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GAMMA-GAMMA ANGULAR-CORRELATION MEASUREMENTS IN THE ^{44}Ca(n, γ)^{45}Ca REACTION

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Abstract: Angular correlation measurements of γ-radiation following thermal neutron capture in ^{44}Ca have been performed with a combination of Ge(Li) and NaI detectors. Spins could be assigned to the following ^{45}Ca levels (E_x in MeV): $J^\pi(0.17) = (\frac{5}{2}, \frac{7}{2}^+)$, $J^\pi(1.44) = \frac{3}{2}^-$, $J^\pi(1.90) = \frac{3}{2}^-$ and $J^\pi(2.25) = \frac{1}{2}, (\frac{3}{2})^-$. The $J^\pi(2.25) = \frac{1}{2}^-$ assignment is consistent with recent shell-model calculations. Some E2/M1 mixing ratios of transitions between bound states of ^{45}Ca have been determined.

E | NUCLEAR REACTIONS ^{44}Ca(n, γ), E = thermal; measured $\gamma\gamma(\theta)$. ^{45}Ca levels deduced J, δ. Enriched target. Ge(Li) and NaI detectors.

1. Introduction

A summary of spin and parity assignments to levels in ^{45}Ca is given in table 1. The positive-parity states have been omitted from this table. Most spin assignments are based on the J-dependence of $l_n = 1$ angular distributions from (d, p) work. As can be seen from table 1, some discrepancies occur for the spins assigned to the $E_x = 1.44$ and 2.25 MeV levels.

TABLE 1

Spin and parity assignments to states in ^{45}Ca

Reaction	Method	Ref.	E_x (MeV)							
			0	0.17	1.44	1.90	2.25	2.84	2.34	3.42
(d, p)	J-dep. $l_n = 1$ ang. distr. [a]	[1]			$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{3}{2}^-$			
(n, γ)	γ–γ ang. corr.	[2]					$\frac{3}{2}^-$			
(d, p)	ang. distr. [b]	[3]		$(\frac{5}{2}^-)$						
(d, p)	J-dep. $l_n = 1$ ang. distr. [b]	[4]			$(\frac{3}{2})^-$	$(\frac{3}{2})^-$	$(\frac{1}{2})^-$	$(\frac{3}{2})^-$	$(\frac{1}{2})^-$	$(\frac{1}{2})^-$
(d, p)	J-dep. $l_n = 3$ ang. distr. [a]	[5]	$\frac{7}{2}^-$							
(n, γ)	Partial γ-decay to ^{45}Ca(0)	[6]			$\frac{3}{2}^-$	$\frac{3}{2}^-$		$\frac{3}{2}^-$		
(d, pγ)	p–γ ang. corr.	[7]			$\frac{3}{2}^-$	$\frac{3}{2}^-$				
(n, γ)	γ–γ ang. corr. (present work)			$(\frac{5}{2}, \frac{7}{2}^+)$	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-, (\frac{3}{2})^-$			
conclusion			$\frac{7}{2}^-$	$(\frac{5}{2}^-)$	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$(\frac{1}{2})^-$	$\frac{3}{2}^-$		

[a]) $E_d \approx 10$ MeV. [b]) $E_d \approx 7$ MeV.

The present investigation was initiated to try to solve these discrepancies. The interpretation of γ–γ angular-correlation measurements in the ^{44}Ca(n, γ)^{45}Ca reaction is easy, because the spin and parity of the capturing state ($J^{\pi} = \frac{1}{2}^{+}$) are known. From previous work [6]) it is known that the primary γ-ray transitions exclusively proceed to p-states. In the present investigation, only cascades, originating from the capturing state are studied. For these cascades the initial spin is $J_i = \frac{1}{2}$ and the intermediate spin either $J = \frac{1}{2}$ or $J = \frac{3}{2}$, such that the angular correlation function may be written as $W(\theta) \propto 1 + a_2 P_2(\cos\theta)$, where P_2 is the second-order Legendre polynomial.

If the angular correlation is anisotropic, $J^{\pi} = \frac{3}{2}^{-}$ can be unambiguously assigned to the intermediate p-level. In this case the quadrupole/dipole amplitude mixing ratio y for the second transition may be determined, if it is assumed that the first γ-transition has pure E1 character and if the spin of the final state is known. In general two values for the mixing ratio are obtained.

2. Experimental arrangement

Thermal neutrons were obtained from a horizontal beam of the Dutch High Flux Reactor in Petten. The thermal neutron flux at the target was about 2×10^6 cm$^{-2} \cdot$ s^{-1}.

The γ–γ angular correlation set-up has been described previously by Van Middelkoop and Spilling [8]). One of the two 12.7×12.7 cm NaI detectors has now been replaced by a true coaxial 23 cm^3 Ge(Li) detector. The NaI detector can rotate in a vertical plane perpendicular to the beam direction. The detector solid angles are 0.22 and 0.64 sr for the movable and stationary counter, respectively. The solid-angle attenuation factor, used in the calculations was $Q_2 = 0.87$. This value was obtained by interpolation from the tables given in ref. [10]), in which it is assumed that both detectors are of the NaI type.

The fast coincidence system had a time resolution of $2\tau = 50$ ns. Less than 8 % of the pulses were due to random events. The energy discrimination was performed on the γ-rays detected with the NaI detector. A digital-window discriminator [9]) was used, working on one of the two analogue-to-digital converters of a 4096-channel pulse-height analyser.

The coincidence spectra were measured at three angles, $\theta = 90°$, 135° and 180°. At each angle the measuring time, corrected for dead time, was 100 min. After each measurement, the contents of the memory of the analyser was recorded on magnetic tape, while additional information, such as the neutron flux and the number of coincidences, was printed with a typewriter. A cycle of three angles was repeated many times. The system is fully automatized.

The target, consisting of 275 mg CaO (97 % enriched in ^{44}Ca) was enclosed in a teflon cylinder with an inner diameter of 1 cm and a length of 0.5 cm. The isotopic composition of this sample has been given previously in table 1 of ref. [6]).

Two sets of measurements, with partially different gate settings were performed.

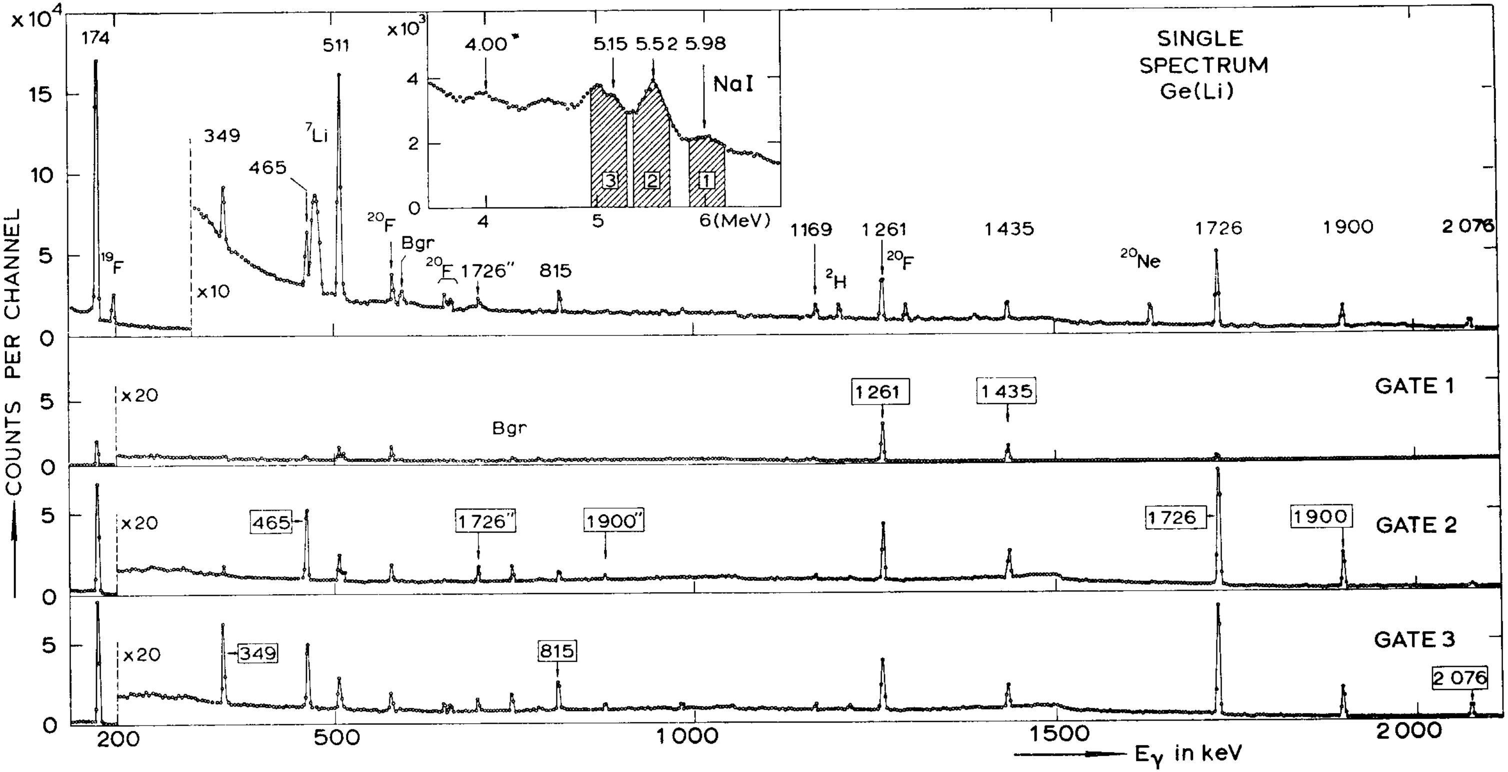

Fig. 1. Some examples of γ–γ coincidence spectra from the reaction $^{44}Ca(n, \gamma)^{45}Ca$. The gate settings in the NaI pulse-height spectrum, and the single spectrum, measured with the Ge(Li) detector, are shown in the upper part of the figure. The spectra coincident with gates 1–3 are measured simultaneously and summed over the three angles $\theta = 90°$, $135°$ and $180°$. The peaks in the Ge(Li) spectra are labelled with unprimed or doubly-primed energies in keV, indicating full-energy or double-escape peaks, respectively. Peaks of γ-transitions, which were not observed in the spectrum coincident with the preceding gate, are indicated by boxed energies. Peaks due to contamination of the target are labelled with the corresponding final nucleus or with the symbol "Bgr" if the peak could not be identified.

The measuring time for one complete set was about one week. In fig. 1 some examples of γ–γ coincidence spectra are shown. The gate settings in the NaI pulse-height spectrum, and a single spectrum, measured with the Ge(Li) detector, are shown in the upper part of the figure. The spectra coincident with gates 1 through 3 were measured simultaneously and summed over the three angles $\theta = 90°$, $135°$ and $180°$.

3. Analysis of the measurements

The spectra measured at the same angle and energy gate were summed. Since the coincidence spectra were measured with the Ge(Li) detector, the total number of counts in a peak could be determined easily. These experimental data N^{exp} were corrected for background.

For the γ-cascades, studied in this paper, with initial spin $J_i = \frac{1}{2}$ and intermediate spin $J = \frac{1}{2}$ or $\frac{3}{2}$, the theoretical expression for the number of counts as a function of angle, has the simple form $N^{\text{theor}} = C\{1+a_2Q_2P_2(\cos\theta)\}$. Here C is a normalization constant and the coefficient a_2 is a function of the multipole amplitude mixing-ratios x and y of the first and second γ-transition. The coefficient a_2, which also depends on the spins of the three levels involved in two-step cascades, is tabulated for instance in ref. [10]). In this paper it will be assumed (if necessary) that the primary γ-rays have pure E1 character ($x = 0$). For a given spin combination a_2 then is only a function of y.

For all possible spin combinations the expression $Q^2 = \sum_i W_i(N_i^{\text{exp}} - N_i^{\text{theor}})^2/(N-M)$, where i labels the different angles, was minimized with respect to the parameters C and y. In this expression the weighting factor W_i is equal to the inverse squared error in N_i^{exp}, and $N-M$ represents the number of free parameters, which equals 1 in the present case ($N-M = 2$ for a pure multipole transition). The minimum of Q^2 was obtained with a non-linear least-squares method, giving the best value of y and its error. The value of Q^2, after minimization only with respect to C, as a function of y, is given in a "$Q^2(y)$ plot" (see for example fig. 3). Acceptable solutions of y, and of the spins of the levels involved, have a $\chi^2 = Q^2_{\text{min}}$ below the 0.1 % probability limit.

4. Results

4.1. ANGULAR-CORRELATION MEASUREMENTS

The angular correlation measurements are summarized in table 2, where the a_2 coefficients in the expression $W(\theta) \propto 1+a_2P_2(\cos\theta)$, corrected for solid angle, are given. The relevant part of the decay scheme is given in fig. 2. The excitation energies and branching ratios in this figure are from ref. [6]), whereas the l_n values are from ref. [4]). The spin of the ground state follows from the J-dependence of the (d, p) angular distribution for $l_n = 3$ transitions [5]).

In the following discussion, some conclusions from the present work will be drawn. In subsects. 4.1.3. and 4.1.5. the spin assignments depend on the reasonable assumption that in the case of a $J^{\pi} = \frac{1}{2}^{+} \rightarrow \frac{3}{2}^{-}$ transition the primary γ-ray has pure E1 character.

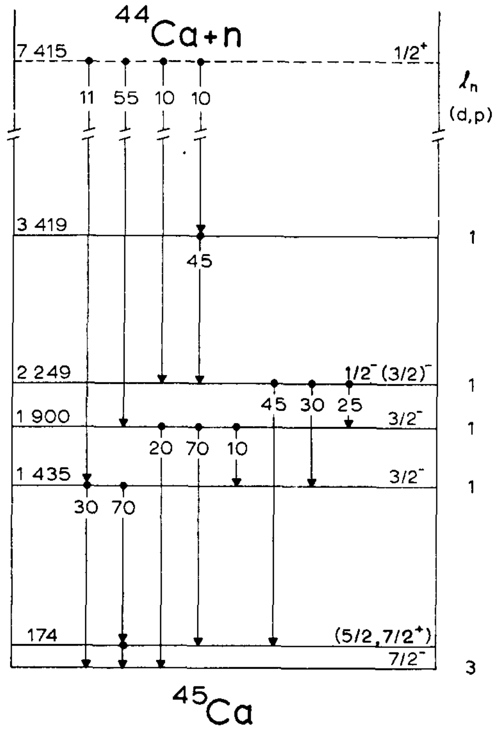

Fig. 2. Partial decay scheme of ^{45}Ca, relevant to the present work. The excitation energies (in keV) and branching ratios are from ref. [6]), whereas the l_n values are from ref. [4]). The spin of the ground state is from ref. [5]), the other spins are consistent with the present work.

TABLE 2

Angular-correlation coefficients a_2 in the expression $W(\theta) \propto 1+a_2P_2(\cos\theta)$, corrected for solid angle

Cascade [a]) (E_x in MeV)	a_2
$C \rightarrow 1.44 \rightarrow 0$	-0.15 ± 0.06
$C \rightarrow 1.44 \rightarrow 0.17$	-0.09 ± 0.03 [b])
$C \rightarrow 1.90 \rightarrow 0$	-0.13 ± 0.05
$C \rightarrow 1.90 \rightarrow 0.17$	$+0.23\pm0.02$
$C \rightarrow 1.90 \rightarrow 1.44$	-0.20 ± 0.03 [b])
$C \rightarrow 2.25 \rightarrow 0.17$	$+0.07\pm0.05$
$C \rightarrow 2.25 \rightarrow 1.44$	$+0.03\pm0.03$ [b])
$C \rightarrow 2.25 \rightarrow 1.90$	$+0.03\pm0.06$ [b])
$C \rightarrow 3.42 \rightarrow 2.25$	-0.10 ± 0.08

[a]) The capturing state is denoted by C.
[b]) Mean of two measurements.

4.1.1. *The* $E_x = 1.90$ MeV *level.* The large measured anisotropies allow the unambiguous conclusion: $J^\pi(1.90) = \frac{3}{2}^-$.

4.1.2. *The* $E_x = 1.44$ MeV *level.* If $J^\pi(1.44) = \frac{1}{2}^-$, the two cascades through this level should show isotropic angular correlations. From a least-squares analysis of the combined data from both cascades it then follows that χ^2 is above the 0.1 % probability limit. Thus $J^\pi(1.44) = \frac{3}{2}^-$.

This assignment also follows from the upper limit of the mean life $\tau_m(1.44) < 25$ ns (resolving time of the coincidence system). The 30 % ground state branch then leads to $\Gamma_\gamma(1.44 \to 0) > 8$ neV. If $J^\pi(1.44) = \frac{1}{2}^-$, the $1.44 \to 0$ transition would have M3 character, for which the Weisskopf estimate is 0.014 neV. Thus $|M^2(\text{M3})| > 570$ W.u., which eliminates $J^\pi(1.44) = \frac{1}{2}^-$. Conclusion: $J^\pi(1.44) = \frac{3}{2}^-$.

4.1.3. *The* $E_x = 2.25$ MeV *level.* The three cascades through this level show isotropic or almost isotropic angular correlations, which strongly suggest that $J^\pi(2.25) = \frac{1}{2}^-$. If the spin of this level were $\frac{3}{2}$, the E2/M1 amplitude mixing ratios for the $2.25 \to 1.90$ and $2.25 \to 1.44$ transitions would be at least $|y| = 0.31 \pm 0.06$ and $|y| = 0.31 \pm 0.09$, respectively. Though these values lead to high quadrupole admixtures, no final conclusion about the spin of the 2.25 MeV level can be made, because M1 transitions between states in ^{45}Ca may be attenuated appreciably (see sect. 5). The most probable value of $J^\pi(2.25)$ however is $\frac{1}{2}^-$.

A $J^\pi(2.25) = \frac{1}{2}^-$ assignment is also in agreement with the fact that no transition from this level to the ground state was observed [6]), whereas the $E_x = 1.44$, 1.90 and 2.84 MeV levels, with $J^\pi = \frac{3}{2}^-$, do have branchings to ^{45}Ca(0). Conclusion: $J^\pi(2.25) = \frac{1}{2}^-, (\frac{3}{2})^-$.

4.1.4. *The* $E_x = 3.42$ MeV *level.* The $C \to 3.42 \to 2.25$ cascade shows an angular correlation from which no final conclusions can be drawn, since the error in the a_2 coefficient is rather large.

4.1.5. *The* $E_x = 0.17$ MeV *level.* Recently, the mean life for this state has been measured [11]) as $\tau_m(0.17) = 400 \pm 40$ ps. This short mean life implies that the 0.17 MeV γ-ray has E1 or M1 character. Since the spin of the ground state is $\frac{7}{2}$, the first-excited state thus can only have $J^\pi = \frac{5}{2}^\pm, \frac{7}{2}^\pm$ or $\frac{9}{2}^\pm$.

From the upper limit $\tau_m(1.90) < 25$ ns and the branching ratio one finds $\Gamma_\gamma(1.90 \to 0.17) > 18$ neV. The assignment $J^\pi(0.17) = \frac{9}{2}^-$ can be excluded since it would imply $|M^2(\text{M3})| > 380$ W.u. for the $\frac{3}{2}^- \to \frac{9}{2}^-$ transition.

For $J^\pi(0.17) = \frac{9}{2}^+$ or $\frac{7}{2}^-$, one may assume that the $1.90 \to 0.17$ transition is unmixed. From the angular correlation (see fig. 3) it follows immediately that these J^π possibilities are excluded.

The angular correlation associated with the $C \to 1.44 \to 0.17$ cascade gives no additional information about $J^\pi(0.17)$. Further restrictions on the spin and parity of the $E_x = 0.17$ MeV level could be made if the mean life of the $E_x = 1.90$ MeV level was known. Conclusion: $J^\pi(0.17) = (\frac{5}{2}, \frac{7}{2}^+)$.

4.2. MIXING RATIOS

In table 3 the quadrupole/dipole amplitude mixing ratios for three γ-transitions between states in ^{45}Ca are summarized. The results obtained here depend on the validity of the E1-assumption for primary γ-rays (see subsect. 4.1). The mixing ratios for the 1.90 → 0.17 and 1.44 → 0.17 transitions are calculated for the most probable value of the spin and parity of the final state [$J^{\pi}(0.17) = (\frac{5}{2}^{-})$, ref. [3]]. The agreement with the results from (d, pγ) work [7]) is very good.

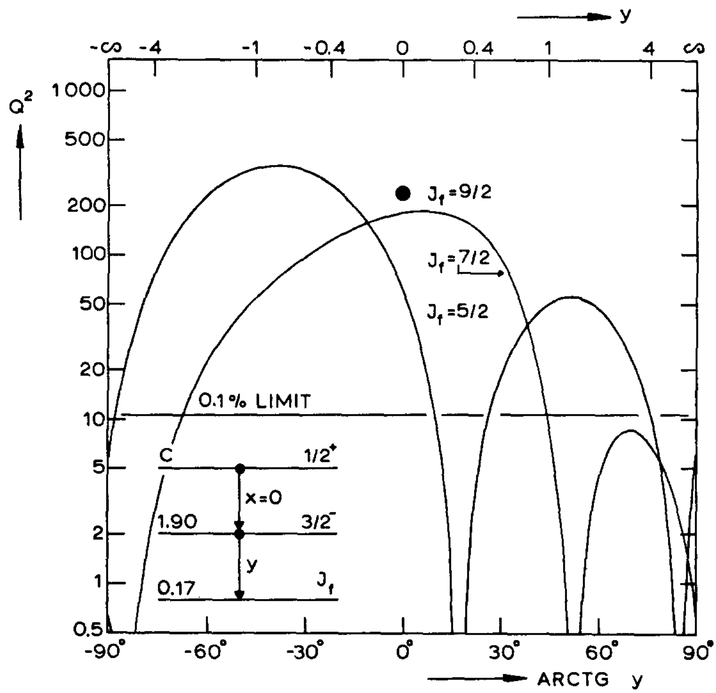

Fig. 3. A plot of Q^2 as a function of the amplitude mixing ratio y of the second γ-transition in the $C \to 1.90 \to 0.17$ MeV cascade, with the spin of the final state as a parameter.

TABLE 3

Quadrupole/dipole amplitude mixing ratios

Transition (E_x in MeV)	J^{π}	J_f^{π}	mixing ratios: this work [a])	mixing ratios: (d, pγ) [b])
1.44 → 0.17	$\frac{3}{2}^-$	$(\frac{5}{2}^-)$	-0.26 ± 0.08 or -2.0 ± 0.4	
1.90 → 0.17	$\frac{3}{2}^-$	$(\frac{5}{2}^-)$	$+0.32\pm0.05$ or $+11\ \pm5$	$+0.38\pm0.06$ or $+7.1\pm2.5$
1.90 → 1.44	$\frac{3}{2}^-$	$\frac{3}{2}^-$	-0.01 ± 0.04 or $+4.0\pm0.7$	

[a]) Based on assumed E1 character for the primary γ-rays.
[b]) Ref. [7]).

5. Discussion

The spin assignments to ^{45}Ca levels from other work are summarized in table 1. The results from the J-dependence of (d, p) angular distributions for $l_n = 1$ states at deuteron energies of 7 MeV agree very well with the present results, unlike those from the (d, p) work at higher deuteron energies. The spin of the 2.25 MeV level was previously determined in an (n, $\gamma\gamma$) angular correlation experiment [2]), yielding $J^\pi(2.25) = \frac{3}{2}^-$. In the latter work two NaI detectors were used and the decay scheme of ^{45}Ca was not known very well. Therefore, it is possible that the measured large anisotropy ($a_2 = +0.26 \pm 0.04$) was associated with the 1.90 MeV state, rather than with the 2.25 MeV level. This is possible since the single-escape peak of the 5.52 MeV γ-transition is superimposed on the full-energy peak of the γ-transition at 5.17 MeV.

The states at $E_x = 0$, 0.17, 1.44 and 1.90 MeV are reasonably well described by wave functions in which the main components are the $1f_{\frac{7}{2}}^5$ and $1f_{\frac{7}{2}}^4 2p_{\frac{3}{2}}$ configurations [12–14]). The lowest $J^\pi = \frac{1}{2}^-$ state in ^{45}Ca was predicted at $E_x = 2.12$ MeV by McGrory and Wildenthal [15]), who used all four f–p shell configurations in their calculations. This result is in good agreement with the position of the $J^\pi = (\frac{1}{2})^-$ state at 2.25 MeV.

If the low-lying states in ^{45}Ca were pure $1f_{\frac{7}{2}}^5$ configurations, magnetic dipole transitions would be forbidden. A similar situation exists in ^{43}Ca, where the lowest states mainly have $1f_{\frac{7}{2}}^3$ configurations. The M1 transition strengths between states in ^{43}Ca calculated by Zamick and Ripka [16]), who found probabilities of 7×10^{-3}, 6×10^{-4} and 7×10^{-6} W.u. for the 0.59 ($\frac{5}{2}$) → 0.37 ($\frac{5}{2}$), 2.05 ($\frac{3}{2}$) → 0.37 ($\frac{5}{2}$) and 2.05 ($\frac{3}{2}$) → 0.59 ($\frac{3}{2}$) transitions, respectively (spins of levels between brackets).

From the present work large E2/M1 mixing ratios are found for the corresponding 1.44 ($\frac{3}{2}$) → 0.17 ($\frac{5}{2}$) and 1.90 ($\frac{3}{2}$) → 0.17 ($\frac{5}{2}$) transitions between states in ^{45}Ca. So, it is not excluded that in ^{45}Ca, M1 transitions between the low-lying states are attenuated. It has to be noted, however, that from empirical data the most likely *a priori* values [17]) for the transition strengths of M1 and E2 radiations in nuclei with $A \approx 40$ are $|M^2(\mathrm{M1})| \approx 0.01$ W.u. and $|M^2(\mathrm{E2})| \approx 1$ W.u.

6. Conclusions

The spin assignments from the present work are consistent with the results from shell-model calculations [12–15]). A measurement of the mean lives of the low-lying states in ^{45}Ca will be needed to solve some remaining ambiguities.

It is worth mentioning that the $J(1.44) = \frac{3}{2}$ and $J(2.25) = (\frac{1}{2})$ assignments disagree with those [1]) based on $l_n = 1$ (d, p) angular distributions at $E_d \approx 10$ MeV, but agree with those [4]) at $E_d \approx 7$ MeV.

The (n, γ) angular correlation measurement with a combination of NaI and Ge(Li) detectors proved to be useful, mainly because of the unequivocal determination of the intensities of low-energy γ-transitions from the Ge(Li) spectrum.

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