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# ANGULAR DISTRIBUTION OF NEUTRON CAPTURE $\gamma$-RAYS IN THE SEMIDIRECT CAPTURE MODEL

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*Abstract:* The angular distribution of prompt $\gamma$-rays from the radiative capture of a neutron in the excitation energy region of giant dipole resonance is calculated according to the semi-direct radiative capture model. Results are compared with a few available experimental values. For further analysis more experimental data are needed.

## *1. Introduction*

Following the success of the direct-semidirect (DSD) capture model in describing (n, $\gamma$) excitation functions in the region of the giant dipole resonance[1,2] we calculated the angular distribution of $\gamma$-rays within the framework of this model.

## *2. Theory*

In the semidirect capture model[3] the amplitude for the transition via the giant dipole intermediate state is added to the amplitude for simple direct dipole transition of a single particle from the initial continuum state to the final bound state.

As the dipole state is coupled with other states forming the resonance of width $\Gamma$ and peak energy $E_D$, the DSD transition amplitude (matrix element) for the process in which the photon of energy $E_\gamma = \hbar c k_\gamma$ is emitted, can be written

$$T_\gamma^\nu = \left\langle \varphi_{nljm}(x) \left| \mathrm{d}^\nu\ (x) + \frac{V_1^\nu(x)}{E_\gamma - E_D + \frac{1}{2} i \Gamma} \right| \varphi_{l'j'}(x) \right\rangle,$$

where $\mathrm{d}^\nu(x)$ is the single particle operator $\mathrm{d}^\nu(x) = e_{\mathrm{eff}}\, r\, Y_{1\nu}(\hat{r})$ and $V_1^\nu(x)$ is the form factor for the inelastic excitation of the dipole state by the incident neutron. The term added to the single particle dipole operator $\mathrm{d}^\nu(x)$ represents the effect of the target nucleus polarisation on the capture process. Expressing $V_1^\nu(x) = e_{\mathrm{eff}}\ Y_{1\nu}(\hat{r})\, h(r)$, where $h(r)$ is the so called coupling interaction function, one gets

$$T_\gamma^\nu = \langle \varphi_{nljm}(x) \,|\, \mathrm{d}^\nu(x) \,|\, \varphi_{l'j'}(x) \rangle \cdot F(nlj, l'j').$$

The symbol $F(n\,l j,\ l' j')$ means the effective charge factor[4]

$$F(n\,lj,\ l'j') = \left| 1 + \frac{1}{E_\gamma - E_D + \frac{1}{2} i\Gamma} \cdot \frac{\int u_{nlj}(r)\, h(r)\, u_{l'j'}(r)\, \mathrm{d}r}{\int u_{nlj}(r)\, r\, u_{l'j'}(r)\, \mathrm{d}r} \right|.$$

Here $u_{l'j'}(r)$ and $u_{nlj}(r)$ are continuum and bound state radial neutron wave functions, respectively.

It is worthwhile to note that the coupling interaction function is in general complex and includes the strength of the real and imaginary part of the symmetry potential $V_1$ and $W_1$ as free parameters. The real part of this function has been considered by several authors[1-5]; the imaginary part has been introduced recently by Potokar[2].

The differential cross section for capture of a neutron of reduced mass $M$, effective charge $e_{eff}$ and wave number $k$ is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{M}{\hbar k} \frac{8\pi\, k_\gamma^3\, e_{\mathrm{eff}}}{3\hbar} (2j+1) \sum_\nu \left| \sum_{l'j'} (-i)^{l'} (2j+1) \begin{pmatrix} j & 1 & j' \\ m & -\nu & \frac{1}{2} \end{pmatrix} \begin{pmatrix} j & 1 & j' \\ -\frac{1}{2} & 0 & \frac{1}{2} \end{pmatrix} \cdot \right.$$

$$\left. \cdot R(n\,lj,\ l'j') \cdot F(n\,lj, l'j') \right|^2 \cdot Z_{1\nu}(\vartheta_\gamma),$$

with $R(n\,lj, l'j') = \int u_{nlj}(r)\, r\, u_{l'j'}(r)\, \mathrm{d}r$ the radial dipole single particle integral and $Z_{1\nu}(\vartheta_\gamma)$ describing the angular functions

$$Z_{1\pm 1}(\vartheta) = \frac{3}{16\pi}(1 + \cos^2\vartheta),\ Z_{10}(\vartheta) = \frac{3}{8\pi}\sin^2\vartheta.$$

Summation includes all values of $l'$ and $j'$ satisfying selection rules: $l' = l \pm 1$, $j' = j, j \pm 1$. If we neglect the phase relations and the l. s coupling in the initial wave function, the well known Courant[6] angular distribution formulas are obtained.

In the limit $l' \to \infty$ the radial matrix element $R\,(n\,l\,j,\, l'\,j')$ is nearly the same for $l' = l + 1$ and $l' = l - 1$. In this case the angular distribution coefficient $a_2$ from the expansion $d\sigma/d\Omega = A_0\,[1 + \sum a_n\, P_n\,(\cos\vartheta_\gamma)]$ tends the value of $+0.5$. This is in agreement with the conclusion of Halpern[7], obtained from classical considerations.

## 3. *Comparison with experiments*

Until very recently there were no experimental data to be compared with DSD calculations. The present analysis was done on data for the reaction $^{40}$Ca $(n, \gamma_0)^{41}$ Ca which were reported last year[8]. In this reaction the spinless nucleus $^{40}$Ca captures the neutron into the $1f_{7/2}$ state. Results are presented in Fig. 1. Though there is no agreement between the measured and calculated data, one should notice that the $a_2$ value calculated from DSD model is closer to the experimental value than the corresponding $a_2$ value based on the simple direct capture model. In the former calculation the complex particle-vibration interaction function was used. Values computed by taking only real function $h\,(r)$ appear between two curves in Fig. 1.

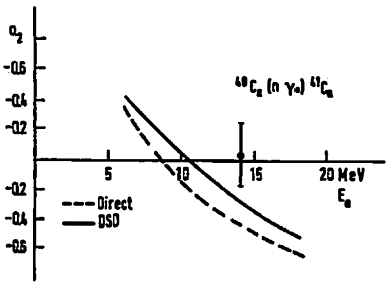


Fig. 1. Comparison of experimental and calculated $a_2$ coefficients for the reaction $^{40}$Ca $(n, \gamma_0)^{41}$Ca.

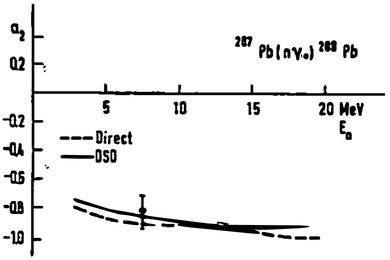


Fig. 2. Comparison of experimental and calculated $a_2$ coefficients for the reaction $^{207}$Pb $(n, \gamma_0)$ $^{208}$Pb.

The second case which is considered here is the reaction $^{208}$Pb $(\gamma, n_0)^{207}$Pb which was measured by Bertozzy et al.[9] about 10 years ago. We calculated the $a_2$ coefficient for the inverse $^{207}$Pb$\,(n, \gamma_0)^{208}$Pb reaction, in which the $^{207}$Pb nucleus captures the neutron into the $3\,p_{1/2}$ hole state. Calculation was performed after an additional analysis which showed that one obtains the same angular distribution of capture $\gamma$-rays if in the reaction the hole state or the single particle state of the same spin is populated. The additional requirement is that the final state in the former case and the initial state in the later case have spin 0. Results of the analysis are shown in Fig. 2. The $a_2$ value obtained from the direct capture model is, in contrast to the $^{40}$Ca case, only slightly more negative than that calculated from the DSD model. Both values of $a_2$ fit the experimental value $a_2 = -0.8 \pm 0.1$.

## 4. *Discussion*

From additional computations performed for other nuclei, it was found that the results from the analysis presented here are generally valid, i.e., that in capture processes populating the low spin state the effect of the semidirect process on angular distribution of capture $\gamma$-rays is not important. If the neutron is captured, e.g. into the $s_{1/2}$ state, the $a_2$ coefficient is $-1$ within a few percent, independent of the neutron energy and insensitive to the model applied. If, on the other hand, the high spin states are populated, the contribution of the semidirect process changes the angular distribution appreciably. To evaluate the significance of this contribution more experimental data on (n, $\gamma$) processes leading to high spin states are called for.

In the computation of radial functions the Woods-Saxon type of potentials were used. Optical model parameters were taken from Rosen et al.[10]. The depths of the final nuclei potentials were adjusted to reproduce the neutron binding energies. The strength of the symmetry potential parameters $V_1$ and $W_1$ was taken the same as in Ref.[2].

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References

1) I. Bergqvist, D. M. Drake and D. M. McDaniels, Nucl. Phys. **A191** (1972) 641;
2) M. Potokar, Phys. Lett. **46B** (1973) 346;
3) C. F. Clement, A. M. Lane and J. R. Rook, Nucl. Phys. **66** (1965) 273;
4) J. Zimanyi, I. Halpern and V. A. Madsen, Phys. Lett. **33B** (1970) 205;
5) G. Longo and F. Saporetti, Phys. Lett. **42B** (1972) 17;
6) E. P. Courant, Phys. Rev. **82** (1951) 703;
7) I. Halpern, Proc. International Conference on Photonuclear Reactions and Applications, Asilomar, March 1973, Pacific Grove 1973, 912;
8) D. M. Drake E. D. Arthur and I. Halpern, Proc. Second International Symposium on Neutron Capture $\gamma$-ray Spectroscopy and Related Topics, Petten (1974), preprints p. 474;
9) W. Bertozzi, S. Kowalski, G. S. Mutchher C. P. Sargent and W. Turchinez, Gordon Conference on Photonuclear Reactions, Tilton, New Hampshire (1965) p. 5;
10) L. Rosen, J. G. Berry, A. S. Goldhaber and E. H. Auerbach, Ann. of Phys. **36** (1965). 96.

# KOTNA PORAZDELITEV ŽARKOV GAMA IZ SEVALNEGA ZAJETJA NEVTRONOV V POLDIREKTNEM MODELU ZAJETJA

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Vsebina

Po modelu poldirektnega zajetja je izračunana kotna porazdelitev takojšnjih žarkov gama iz sevalnega zajetja nevtronov pri vzbuditvenih energijah v področju dipolne veleresonance. Rezultati so primjerjani s skromnimi eksperimentalnimi podatki. Za nadaljnje analize je potrebno več novih merskih rezultatov.