ENHANCEMENT OF THE FUNDAMENTAL SYMMETRY BREAKING EFFECTS IN NEUTRON RESONANCES: KINEMATIC OR RESONANCE?

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About 40 years ago theoretical predictions appeared of a possible huge (by a factor about a million) enhancement of P-violation effects in resonance neutron transmission. The P-violation experiment in neutron transmission was done at Frank Laboratory of Neutron Physics in JINR discovering the effect of several percents (instead of the usual 10^{-7}). Similar results were obtained later at Los Alamos (USA) and KEK (Japan).

However, the theoretical explanations of these enhancements still differ.

Consider **P-violation in polarized neutron transmission through unpolarized target**. The observed **longitudinal asymmetry** would be:

$$P_{\exp} = \frac{N_{+} - N_{-}}{N_{+} + N_{-}} \approx \frac{\Delta_{tot}^{P}}{\sigma_{tot}}$$

Here $N_{\pm}$ is the number of neutrons with opposite helicities transmitted through the target sample, while the corresponding total cross-section for such neutrons is

$$\sigma_{tot}^{\pm} = \sigma_{tot} \pm \frac{\Delta_{tot}^{P}}{2}$$

There are **two different theoretical approaches to the problem** existing for already 40 years.

One of them (e.g. O. Sushkov and V. Flambaum, Sov. Phys. Usp. 25, 1(1982); V. V. Flambaum , A.J. Mansour. Phys. Rev. C **105**, 015501).

In the p-wave resonance ($l=1$) (i.e. at neutron energy $E_n \simeq E_p$) the effect is:

$$P \approx 2\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}}\frac{V_P}{D}$$

Here V_P is the weak interaction matrix element between the s- and p-resonance wave functions. $\Gamma_{s,p}^n$ are s- or p-resonance neutron widths. D is the spacing between the neighboring s- an p- levels of the compound nucleus. For the low-energy resonances in the eV region the **ratio** $\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}} \approx \frac{1}{kR} \approx 10^3$ **makes the kinematical enhancement factor**. The quantity $V_P / D \approx 10^3$ contains another factor of **dynamical enhancement** due to the smallness of the compound resonance spacing D.

No consistent derivation was ever given of this expression. Just semi-intuitive guesses based on the analogy to the P-violation for the bound states. All the enhancements of the P-violation effects in γtransitions between the compound-nucleus states were analyzed in the classical paper by I.S. Shapiro (I.S.Shapiro, Sov. Phys.Uspekhi. **95**, 647 (1968). The source of these effects is the weak interaction V_W leading to the fact that the wave function ψ_i of this state contains, besides the wave function of a definite parity ψ_1, the small admixture ψ_2 of the opposite parity state

$$\psi_i = \psi_1 + c\psi_2$$

The effect is defined by the ratio of the P-forbidden transition normalized by the total transition value:

$$R = \frac{c(A_a \bullet A_f)}{(A_a + A_f)^2} \approx \frac{cA_f}{A_a}$$

Here A_a and A_f are the amplitudes of the P-allowed and P-forbidden γ-transitions, while c is the parity admixture coefficient:

$$c = \frac{<\psi_2 | V_W | \psi_1>}{|E_1 - E_2|} \equiv \frac{V_p}{D}$$

According to Shapiro, **the kinematical enhancement** appears when the allowed transition A_a is the magnetic one which is smaller than the forbidden electric A_f of the same multipolarity by the factor $A_f / A_a \approx 10$.

The intuitive guess was to substitute the amplitudes A_a and A_f by the values $\sqrt{\Gamma_p^n}$ and $\sqrt{\Gamma_s^n}$ correspondingly, thus obtaining the kinematical enhancement of the effect by the ratio $\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}} \approx \frac{1}{kR} \approx 10^3$.

<u>**Thus we are lead to the absurd conclusion**</u>: The largest effect is obtained by choosing the vanishingly small p-wave resonance with $\Gamma_p^n \to 0$. Even better is to look not for the p-wave, but rather for the f-wave (i.e. $l = 3$) resonance. Then the enhancement would be $\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}} \approx \frac{1}{kR^3} \approx 10^9$ (???). Of course, the contribution of these resonances to the cross-section is so negligible that they were never observed. We also understand that the P-violation should not exceed 100%. Nevertheless, these are the absurd implications of this theoretical approach.

In the alternative theoretical approach (e.g. V. Bunakov, V. Gudkov. Nucl. Phys. A 401, 93 (1983); V. E. Bunakov, L.B. Pikelner. Prog. Part. Nucl. Phys. **39,** 337 (1997**)** **one calculates the quantity:**

$$\Delta_{tot}^{P} = \sigma_{tot}^{+} - \sigma_{tot}^{-} = \frac{4\pi}{k} \mathrm{Im}(f_{+} - f_{-}) = \frac{8\pi}{k} \mathrm{Im}\, f_W$$

Here $f_{\pm}$ are forward angle scattering amplitudes for polarized neutrons with opposite helicities, while f_W **is the weak interaction part of this amplitude**. In these calculations we follow the approach of Mahaux and Weidenmueller (“Shell-model approach to nuclear reactions”. North-Holland, Amsterdam, 1966) which is a projection of Feschbah’s unified theory of nuclear reactions on the realistic shell-model basis. The calculations give **9 terms corresponding to 9 different processes** (neutron potential scattering by weak potential, weak interaction absorption into resonance states, etc.). The **largest among them is the weak interaction mixing of s- and p- wave resonanc**es because it contains the dynamical enhancement factor V_P / D). Thus, one obtains:

$$\Delta_{tot}^{P} = \frac{8\pi}{k^2} \frac{\sqrt{\Gamma_p^n} \cdot V_P \cdot \sqrt{\Gamma_s^n}}{[(E-E_p)^2 + \Gamma_p^2/4][(E-E_s)^2 + \Gamma_s^2/4]} [(E-E_s)\Gamma_p + (E-E_p)\Gamma_s]$$

Near p-wave resonance energy we have:

$$\Delta_{tot}^{P} \approx \frac{8\pi}{k^2} \frac{V_p}{D} \frac{\sqrt{\Gamma_s^n \Gamma_p^n} \cdot \Gamma_p}{(E-E_p)^2 + \Gamma_p^2/4}$$

containing “resonance” enhancement factor:

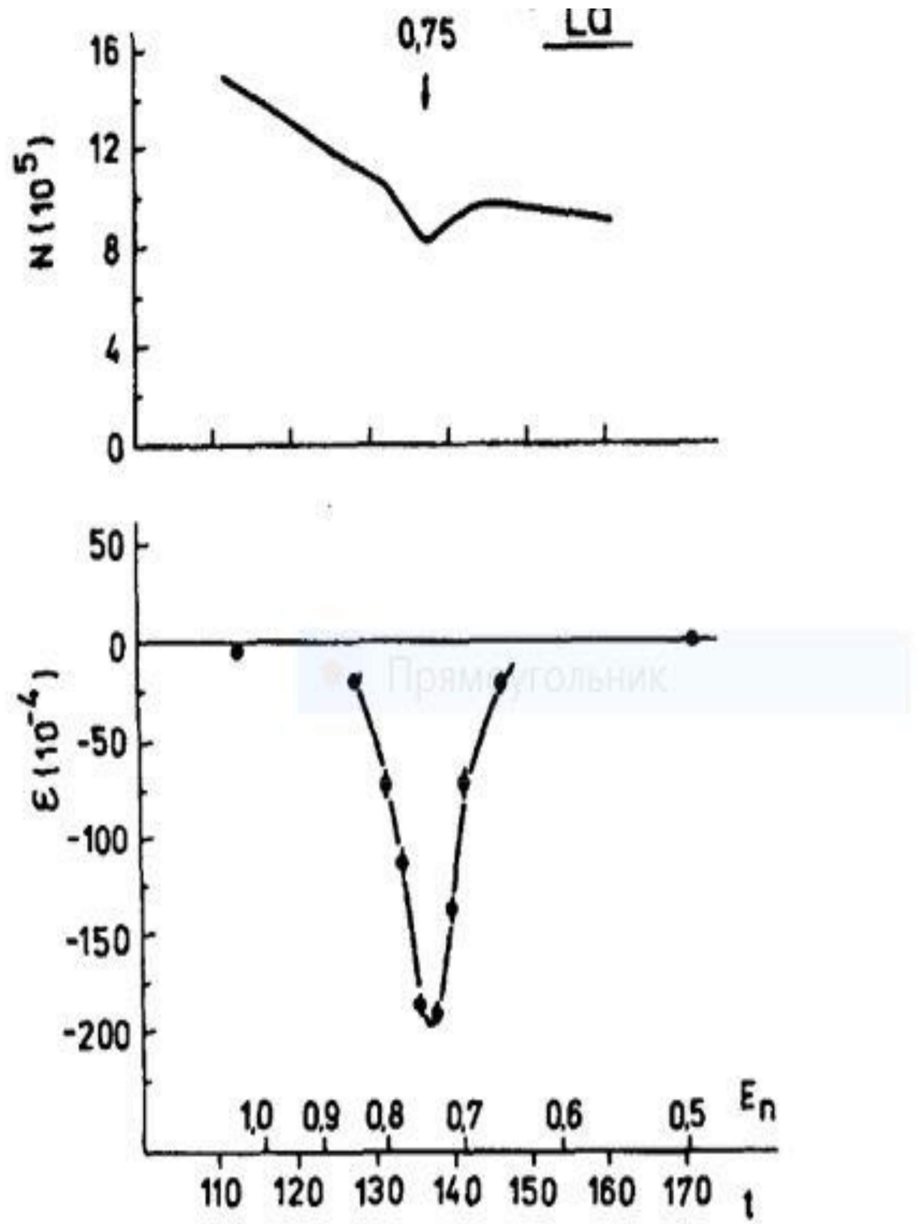
$$\frac{\Gamma_p}{(E-E_p)^2+\Gamma_p^2/4}=\frac{T(E)}{\hbar}$$

where $T(E)$ is the **"delay time" spent by the neutron in the weak field of the target nucleus** (Wu, T. Ohmura. Quantum Theory of Scattering. Prentice Hill, N.J. 1962).

When the energy changes from the off-resonance point $|E-E_p|\approx|E-E_s|\approx D/2$ to resonance maxima $E=E_p$ **the RESONANCE ENHANCEMENT** takes place by a factor of about $(D/\Gamma)^2\sim 10^6$ caused by the fact that **neutron spends a larger time (**$\tau_{res}\approx\hbar/\Gamma$**) in the weak P-violating field.** The denominator of $P_{\exp}(E)$ is roughly**:**

$$\sigma_{tot}(E)\approx\frac{\pi}{k^2}\left[\sum_s\frac{\Gamma_n^s\Gamma_s}{(E-E_s)^2+\Gamma_s^2/4}+4(kR)^2+\frac{\Gamma_n^p\Gamma_p}{(E-E_p)^2+\Gamma_p^2/4}\right]$$

Even in the p-wave resonance maximum the main contribution to $\sigma_{tot}(E)$ comes from the "s-resonances' tails" and potential scattering: Experimental spectrum of neutrons transmitted through the sample of La^{139} in the vicinity of p-wave resonance at $E_p=0.75eV$ shows that p-resonance contribution to σ_{tot} is negligible, while $\sigma_{tot}(E)$ value remains practically constant (less than 10% deviation).



0,75
La
N (10^5)
16
12
8
4
0
50
0
-50
-100
-150
-200
ε (10^-4)
Прямоугольник
1,0
0,9
0,8
0,7
0,6
0,5
E_n
110
120
130
140
150
160
170
t

Therefore, the experimentally observed quantity:

$$P_{\exp}(E) \approx \frac{4\pi}{k^2\sigma_{tot}(E)} \frac{W_p}{D} \frac{\sqrt{\Gamma_s^n\Gamma_p^n}\cdot\Gamma_p}{(E-E_p)^2+\Gamma_p^2/4} \equiv \varepsilon(E)$$

shows resonance behavior with the value **at maximum** $|P_{\exp}(E_p)| = 0.02$**.**

The effect is <u>proportional</u> to $\sqrt{\Gamma_p^n}$ **(one should choose the strong p-resonance for larger effect).**

<u>Summary</u>: The "kinematical enhancement" approach to neutron transmission experiments gives a very distorted picture of the enhancement phenomenon and leads to absurd conclusions on the choice of the best experimental option.

Resonance enhancement reveals the real origin of the phenomenon (delay time spent by neutron in the target weak interaction field) and is supported by experiment.

P.S. The kinematic enhancement in case of the bound states experiments although does not lead to absurd conclusions, but can not increase the accuracy of the symmetry-breaking measurements while the resonance enhancement can (e.g. V. E. Bunakov, Phys. Atom. Nucl. **77**, 85 (2014)).