MIXING OF THE *S*-WAVE AND *P*-WAVE RESONANCES AND *P*-ODD ASYMMETRY OF γ-QUANTUM EMISSION IN THE RADIATIVE CAPTURE OF A SLOW POLARIZED NEUTRON BY A SPINLESS NUCLEUS

V. L. Lyuboshitz, V. V. Lyuboshitz *

Joint Institute for Nuclear Research,
141980 Dubna, Moscow Region, Russia

** E-mail: Valery.Lyuboshitz@jinr.ru*

Abstract

Using the technique of helicity amplitudes, the theoretical consideration of the *P*-odd asymmetry of γ-quantum emission in the radiative capture of an *S*-wave polarized neutron by a nucleus with zero spin, which is conditioned by the mixing of *S*-wave and *P*-wave resonances with equal spins and opposite space parities on account of weak interaction, has been performed. It is shown that, under the parity nonconservation, the differential cross section of the radiative capture of a slow neutron by a spinless nucleus is anisotropic and has the following structure: $A + B\,(\mathbf{P}, \mathbf{l}_\gamma)$, where the coefficients *A* and *B* depend on the neutron energy but do not depend upon the angle of γ-quantum emission, the coefficient *A* depends also on the parameters of the *S*-wave resonance, and the coefficient *B* depends upon the parameters of both the *S*-wave and *P*-wave resonances as well as upon the matrix element of mixing due to weak interaction, **P** is the neutron polarization vector and $\mathbf{l}_\gamma$ is the unit vector directed along the γ-quantum momentum .

1. Helicity amplitudes and differential cross sections of resonance binary processes

The helicity amplitude of a binary resonance process $a + b \to R \to c + d$ has the following structure :

$$f_{ab\to cd}(\lambda_a,\lambda_b;\ \lambda_c,\lambda_d) = \frac{2J_R+1}{2\sqrt{k_{ab}\,k_{cd}}}\ \frac{A_b(\lambda_a,\lambda_b)\, d^{(J_R)}_{\Lambda'\Lambda}(\theta)\, e^{i\Lambda\varphi} A_f(\lambda_c,\lambda_d)}{E_R - E - \frac{i}{2}\Gamma_R} \quad . \quad (1)$$

Here J_R is the resonance spin , E_R is the resonance energy, Γ_R is the total resonance width, $\lambda_a,\lambda_b,\lambda_c,\lambda_d$ are helicities of the primary and final particles, $A_b(\lambda_a,\lambda_b)$ are the helicity amplitudes of resonance decay into the channel $R \to a + b$, $A_f(\lambda_c,\lambda_d)$ are the helicity amplitudes of resonance decay into the channel $R \to c + d$, $d^{(J_R)}_{\Lambda'\Lambda}(\theta)$ are Wigner d -functions of the order J_R , θ is the angle between the momentum $\hbar\,\mathbf{k}_{ab}$ of the primary particle a and the momentum $\hbar\,\mathbf{k}_{cd}$ of the final particle c in the reaction c.m. frame, φ is the azimuthal angle , $k_{ab} = |\,\mathbf{k}_{ab}\,|$, $k_{cd} = |\,\mathbf{k}_{cd}\,|$,

$$\Lambda' = \lambda_c - \lambda_d\,,\quad \Lambda = \lambda_a - \lambda_b \tag{2}$$

are the differences of helicities for the final particles and primary particles, respectively, which satisfy the conditions :

$$\Lambda' \le J_R\,,\quad \Lambda' \le s_c + s_d\,;\qquad \Lambda \le J_R\,,\quad \Lambda \le s_a + s_b\quad , \tag{3}$$

where s_a, s_b, s_c, s_d are the spins of the primary and final particles .

In doing so, the sums

$$\sum_{\lambda_a\lambda_b} |\,A_b(\lambda_a,\lambda_b)\,|^2 = \Gamma^{(R)}_{ab},\qquad \sum_{\lambda_c\lambda_d} \left|\,A_f(\lambda_c,\lambda_d)\,\right|^2 = \Gamma^{(R)}_{cd} \tag{4}$$

have the meaning of partial widths of the resonance decay into the channels $R \to a + b$ and $R \to c + d$, respectively. It is obvious that

$$\sum_{ab}\Gamma^{(R)}_{ab} = \sum_{cd}\Gamma^{(R)}_{cd} = \Gamma_R \quad , \tag{5}$$

where Γ_R is the total resonance width included in Eq. (1) .

The differential cross section of the resonance binary process , summed over the spin projections of the final particles c and d and averaged over the spin projections of the primary particles a and b , amounts to :

$$\frac{d\sigma_{a+b\to R\to c+d}}{d\Omega}(\lambda_a,\lambda_b;\ \lambda_c,\lambda_d) = \frac{k_{cd}}{k_{ab}}\left| f_{ab\to cd}(\lambda_a,\lambda_b;\ \lambda_c,\lambda_d)\right|^2 =$$

$$= \frac{(2J_R+1)^2}{4k^2(2s_a+1)(2s_b+1)}\ \frac{1}{(E_R-E)^2+\frac{1}{4}\Gamma_R^2} \times \tag{6}$$

$$\times \sum_{\lambda_a\lambda_b}\sum_{\lambda_c\lambda_d}\left[(A_b(\lambda_a,\lambda_b))^2 (d^{(J_R)}_{\Lambda'\Lambda}(\theta))^2 (A_f(\lambda_c,\lambda_d))^2\right]$$

(here $k \equiv k_{ab}$) .

Taking into account the relation :

$$\int (d^{(J_R)}_{\Lambda'\Lambda}(\theta))^2 d\Omega = \frac{4\pi}{2J_R + 1} \qquad , \qquad (7)$$

which is true at any values of Λ' and Λ (integration is performed over the full solid angle), the integral cross section of the resonance binary reaction $a + b \to R \to c + d$ equals :

$$\sigma_{a+b\to R\to c+d} = \frac{2J_R + 1}{(2s_a + 1)(2s_b + 1)} \frac{\pi}{k^2} \frac{\Gamma^{(R)}_{ab}\Gamma^{(R)}_{cd}}{(E_R - E)^2 + \frac{1}{4}\Gamma_R^2} \qquad (8)$$

(we have applied Eqs. (4)) .

Let us consider now the neutron radiative capture by a nucleus $n + a \to \gamma + c$. According to Eq. (8), the integral cross section of resonance radiative capture on an unpolarized nucleus is as follows :

$$\sigma_{n+a\to R\to\gamma+c} = \frac{2J_R + 1}{2\,(2s_a + 1)} \frac{\pi}{k^2} \frac{\Gamma_n\,\Gamma_\gamma}{(E_R - E)^2 + \frac{1}{4}\Gamma_R^2} \qquad , \qquad (9)$$

where Γ_n is the neutron width and Γ_γ is the radiative width .

If the nucleus a is spinless , then in case of the S-wave resonance $J_R = \frac{1}{2}$, $s_a = 0$, and Eq. (9) gives :

$$\sigma_{n+a\to R\to\gamma+c} = \frac{\pi}{k^2} \frac{\Gamma^{(s)}_n\,\Gamma_\gamma}{(E_R - E)^2 + \frac{1}{4}\Gamma_R^2} \qquad . \qquad (10\ )$$

It is easy to see that in this case the differential cross-section of radiative capture is isotropic and it does not depend upon the neutron polarization :

$$\frac{d\sigma_{n+a\to R\to\gamma+c}}{d\Omega}=\frac{1}{4k^2}\frac{\Gamma_n^{(s)}\,\Gamma_\gamma}{(E_R-E)^2+\frac{1}{4}\Gamma_R^2} \quad . \tag{11}$$

2. Mixing of the S-wave and P-wave resonances with opposite space parities

Under the space parity nonconservation, the *S*-wave and *P*-wave resonances with equal spins are mixed by the weak interaction. The new quasistationary states with mixed parity have the form [1,2] :

$$|s'\rangle=|s\rangle+\varepsilon|p\rangle \ , \quad |p'\rangle=|p\rangle-\varepsilon|s\rangle \ , \tag{12}$$

where $|s\rangle$ and $|p\rangle$ are the *S*-wave and *P*-wave states with the positive and negative parity, respectively, ε is the mixing parameter. In the Born approximation, we have :

$$\varepsilon=\frac{W_{sp}}{E_s-E_p-\frac{i}{2}(\Gamma_s-\Gamma_p)} \quad , \tag{13}$$

where $W_{sp}=\langle p|W|s\rangle$ is the matrix element of weak interaction, E_s ,E_p are energies of the *S*- and *P*-wave resonances being mixed, Γ_s, Γ_p are their widths. Due to hermiticity and *T* invariance, $W_{sp}=W_{ps}$, Im $W_{sp}=0$. Obviously, $|\varepsilon|<<1$.

Taking into account the smallness of the mixing parameter, we have neglected the contribution of terms of the order of $|\varepsilon|^2$ into the normalizing multipliers for the states $|s'\rangle$ and $|p'\rangle$. In doing so, $E_{s'}\approx E_s$, $\Gamma_{s'}\approx\Gamma_s$, $E_{p'}\approx E_p$, $\Gamma_{p'}\approx\Gamma_p$.

According to relations (12), the states with definite space parity represent the superpositions of the quasistationary states $|s'\rangle$ and $|p'\rangle$:

$$|s\rangle=|s'\rangle-\varepsilon|p'\rangle \ , \quad |p\rangle=|p'\rangle+\varepsilon|s'\rangle \quad . \tag{14}$$

Since the slow neutron is captured by the nucleus a into the *S*-state ($|s\rangle$) , the spins of the *S*-wave resonance and the *P*-wave resonance being admixed are equal to :

$$J_R^{(S)}=J_R^{(P)}=s_a\pm\frac{1}{2} \quad , \tag{15}$$

where s_a is the spin of the primary nucleus a .

3. Helicity amplitudes of resonance radiative capture of neutrons at the mixing of S-wave and P-wave resonances

Let us consider the *P*-odd asymmetry at the radiative capture of a polarized slow neutron by a nucleus with zero spin [2,3] . In this case, the neutron is captured into the *S*-state $|\, s\rangle = |\, s'\rangle - \varepsilon\, |\, p'\,\rangle$ with spin $J_R^{(S)} = J_R^{(P)} = \frac{1}{2}$.

At the electric and magnetic dipole radiation, the spins of the final nucleus c can take the values $s_c = \frac{1}{2}$ and $s_c = \frac{3}{2}$. To be definite, we will consider that $s_c = \frac{1}{2}$. The γ-quantum helicities can take the values $\lambda_\gamma = +1$ and $\lambda_\gamma = -1$, and the helicities of the final nucleus c with spin $\frac{1}{2}$: $\lambda_c = +\frac{1}{2}$ and $\lambda_c = -\frac{1}{2}$.

At the total angular momentum $J_R = \frac{1}{2}$, the nonzero helicity amplitudes of the decay into the γ quantum and the final nucleus are : $a_\gamma(1, -\frac{1}{2})$ and $a_\gamma(-1, +\frac{1}{2})$.

In doing so,

$$a_n^{(s)}(-\frac{1}{2}) = a_n^{(s)}(+\frac{1}{2}) \ , \quad a_\gamma^{(s)}(1, -\frac{1}{2}) = a_\gamma^{(s)}(-1, +\frac{1}{2}) \quad , \qquad (16)$$

$$a_\gamma^{(p)}(1, -\frac{1}{2}) = -\, a_\gamma^{(p)}(-1, +\frac{1}{2}) \quad . \qquad (17)$$

Taking into account relations (1) and (12)–(14), the helicity amplitudes of the resonance process have the form :

$$f_{n+a\to\gamma+c}(+\frac{1}{2};\,1,-\frac{1}{2})=$$

$$=\frac{a_n^{(s)}(+\frac{1}{2})}{\sqrt{k_n k_\gamma}}\,d^{(1/2)}_{1/2,1/2}(\theta)\,e^{i\frac{\varphi}{2}}\left[\frac{a_\gamma^{(s)}(1,-\frac{1}{2})+\varepsilon\,a_\gamma^{(p)}(1,-\frac{1}{2})}{E_s-E-\frac{i}{2}\Gamma_s}-\frac{\varepsilon\,a_\gamma^{(p)}(1,-\frac{1}{2})}{E_p-E-\frac{i}{2}\Gamma_p}\right]=$$

$$=\frac{a_n^{(s)}(+\frac{1}{2})}{\sqrt{k_n k_\gamma}}\,d^{(1/2)}_{1/2,1/2}(\theta)\,e^{i\frac{\varphi}{2}}\left[\frac{a_\gamma^{(s)}(1,-\frac{1}{2})}{E_s-E-\frac{i}{2}\Gamma_s}+\frac{W_{sp}\,a_\gamma^{(p)}(1,-\frac{1}{2})}{(E_s-E-\frac{i}{2}\Gamma_s)\,(E_p-E-\frac{i}{2}\Gamma_p)}\right]\ ,$$

$$f_{n+a\to\gamma+c}(+\frac{1}{2};-1,+\frac{1}{2})=$$

$$=\frac{a_n^{(s)}(+\frac{1}{2})}{\sqrt{k_n k_\gamma}}\,d^{(1/2)}_{-1/2,1/2}(\theta)\,e^{i\frac{\varphi}{2}}\left[\frac{a_\gamma^{(s)}(-1,+\frac{1}{2})}{E_s-E-\frac{i}{2}\Gamma_s}+\frac{W_{sp}\,a_\gamma^{(p)}(-1,+\frac{1}{2})}{(E_s-E-\frac{i}{2}\Gamma_s)\,(E_p-E-\frac{i}{2}\Gamma_p)}\right]\ ,$$

(18)

$$f_{n+a\to\gamma+c}(-\frac{1}{2};\,1,-\frac{1}{2})=$$

$$=\frac{a_n^{(s)}(-\frac{1}{2})}{\sqrt{k_n k_\gamma}}\,d^{(1/2)}_{1/2,-1/2}(\theta)\,e^{-i\frac{\varphi}{2}}\left[\frac{a_\gamma^{(s)}(1,-\frac{1}{2})}{E_s-E-\frac{i}{2}\Gamma_s}+\frac{W_{sp}\,a_\gamma^{(p)}(1,-\frac{1}{2})}{(E_s-E-\frac{i}{2}\Gamma_s)\,(E_p-E-\frac{i}{2}\Gamma_p)}\right]\ ,$$

$$f_{n+a\to\gamma+c}(-\frac{1}{2};\,-1,+\frac{1}{2})=$$

$$=\frac{a_n^{(s)}(-\frac{1}{2})}{\sqrt{k_n k_\gamma}}\,d^{(1/2)}_{-1/2,-1/2}(\theta)\,e^{-i\frac{\varphi}{2}}\left[\frac{a_\gamma^{(s)}(-1,+\frac{1}{2})}{E_s-E-\frac{i}{2}\Gamma_s}+\frac{W_{sp}\,a_\gamma^{(p)}(-1,+\frac{1}{2})}{(E_s-E-\frac{i}{2}\Gamma_s)\,(E_p-E-\frac{i}{2}\Gamma_p)}\right]\ .$$

(19)

Here $k_n = |\mathbf{k}_n|$, $k_\gamma = |\mathbf{k}_\gamma|$, where $\hbar\,\mathbf{k}_n$ and $\hbar\,\mathbf{k}_\gamma$ are the respective momenta of the neutron and γ quantum in the c.m. frame of the resonance reaction $n + a \to \gamma + c$.

4. P-odd asymmetry at the radiative capture of slow polarized neutrons

Let us remark that, taking into account *T* invariance, all the helicity amplitudes of decay may be considered to be real, neglecting the electromagnetic final-state interaction .

In accordance with relations (16), we have :

$$\left(a_n^{(s)}(+\frac{1}{2})\right)^2 = \left(a_n^{(s)}(-\frac{1}{2})\right)^2, \quad \left(a_\gamma^{(s)}(1,-\frac{1}{2})\right)^2 = \left(a_\gamma^{(s)}(-1,+\frac{1}{2})\right)^2,$$

$$\left(a_\gamma^{(p)}(1,-\frac{1}{2})\right)^2 = \left(a_\gamma^{(p)}(-1,+\frac{1}{2})\right)^2, \tag{20}$$

$$a_\gamma^{(s)}(-1,+\frac{1}{2})\,a_\gamma^{(p)}(-1,+\frac{1}{2}) = -\,a_\gamma^{(s)}(1,-\frac{1}{2})\,a_\gamma^{(p)}(1,-\frac{1}{2}) \ .$$

.Disregarding the second-order terms $\sim W_{sp}^2$, we obtain – taking into account equalities (20) – the following expressions for the differential cross section of radiative capture of slow neutrons with the helicities $(+\frac{1}{2})$ and $(-\frac{1}{2})$ by a spinless nucleus :

$$\frac{d\sigma}{d\Omega}(+\frac{1}{2})\Big|_{n+a\to\gamma+c} =$$

$$= \frac{k_\gamma}{k_n}\left[\left|f_{n+a\to\gamma+c}(+\frac{1}{2};\ 1,\ -\frac{1}{2})\right|^2 + \left|f_{n+a\to\gamma+c}(+\frac{1}{2};\ -1,\ +\frac{1}{2})\right|^2\right] =$$

$$= \frac{1}{k_n^2}\,\frac{|a_n^{(s)}(\ +\frac{1}{2}\ )|^2\ |a_\gamma^{(s)}(\ 1,\ -\frac{1}{2}\ )|^2}{(E_s-E)^2+\frac{\Gamma_s^2}{4}}\ \left[\left(d^{(1/2)}_{1/2,\,1/2}(\theta)\right)^2+\left(d^{(1/2)}_{-1/2,\,1/2}(\theta)\right)^2\right]+$$

$$+\frac{2}{k_n^2}\,\frac{|a_n^{(s)}(\ +\frac{1}{2}\ )|^2\ a_\gamma^{(s)}(\ 1,\ -\frac{1}{2}\ )\ W_{sp}\ a_\gamma^{(p)}(\ 1,\ -\frac{1}{2}\ )\ (E_p-E)}{\left[(E_s-E)^2+\frac{\Gamma_s^2}{4}\right]\left[(E_p-E)^2+\frac{\Gamma_p^2}{4}\right]}\times$$

$$\times\left[\left(d^{(1/2)}_{1/2,\,1/2}(\theta)\right)^2-\left(d^{(1/2)}_{-1/2,\,1/2}(\theta)\right)^2\right],$$

(21)

$$\frac{d\sigma}{d\Omega}(-\frac{1}{2})\Big|_{n+a\to\gamma+c} = \frac{k_\gamma}{k_n}\left[\left|f_{n+a\to\gamma+c}(-\frac{1}{2};\ 1,-\frac{1}{2})\right|^2 + \left|f_{n+a\to\gamma+c}(-\frac{1}{2};\ -1,+\frac{1}{2})\right|^2\right] =$$

$$= \frac{1}{k_n^2}\,\frac{|\,a_n^{(s)}(-\frac{1}{2})\,|^2\,|\,a_\gamma^{(s)}(1,-\frac{1}{2})\,|^2}{(E_s-E)^2+\frac{\Gamma_s^2}{4}}\ \left[\left(d^{(1/2)}_{1/2,\,-1/2}(\theta)\right)^2+\left(d^{(1/2)}_{-1/2,\,-1/2}(\theta)\right)^2\right]+$$

$$+\frac{2}{k_n^2}\,\frac{|\,a_n^{(s)}(-\frac{1}{2})\,|^2\ a_\gamma^{(s)}(1,-\frac{1}{2})\,W_{sp}\ a_\gamma^{(p)}(1,-\frac{1}{2})\,(E_p-E)}{\left[(E_s-E)^2+\frac{\Gamma_s^2}{4}\right]\left[(E_p-E)^2+\frac{\Gamma_p^2}{4}\right]}\times$$

$$\times\left[\left(d^{(1/2)}_{1/2,\,-1/2}(\theta)\right)^2-\left(d^{(1/2)}_{-1/2,\,-1/2}(\theta)\right)^2\right].$$

(22)

As it is known, the d -functions corresponding to the angular momentum $1/2$ have the form :

$$d^{(1/2)}_{1/2,\,1/2}(\theta)=d^{(1/2)}_{-1/2,\,-1/2}(\theta)=\cos\frac{\theta}{2}\ ,\qquad d^{(1/2)}_{-1/2,\,1/2}(\theta)=-\,d^{(1/2)}_{1/2,\,-1/2}(\theta)=\sin\frac{\theta}{2}\ . \qquad (23)$$

Without losing generality, the phases of states $|s\rangle$ and $|p\rangle$ may be chosen in such a way that :

$$|a_n^{(s)}(+\frac{1}{2})|^2 = \frac{\Gamma_n^{(s)}}{2}\ , \quad \left(a_\gamma^{(s)}(1,-\frac{1}{2})\right)^2 = \frac{\Gamma_\gamma^{(s)}}{2}, \quad \left(a_\gamma^{(p)}(1,-\frac{1}{2})\right)^2 = \frac{\Gamma_\gamma^{(p)}}{2},$$

$$a_\gamma^{(s)}(1,-\frac{1}{2})\ a_\gamma^{(p)}(1,-\frac{1}{2}) = \frac{1}{2}\sqrt{\Gamma_\gamma^{(s)}\Gamma_\gamma^{(p)}}\quad , \tag{24}$$

where Γ_n is the neutron width of the *S*-wave resonance, $\Gamma_\gamma^{(s)}$ and $\Gamma_\gamma^{(p)}$ are the radiative widths of the *S*-wave and *P*-wave resonances, respectively .

Taking into account Eqs. (23) and (24), in the considered case of radiative capture of slow neutrons with helicities $(+\frac{1}{2})$ and $(-\frac{1}{2})$ the differential cross section has the following structure :

$$\frac{d\sigma}{d\Omega}(+\frac{1}{2})\Big|_{n+a\to\gamma+c} = A + B\cos\theta\ ,$$

$$\frac{d\sigma}{d\Omega}(-\frac{1}{2})\Big|_{n+a\to\gamma+c} = A - B\cos\theta\ , \tag{25}$$

where

$$A = \frac{1}{4k_n^2}\ \frac{\Gamma_n^{(s)}\ \Gamma_\gamma^{(s)}}{(E_s - E)^2 + \frac{\Gamma_s^2}{4}}\quad , \tag{26}$$

$$B = \frac{1}{2k_n^2}\ \frac{\Gamma_n^{(s)}\, W_{sp}\sqrt{\Gamma_\gamma^{(s)}\Gamma_\gamma^{(p)}}\ (E_p - E)}{\left[(E_s - E)^2 + \frac{\Gamma_s^2}{4}\right]\left[(E_p - E)^2 + \frac{\Gamma_p^2}{4}\right]}\quad , \tag{27}$$

and θ has the meaning of the angle between the neutron and γ-quantum momenta .

Let us note that, as follows from relations (18), (19) and equalities (16), (20), the products of helicity amplitudes of the reaction $n + a \to \gamma + c$, correspond-ding to the opposite primary helicities and equal final helicities, are expressed through the quantity B and the angles determining the direction of vector $\mathbf{k}_\gamma$:

$$\frac{k_\gamma}{k_n}\left[f^*_{n+a\to\gamma+c}(+\frac{1}{2};\ 1,-\frac{1}{2})\ f_{n+a\to\gamma+c}(-\frac{1}{2};\ 1,-\frac{1}{2}) + \right.$$
$$\left. + \ f^*_{n+a\to\gamma+c}(+\frac{1}{2};\ -1,+\frac{1}{2})\ f_{n+a\to\gamma+c}(-\frac{1}{2};-1,+\frac{1}{2}) \right] =$$

$$= B\left[d^{(1/2)}_{1/2,1/2}(\theta)\, d^{(1/2)}_{1/2,-1/2}(\theta)\, e^{\,i\varphi} - d^{(1/2)}_{-1/2,1/2}(\theta)\, d^{(1/2)}_{-1/2,-1/2}(\theta)\, e^{-i\varphi} \right] = B\sin\theta\cos\varphi \ .$$

(28)

Thus, at the parity-violating mixing of the *S*-wave and *P*-wave resonances, the differential cross section of radiative capture of a slow neutron with an arbitrary vector of spin polarization $\mathbf{P}$ is as follows :

$$\left.\frac{d\sigma}{d\Omega}\right|_{n+a\to\gamma+c} = A + B\,(P_{||}\cos\theta + P_\perp \sin\theta\cos\varphi\,) \quad , \qquad (29)$$

where the quantities A and B are determined according to Eqs. (26), (27), $P_{||}$ is the degree of neutron longitudinal polarization, $P_\perp$ is the degree of neutron transverse polarization, θ is the angle between the vectors $\mathbf{k}_n$, $\mathbf{k}_\gamma$; φ is the angle between the neutron polarization plane $(\mathbf{P},\mathbf{k}_n)$ and the reaction plane $(\mathbf{k}_\gamma,\ \mathbf{k}_n)$.

Formula (29) may be rewritten in the simple form :

$$\left.\frac{d\sigma}{d\Omega}\right|_{n+a\to\gamma+c} = A + B\,(\,\mathbf{P},\mathbf{l}_\gamma) \quad , \qquad (30)$$

where $\mathbf{l}_\gamma$ is the unit vector along the γ-quantum momentum .

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