal{D}$ is the interval between the levels of the compound nucleus, then $\mathcal{N} \sim \Delta E/\mathcal{D}$. Remind that $\mathcal{D}$ decreases exponentially with increasing the number of excited particles. In heavy fissionable nuclei ($A \approx 240$) $\mathcal{D}$ is about 1 eV. In medium nuclei (Cd, Sn,...) $\mathcal{D}$ is about 10-100 eV. The typical value of $\Delta E \sim \omega \sim 1$ MeV (ω is the interval between single-particle levels), and hence $\mathcal{N} \sim 10^4$-10^6. It is clear that for such strong intermixing the coefficients a_i are of the same order of magnitude. According to the normalization condition, $|a_i| \sim 1/\sqrt{\mathcal{N}}$.

Let us consider now the matrix element of the single-particle operator H_w between two states of the compound nucleus:

$$M = \langle \sum_i a_i \varphi_i \mid H_w \mid \sum_K b_K \varphi_K \rangle = \sum_{iK} a_i^* b_K \langle i | H_w | K \rangle \qquad (A.4)$$

The matrix element at each fixed i is not equal to zero only at one or several values of K when φ_K is distinguished from φ_i by the state of one particle. The signs of the terms in the sum (A.4) are naturally considered to be random. Hence, we have, in formula (A.4), the non-coherent sum of $\mathcal{N}$ terms, each being of the order of $\langle H_w \rangle/\mathcal{N}$. As a result,

$$|M| \sim |\langle H_w \rangle| / \sqrt{N} \tag{A.5}$$

where $\langle H_w \rangle$ is the typical matrix element between the single-particle states. Since the matrix elements in the mixing of different levels in the compound nucleus are of the same order of magnitude, the maximum mixing will occur between the nearest levels. The mixing coefficient is

$$|\varepsilon| \sim \frac{|M|}{D} \sim \frac{|\langle H_w \rangle|}{\omega} \sqrt{N} \sim F\sqrt{N} \tag{A.6}$$

The typical mixing of single-particle levels is F, i.e. the enhancement factor in the fissionable nuclei is $\sqrt{N} \sim 10^3$ and $\sqrt{N} \sim 10^2$ in Cd, Sn,... .

It is worth emphasizing that for dynamical enhancement the fact is of importance that the intensity of the residual nucleon-nucleon interaction, which mixes the single-particle levels, is comparable with the interval between the single-particle levels of opposite parity. For example, let us consider the gas of the particles which move in a common potential but do not interact with each other. In this case, even at high density of the system's levels the interval between mixing levels remains single-particle, and no dynamical enhancement occurs.

REFERENCES

1. M.Forte, B.R.Heckel, N.F.Ramsey, K.Green, G.L.Greene, J.Byrne, J.M.Pendlebury. Phys.Rev.Lett. 45, 2088, 1980.
2. O.P.Sushkov, V.V.Flambaum. Pisma ZhETF (Sov.Phys. JETP Lett.), 32, 377, 1980.
3. L.M.Barkov, M.S.Zolotoryev. Pisma ZhETF (Sov.Phys.JETP Lett.), 27,379, 1978.
4. L.M.Barkov, M.S.Zolotoryev, I.B.Khriplovich. Usp.Fiz.Nauk 132. 410, 1980.
5. F.C.Michel. Phys.Rev., 329B, 133, 1964.
6. L.Stodolsky. Phys.Lett., 50B, 352, 1974.
7. M.Forte. ILL Research proposal 03-03-002, 1976.
8. M.Forte. Inst. Phys. Conf., Ser.N°42, Chapter 2, p. 86,1978.
9. G.Karl and D.Tadic. Phys.Rev. 160C, 172, 1977.
10. G.Karl and R.L.Thews. Rutherford Laboratory 77-041/A (1977).
11. A.Barroso and D.Tadic. J.Phys.Ser. G: Nucl.Phys., 3, L147, 1977.
12. A.Barroso and D.Tadic. Nucl.Phys. 294A, 376, 1978.
13. G.Karl and D.Tadic. Phys.Rev., 20C, 1959, 1979.
14. A.Barroso and F.Margaca. J.Phys. Ser. G: Nucl.Phys., 6G, 657, 1980.
15. M.Forte. Nuovo Cimento Lett., 28, 538, 1980.
16. L.Stodolsky. Phys.Lett., 96B, 127, 1980.
17. Neutron Cross Sections, 3rd Edition, vol.1. S.F.Mughabghab and D.J.Garber, Broockhaven National Laboratory (1973).
18. G.V.Danilyan in Proceedings of the XII Leningrad Nuclear Physics Winter School (USSR Acad. Sci., Leningrad,1977),p.4.
19. H.Benkoula et al. Phys.Lett. 71B, 287, 1977.
20. Yu.G.Abov, P.A.Krupchitsky. Usp.Fiz.Nauk, 118, 141, 1976.

21. R.Haas, L.B.Leipuner and R.K.Adair. Phys.Rev., 116, 1221, 1959.

22. R.J.Blin-Stoyle. Phys.Rev. 120, 181, 1960.

23. I.S.Shapiro. Usp.Fiz.Nauk, 95, 647, 1968.

Работа поступила - 25 февраля 1981 г.

Ответственный за выпуск - С.Г.Попов
Подписано к печати 9.3-1981 г. МН 06148
Усл. 1,0 печ.л., 0,8 учетно-изд.л.
Тираж 200 экз. Бесплатно
Заказ № 37.

Отпечатано на ротапринте ИЯФ СО АН СССР