INTERFERENCE OF THE TWO SPIN COMPONENTS OF THE CAPTURE STATE IN THE (n, γ) REACTION

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Measurements of the circular γ-ray polarization for primary transitions in the $^{39}K(n,\gamma)^{40}K$ and $^{57}Fe(n,\gamma)^{58}Fe$ reactions induced by thermal neutrons give strong evidence for the interference of components in the capture state with different J-values.

The fact [e.g. 1] that the components in the thermal-neutron capture state with spins $J_c = J_t \pm 1/2$ (where J_t is the spin of the target nucleus) interfere in measurements of (a) the circular polarization of γ-radiation emitted after polarized neutron capture, (b) the angular distribution of γ-radiation emitted after capture of unpolarized neutrons in aligned nuclei, seems to have been forgotten by experimenters. Attention to this omission has recently been drawn by Honzátko and Kajfosz [2].

The present paper only deals with measurements of type (a). In earlier experiments the experimental errors were so large that it made little difference in the interpretation whether or not interference was taken into account. Recent improvements in neutron flux and degree of polarization, and in energy resolution thanks to the use of Ge(Li) detectors have increased the accuracy by almost an order of magnitude [e.g.3], such that now the interference of the components in the capture state can be tested.

A nice example is offered by the primary γ-ray transition to the 0.80 MeV $J^{\pi} = 2^-$ level in the $^{39}K(n,\gamma)^{40}K$ reaction. The polarization function R (for a definition, see e.g. ref.[3]) as measured with the set-up described in ref. [3] amounts to $R = +0.63 \pm 0.06$ for this transition. Theoretically [1] one finds for either of the two spins of the capture state, 1^+ and 2^+, and for assumed E1 character of the transition, $R = +0.25$. Of course, one still obtains $R = +0.25$, in disagreement with the experimental value, for any incoherent mixture of the two spin components in the capture state. The difficulty disappears if it is assumed that, indeed, the two components mix coherently. In fig.1(a), the curve represents the theoretical value [1] of R plotted as a function of α, the fraction of the 2^+ component in the capture state; $\alpha = 0$ and $\alpha = 1$ correspond, respectively, to the pure 1^+ and 2^+ components. The upper part of the curve ($R > 0.25$) corresponds to constructive interference, the lower part to destructive interference. In principle, one could also allow phase angles other than 0° or 180° but this is only necessary for the unlikely case that the energies of the resonances which contribute most to the thermal cross section differ from thermal energy by an amount which is comparable to the resonance widths. The function $R(\alpha)$ is independent of the number of resonances which are contributing to thermal neutron capture. The interference term is seen to be quite large such that both very large (up to +0.92) and very small (down to -0.42) values of R can be obtained. The experimental value $R = +0.63 \pm 0.06$ can be reproduced for $\alpha = 0.09 \pm 0.04$ or $\alpha = 0.91 \pm 0.04$ with constructive interference.

There is another 2^- state in ^{40}K at $E_x = 2.05$ MeV. The R-value obtained in the present experiment for the primary transition to this state is $R = +0.08 \pm 0.03$, which requires destructive interference between the two components in the capture state.

The circular polarization has also been measured for the primary transitions to the 3^- levels at 0.03 and 2.07 MeV. The results are $R = -0.50 \pm 0.04$, and -0.46 ± 0.05, which agree within the error with the value -0.50 expected

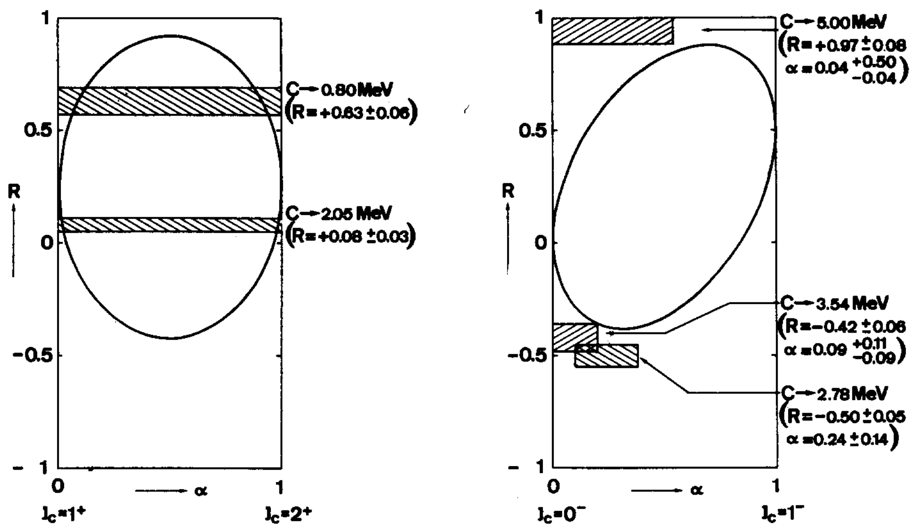

Fig.1. (a) The polarization function R plotted as a function of α, the fraction of the 2^+ component in the capture state C, for a pure E1 transition to a 2^- state in the $^{39}K(n,\gamma)^{40}K$ reaction. The measured values are indicated by shaded bands. (b) Same for primary transitions to 1^+ states in the $^{57}Fe(n,\gamma)^{58}Fe$ reaction. The measured R-values are from the present work, the α-values from ref. [6].

for a pure E1 $2^+ \rightarrow 3^-$ transition.

Perhaps the situation is even more interesting for the primary transitions in the $^{57}Fe(n,\gamma)^{58}Fe$ reaction exciting the 1^+ states [5] at E_x = 2.78, 3.54 and 5.00 MeV, because for these transitions the α-values are known from $(n,\gamma\gamma)$ angular correlation measurements [6]. The components contributing to the capture state, with $J_C^\pi = 0^-$ and 1^-, lead to R = 0 and +0.50, respectively. The R-values measured in the present work and the corresponding α-values (both with their errors) are drawn as rectangles in fig.1(b); they are way outside the R = 0 - 0.50 region, but are not far from the theoretical curve for capture state interference (the deviation for the $C \rightarrow 2.78$ MeV transition is twice the error).

The measured R-values for the transitions to the 2^+ states at 1.67 and 3.08 MeV are -0.41±0.05 and -0.46 ± 0.05, which is in reasonable agreement with the E1 theoretical value, R = -0.50.

One might of course try to explain the measured R-values by assuming that the primary transitions are of mixed E1 + M2 character. This, however, would require for transitions to $J_f = J_t \pm 1/2$ levels a high multipole mixing ratio (δ), e.g. for the transitions to the 0.80 MeV $J^\pi = 2^-$ level in ^{40}K: $\delta \approx 1$. On the other hand, the measured R-values for the $J_t + 1/2 \rightarrow J_t + 3/2$ transitions in ^{40}K and ^{58}Fe are in agreement with the theoretical value R = -0.50 under the E1 assumption. Moreover, primary transitions in (n,γ) work to $l_n(d,p) = 1$ levels are generally considered to have pure E1 character [8], which is supported by circular polarization measurements on transition in which only one spin can participate, like the $1/2^+ \rightarrow 3/2^-$ transitions following capture in even-even target nuclei or the $J_t \pm \frac{1}{2} \rightarrow J_t \pm \frac{3}{2}$ transitions (with parity change) for $J_t \neq 0$. All of these transitions, for assumed pure E1 character, should have R = -0.50; without any exception, the experiment agrees with this value for 12 transitions investigated in refs. [3, 7] and with the present work, and for 8 transitions investigated in ref. [9]. Here only transitions have been considered for which the statistical error is reasonably small ($\Delta R < 0.10$), and for which the final-state spin has been determined unambiguously in other work.

From the present work it should be concluded that the value of the circular polarization method, as a spectroscopic tool, is limited through capture state interference. For example, for the $J_t \pm \frac{1}{2} \rightarrow J_t \pm \frac{3}{2}$ ($J_t \neq 0$) primary transitions with R = -0.50 and for the pure primary E1 $1^- \rightarrow 0^+$ (or $1^+ \rightarrow 0^-$) transitions with R = +1.00, it is almost impossible to obtain an unambiguous spin assignment without extending the method to secondary transitions or comparing the results with other spectroscopic work. The $1/2^+ \rightarrow 1/2^-$ and $1/2^+ \rightarrow 3/2^-$ primary transitions, with R = +1.00 and -0.50, respectively, following capture in even-even nuclei can easily be distinguished, however.

Finally it should be noted that the measured

R-values for primary M1 transitions, which may very well be of mixed M1 + E2 character, can also be explained with capture state interference. An example is given by the strong $^{27}Al(n,\gamma)^{28}Al$ ground-state transition with $R = +0.68 \pm 0.02$ [3], and formerly thought of as of strongly mixed M1 + E2 character. Even for assumed pure M1 character the *R*-value can be reproduced (with $\alpha = 0.074 \pm 0.010$ or $\alpha = 0.852 \pm 0.011$).

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