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GAMMA-GAMMA ANGULAR CORRELATION MEASUREMENTS IN THE ^{35}Cl(n, γ)^{36}Cl REACTION

G. van MIDDELKOOP and P. SPILLING †

Fysisch Laboratorium der Rijksuniversiteit, Utrecht, Nederland

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Abstract: With scintillation spectrometers, angular correlations have been measured of γ-radiation following thermal neutron capture in ^{35}Cl. The following spins in ^{36}Cl are determined: $J(0.788) = 2$ or 3, $J(1.949) = 2$, $J(1.957) = 2$, $J(2.469) = 3$. The latter three spin assignments are based on the assumption that the 2.469 → 1.949 MeV transition has E1 character. The capturing state is predominantly of $J = 2$ character.

E

NUCLEAR REACTIONS ^{35}Cl(n, γ), E = thermal; measured $\gamma\gamma$-angular correlations. ^{36}Cl levels deduced J. Natural target.

1. Introduction

Many experimental and theoretical attempts [1-7]) have been made to determine spins of levels in ^{36}Cl. The spin assignments reported in refs. [1-6]) are listed in table 1.

TABLE 1

Spin and parity assignments to levels in ^{36}Cl

	Shell model calculation		^{35}Cl(d, p)^{36}Cl reaction	^{35}Cl(n, γ)^{36}Cl reaction			
				cross section	γ–γ angular correlation [a])		
E_x (MeV)	Ref. [1])	Ref. [2])	Ref. [3])	Ref. [4])	Ref. [5])	Ref. [6])	Present work
0 [b])	2^+	2^+					
0.788	3^+	3^+	3^+			0^+	$(2, 3)^+$
1.164	1^+	1^+	1^+		2^+	2^+	
1.598	2^+	2^+	$(1, 2)^+$				
1.949	(1^+)		$(1, 2)^+$				(2^+)
1.957							(2^-)
2.469			$(0–3)^-$				$(3)^-$
2.497		1^+	$(1, 2)^+$				
2.870			$(1–5)^-$				
8.577 (C)				2^+	1^+		2^+

[a]) Parities from ref. [3]).

[b]) Experimentally $J^\pi = 2^+$ from β^- decay [11]).

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† On leave of absence from the University of Oslo, Blindern, Norway.

The results of Draper and Fleischer [7]) are omitted, since they are based on transition probabilities only and consequently are dubious.

The gamma radiation from the ^{35}Cl(n, γ)^{36}Cl reaction has been extensively studied by Segel [8]), using coincidence techniques, by Groshev *et al.* [9]), using a high-resolution magnetic-Compton spectrometer and by Draper and Bostrom [10]) with an anticoincidence-NaI(Tl) spectrometer. A compilation of information about ^{36}Cl, obtained until 1962, is given by Endt and Van der Leun [11]). In addition, Meyer [12]) reported angular distributions of electron pairs formed by internal pair production in the ^{35}Cl(n, γ)^{36}Cl reaction, yielding M1 character for the strong C → 2.469 MeV transition.

To test recent shell-model predictions [1,2]), and because there were several discrepancies in the afore-mentioned spin assignments, it was thought worthwhile to measure γ–γ angular correlations using the ^{35}Cl(n, γ)^{36}Cl reaction.

2. Experimental Arrangement

The experimental equipment has been described previously [13]). Only a few essentials will be mentioned.

The target is placed in a thermal neutron beam of the Dutch High Flux Reactor in Petten. The beam flux is about 4×10^6 cm^{-2} · sec^{-1}. The target is viewed by two gain-stabilized 12.7 cm × 12.7 cm NaI(Tl) spectrometers of which one can be moved. The detector solid angles were 0.13 and 0.31 sr for the movable and stationary detector, respectively.

The "fast-slow" coincidence system has a resolving time of $2\tau = 30$ ns. The spectra are recorded by a 400-channel analyser. Angular correlation measurements were performed using a set of five angles, $\theta = 180°$, 150°, 135°, 120° and 90°, which set is scanned automatically. Such a cycle is repeated many times. The measurements are dead-time corrected while the flux, monitored by a BF_3 counter, is read out for each measurement on the analyser-paper tape.

The teflon target holder had an inner diameter and length of 3 and 10 mm, respectively. It was filled with slightly compressed C_2Cl_6 powder.

3. Experimental Results

From the capture cross sections [14]) in natural chlorine and ^{37}Cl, taking into account the isotopic abundances, it follows that more than 99 % of the neutron capture in natural chlorine occurs in ^{35}Cl. Thus all strong gamma rays are assumed to be due to capture in ^{35}Cl.

Fig. 1 shows the part of the ^{36}Cl decay scheme [11]) relevant to the present experiment.

Coincidence and angular correlation measurements were performed with 7.12–8.52, 6.80–7.12, 6.49–6.76 and 5.95–6.27 MeV gates. The 7.12–8.52 MeV gate contains

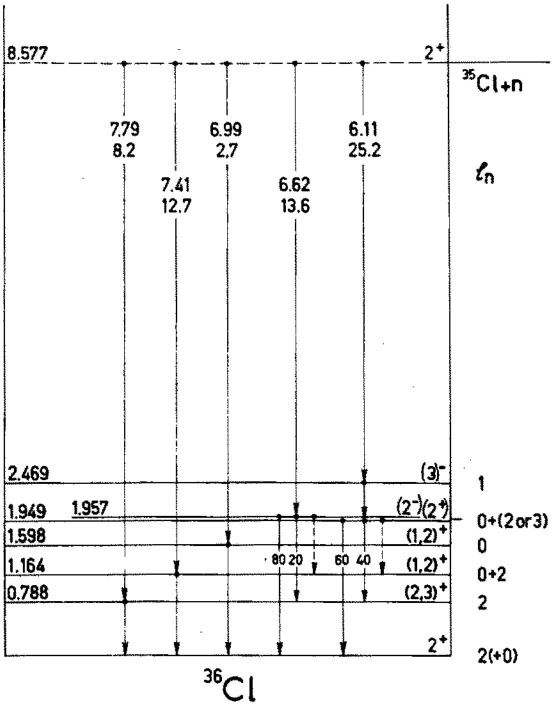

Fig. 1. Decay scheme of ^{36}Cl relevant to the present experiment. The energy levels, gamma-ray transitions and intensities are from ref. [9]), the l_n values are from ref. [3]).

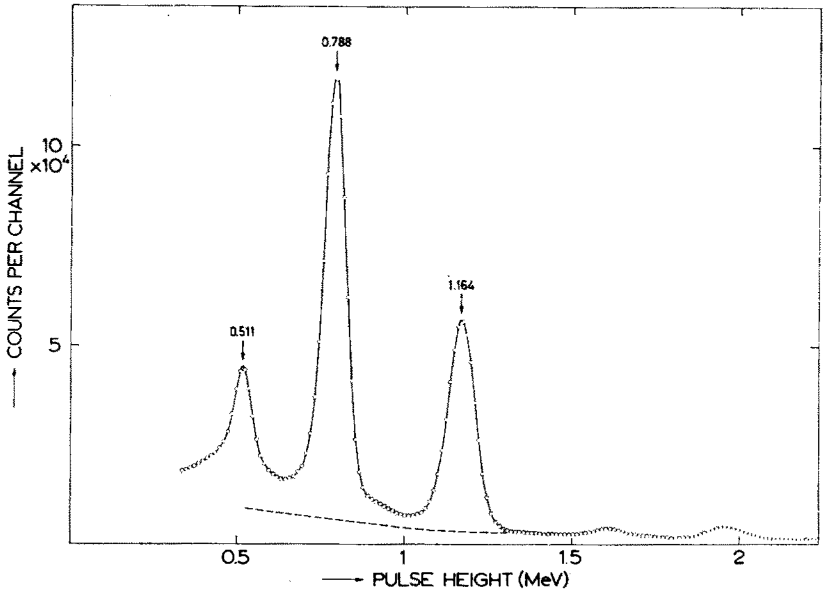

Fig. 2. Coincidence spectrum with a 7.12–8.52 MeV gate, θ = 135°.

photopeaks of the 7.79 and 7.41 MeV gamma rays which are the C → 0.788 and C → 1.164 MeV transitions, respectively (see fig. 1). The coincidence spectrum is shown in fig. 2. The secondary gamma ray in the C → 1.598 → 0 MeV cascade is present because the 6.99 MeV photopeak and the gate partly overlap. The 1.95 MeV peak is due to summing and pile-up. The 6.80–7.12, 6.49–6.76 and 5.95–6.27 MeV gates contain the photopeaks of the 6.99, 6.62 and 6.11 MeV gamma rays, respectively (see fig. 1). Table 2 lists the resulting angular correlation coefficients of the successive gamma-ray cascades.

TABLE 2

Angular correlation coefficients A_2 and A_4 in the expression $W(\theta) \backsim 1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$, corrected for solid angle a)

	Cascade (MeV)	A_2	A_4
1.	C → 0.788 → 0	0.044±0.004	0.016±0.006
2.	C → 1.164 → 0	0.037±0.002	0.001±0.002
3.	C → 1.598 → 0	0.099±0.009	−0.005±0.012
4.	C → 1.957 → 0	0.158±0.015 b)	0.005±0.017
5.	C → 2.469 → 1.949	0.136±0.011 c)	0.016±0.014 c)

a) The given errors are statistical, the experimental eccentricity is ≦ 0.005 in $|A_2|$.

b) Corrected for pile-up contributions.

c) Corrected for annihilation radiation.

In the following only spins and parities consistent with the l_n values as found from the ^{35}Cl(d, p)^{36}Cl reaction 11) (see also fig. 1) are considered. The ground state is characterized 11) by $J^\pi = 2^+$.

Since the ^{35}Cl ground-state spin and parity 11) are $\frac{3}{2}^+$, the capturing-state spin and parity in ^{36}Cl are 1^+ or 2^+.

Measurement 1 rules out $J(0.788) = 4$ because for a 2^+(E2) 4^+(E2)2^+ cascade the A_2 and A_4 coefficients are 0.20 and 0.093, respectively, and because a primary M3 transition ($1^+ \rightarrow 4^+$) should be very weak. Since both A_2 and A_4 are non-zero, also $J(0.788) = 0$ or 1 are excluded. Thus there remains $J(0.788) = 2$ or 3. Moreover, the capturing-state spin is determined as $J(\mathrm{C}) = 2$ from this measurement, if it assumed that this state is mainly influenced by one single resonance (see sect. 4). For $J(\mathrm{C}) = 1$ the theory predicts $A_4 \leqq 0$ for all possible M1/E2 mixings in both the primary and secondary transition.

A calculation of the least-squares fit of the theoretical angular correlation – as a function of the M1/E2 mixing parameters δ_1 and δ_2 in the primary and secondary transition, respectively – with the experimental correlation is shown in fig. 3 for the $2 \rightarrow 2 \rightarrow 2$ and the $2 \rightarrow 3 \rightarrow 2$ spin sequences. The deviation between these correlations is expressed in χ^2. The quantity χ^2 has been normalized by dividing through the number of free parameters (2). The minima are indicated by dots. The value of

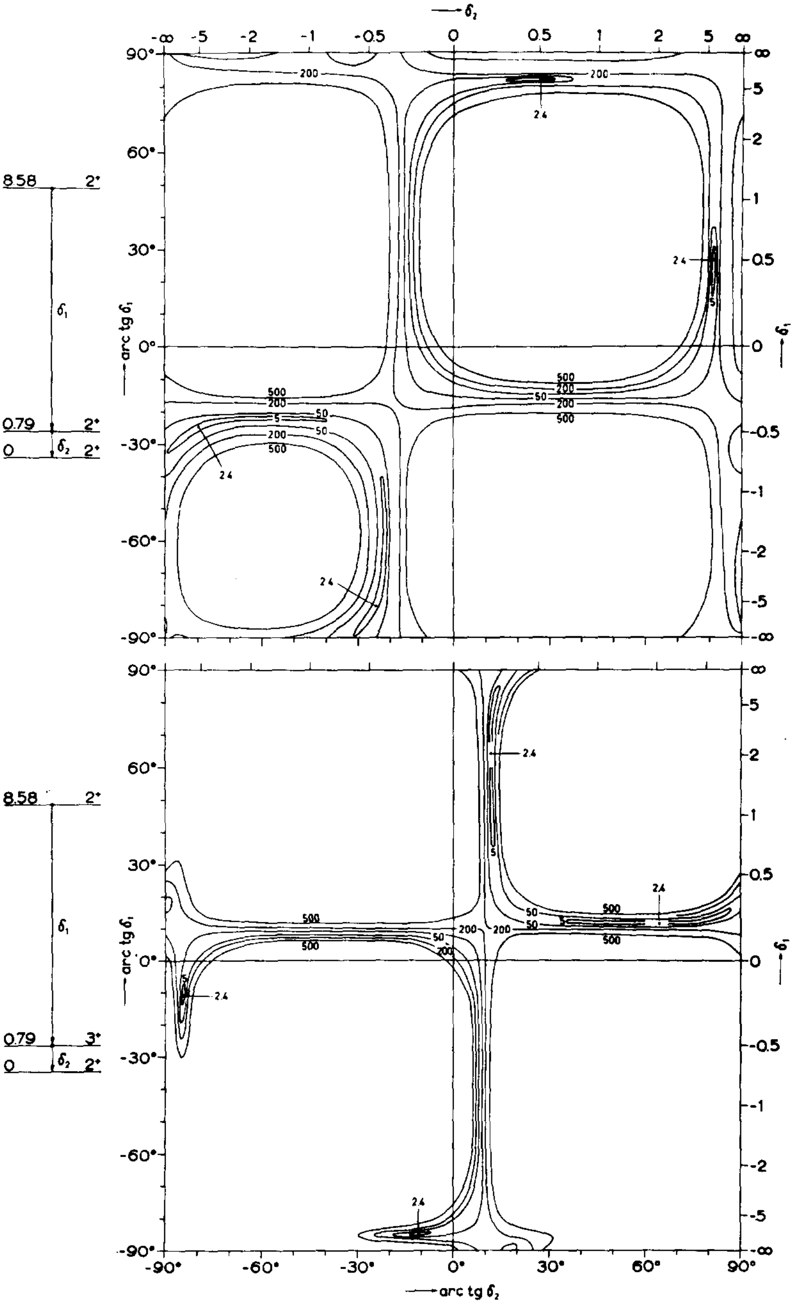

Fig. 3. Chi squared from the angular correlation on the C → 0.788 → 0 MeV cascade plotted as a function of the mixing amplitudes of both gamma rays. Curves of constant chi squared are shown. The upper part represents the result for $J(0.788) = 2$, the lower for $J(0.788) = 3$.

χ^2 in the minima is 2.4 in all cases, while the 0.1 % limit of consistency is 6.8. No choice can thus be made as to the spin of the $E_x = 0.788$ MeV state. Table 3 lists the mixing parameters found from the χ^2 calculation for $J = 2$ and 3.

From measurements 2 and 3 no definite conclusions can be drawn as to the spins of the $E_x = 1.164$ and $E_x = 1.598$ MeV states. The measured A_2 coefficients are non-zero, but this is insufficient to decide between $J^\pi = 1^+$ and 2^+, the two possibilities following from the (d, p) work.

TABLE 3

Mixing parameters of the gamma-ray transitions in the C → 0.788 → 0 MeV cascade for $J(0.788) = 2$ and 3

Mixing parameters if $J(0.788) = 2$		Mixing parameters if $J(0.788) = 3$	
δ_1(or δ_2)	δ_2(or δ_1)	δ_1(or δ_2)	δ_2(or δ_1)
-0.46 ± 0.08	$-5.8^{+4.8}_{-7.3}$	-0.19 ± 0.04	-10.2 ± 0.5
or		or	
0.45 ± 0.10	6.9 ± 0.3	0.21 ± 0.01	$2.1^{+1.7}_{-1.3}$

Several investigations 3,7-9,15) indicate that the 1.95 MeV doublet consists of levels with opposite parity. The existence of a strong 2.469 → 1.949 MeV transition 9)), together with the odd-parity assignment 3)) to the 2.469 MeV state ($l_n = 1$), indicates even parity for the $E_x = 1.949$ MeV level. The $E_x = 1.957$ MeV state is then assigned to have odd parity. Thus it is reasonable to assume pure E1 radiation for both transitions in the C → 1.957 → 0 MeV cascade. Measurement 4 in table 2 then yields $J(1.957) = 2$ and $J(\mathrm{C}) = 2$ (the theoretical A_2 coefficients coming closest to the experimental value are $A_2 = 0.120$ and $A_2 = 0.175$ for the 2 → 3 → 2 and the 2 → 2 → 2 dipole-dipole cascades, respectively). From measurement 5, finally, one obtains $J(2.469) = 3$ and $J(1.949) = 2$, again assuming pure E1 radiation in the C → 2.469 → 1.949 MeV cascade and using the assignment $J(\mathrm{C}) = 2$ from measurements 1 and 4. The theoretical A_2 coefficients closest to the experimental value again are those mentioned in connection with measurement 4.

These results are listed in the last column of table 1.

The spins of the $E_x = 1.949$, $E_x = 1.957$ and $E_x = 2.469$ MeV levels as derived above from measurements 4 and 5 are based on the assumption that the 2.469 → 1.949 MeV transition has E1 character because of the depopulation mode of the $E_x = 2.469$ MeV state. However, this argumentation has to be considered with scepsis, since recently Van der Leun 16)) gave empirical expressions for the E1 and M1 radiation strengths in the s-d shell which show that the M1 radiation is, on the average, a bit faster than E1 radiation: for ^{36}Cl a factor of 1.4. If, indeed, the 2.469 → 1.949 MeV transition is M1, eventually mixed with E2, the spin assignments to the just mentioned levels cannot be held. Additional information, e.g. polarization measurements on the 0.52 MeV γ-ray, is necessary to verify this point.

4. Discussion

The total neutron cross section of natural chlorine and of chlorine enriched in ^{35}Cl has been measured up to a neutron energy of 15 keV by Brugger *et al.* ^{4}). Resonances at $E_n = -140$ eV, $E_n = 405 \pm 6$ eV and $E_n = 8.7 \pm 0.5$ keV are reported. The first two are assigned to ^{35}Cl, the latter probably ^{17}) is a resonance in ^{37}Cl. The calculated incoherent cross section at $E_n = 0.025$ eV agrees with the experimental value if the parameters of the negative-energy s-wave resonance are those ^{4}) with $J_{rcs} = 2$.

Resonance capture in the ^{35}Cl(n, γ)^{36}Cl reaction has been studied by Popov and Shapiro ^{18}). They found resonances at $E_n = -210 \pm 10$ eV, $E_n = 405$ eV, $E_n = 1.1 \pm 0.2$ keV and $E_n = 4.3 \pm 0.3$ keV, the last three probably being p-wave resonances $^{17, 18}$). The reduced neutron width Γ_n^0 ($\Gamma_n^0 = \Gamma_n/\sqrt{E}$) of the p-wave resonances is about 10^{-3} to 10^{-2} times the reduced width of the negative-energy resonance. Recently Garg *et al.* ^{19}) measured the total neutron cross section in natural chlorine at neutron energies from $E_n = 300$ eV to $E_n = 450$ keV. They found a number of new resonances, which are all quite weak. The thermal capture cross section due to these resonances is therefore small. By assuming Γ_γ as a constant, the contribution at thermal energy of the 405 eV resonance ^{18}) is about 0.25 %. The other resonances^{18}) together contribute less than 0.1 %. It is reasonable therefore, assuming that only one negative-energy resonance close to the capturing state is present, to treat the capturing state as a level with definite spin. By the measurements reported in sect. 3 the capturing-state spin is established as $J(\mathrm{C}) = 2$.

The spin assignment to the $E_x = 0.788$ MeV state ($J = 2$ or 3) agrees with shell-model predictions $^{1, 2}$) giving $J = 3$. Additional information is necessary to determine the spin of this level uniquely. A recent investigation of the ^{39}K(n, $\alpha\gamma$)^{36}Cl reaction with 4–8 MeV neutrons by Bass ^{20}) yields a mixing amplitude for the 0.788 → 0 MeV transition of $0.4 < \delta < 1$ if $J = 2$ and $0.4 < \delta < 0.6$ or $3 < \delta < 8$ if $J = 3$. This excludes negative values of the mixing parameters for both transitions in the C → 0.788 → 0 MeV cascade (table 3), but still the present investigation does not determine the spin. Probably a circular polarization measurement of the C → 0.788 MeV gamma ray after capture of polarized thermal neutrons gives an unique spin determination, using the present results.

It is more problematic to assign spins to the second and third excited states. The angular correlation measurements only yield closed contour lines of the minimum χ^2 for the $2 \to 1 \to 2$ spin sequence and thus a range of coupled δ_1, δ_2 values, while also the $2 \to 2 \to 2$ spin sequence in both cascades permits a certain range for both δ_1 and δ_2. It seems improbable that circular polarization measurements together with the present experiment can give unique spin determinations.

The spin assignments to the $E_x = 1.949$, 1.957 and 2.469 MeV states are based on the assumptions that the 1.949 and 1.957 MeV states have even and odd parity, respectively. Consequently, all gamma rays in the cascades involved could be assumed to have E1 character. The parities of these states are quastionable, however.

There can be found some justification for the parity assumptions by comparing the reduced intensities of a few primary transitions. The reduced gamma-ray intensities expressed in

$$k = k_{\mathrm{E1}} = \frac{\Gamma'_{\gamma\,\mathrm{obs}}}{E^3 A^{\frac{2}{3}} D}$$

TABLE 4

Reduced intensities of some primary gamma transitions

Transition [a]) (MeV)	Parity of final state [b])	$k \times 10^3$ ($\mathrm{eV} \cdot \mathrm{MeV}^{-4}$) [c])	
C → 3.606	−	1.0	average 1.6
C → 2.870	−	0.9	
C → 2.469	−	3.2	
C → 1.957	+ or −	1.3	
C → 1.598	+	0.2	average 0.4
C → 1.164	+	0.9	
C → 0.788	+	0.5	
C → 0	+	0.1	

[a]) From ref. [9]).

[b]) From ^{35}Cl(d, p)^{36}Cl reaction, ref. [3]).

[c]) Intensities from ref. [9]); for definition of k see text.

are listed in table 4. The quantity k_{E1} is the E1 radiation strength as defined by Bartholomew [21]), and $\Gamma'_{\gamma\,\mathrm{obs}}$ is the observed partial radiation width (in eV) for a primary transition with energy E (in MeV), A is the mass number and D the average spacing (in MeV) of levels near the capturing state with the same spin and parity as this state. In the calculation the total radiation width $\Gamma_\gamma = 0.5$ eV from ref. [4]) and $D = 0.016$ MeV from Cameron's [22]) inspection of s-wave resonance data given in ref. [14]) (by assuming the number of levels with spin J proportional to $2J+1$) are used.

By using k as the reduced quantity, we are able to employ the criterion adopted by Bartholomew and Vervier [23]): a primary γ-ray has E1 character if $k > 3 \times 10^{-3}$ $\mathrm{eV} \cdot \mathrm{MeV}^{-4}$. It is seen that the C → 2.469 MeV transition fulfills this inequality and thus is an E1 transition, as already assumed from the parity assignment due to Hoogenboom [3]), but in contradiction with Meyer's [12]) (ambiguous) M1 assignment. There is no evidence to assign an E1 character to the C → 1.957 MeV transition. However, recent investigations [24]) of E1 and M1 transition probabilities in a number of odd-odd product nuclei in the s-d shell indicate that the reduced E1 and M1 intensities might be of the same order of magnitude. As is seen from table 4, the ratio of average E1 and M1 reduced intensities is 4, including the C → 1.957 MeV transition as an E1.

The $E_x = 2.469$ MeV state might be the isobaric spin analogue of the $E_x = 9.34$ MeV state in ^{36}Ar. The latter level is situated 2.67 MeV above the ^{36}Cl ground state, if the Coulomb-energy difference ^{1}) of ^{36}Ar and ^{36}Cl is taken as 6.67 MeV. The spin and parity are $J^\pi = 3^-$ as recently determined by Erné ^{25}) from the ^{35}Cl(p, γ)^{36}Ar reaction.

Shell model calculations ^{1}) predict one 2^+ and two 1^+ states in the $E_x = 1$–2 MeV region. If it is assumed that the 2^+ state corresponds to the 1.949 MeV level, one might identify the 1^+ states with the $E_x = 1.164$ and 1.598 MeV levels, which, experimentally, should have either $J^\pi = 1^+$ or 2^+. These 1^+ assignments would be in agreement with the fact that the A_4 coefficients for the cascades through these states are zero within the experimental error (see table 2).

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