Investigations of the Reaction $Cl^{35}(n,\gamma\gamma')Cl^{36}$†*

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Two-step gamma-ray cascades to the ground state of Cl^{36} following thermal neutron capture by Cl^{35} have been investigated with the sum-coincidence apparatus. The direct experimental result is the product I_1b_2 of the intensity I_1 of the initial transition and the branching factor b_2 of the intermediate state to the ground state. The quantity b_2 is separately deduced from auxiliary information about I_1. The lower-energy members of the stronger cascades occur at 0.79, 1.16, 1.60, 1.96, and 2.87 Mev with respective values of I_1b_2 of 8.2, 11.6, 2.9, 12.1, and 5.1 per 100 neutrons captured. Weaker cascades appear at 2.2, 2.48, 2.6, 2.68, and 3.05 Mev. Cascades appearing between 3.3 and 4.3 Mev have $I_1b_2 \leqslant 0.5\%$. The b_2 following the strongest of all initial transitions, viz., 6.11 Mev, is only $\leqslant 0.02$. Approximately 46% of all neutrons captured produce two-step cascades in Cl^{36}.

ALTHOUGH a number of investigations of the levels of $_{17}Cl_{19}{}^{36}$ have been made, there are still no results which clearly define the total angular momenta of any of the excited states. The ground state (d,p) group[1] in $Cl^{35}(d,p)Cl^{36}$ satisfied the stringent test proposed by Bethe and Butler[2] of the shell model in stripping for this nucleus. The orbital angular momentum l_n of the captured neutron in the (d,p) reaction has been measured for the first six levels by Teplov.[3] However, the remaining higher levels were not resolved in his work according to the (d,p) Q-value results of Paris *et al.*[4] Thermal neutron-capture gamma-ray spectra from Cl^{36} have been measured with magnetic spectrometers[5] and recently with a Compton spectrometer[6] of resolution ~0.3%. Segel[7] has recently explored some of the coincidence features of neutron-capture gamma rays from Cl^{36}. Trumpy[8] has reported the results of difficult measurements of the circular polarization of gamma rays following capture of polarized neutrons by Cl^{35}.

The coincidence measurements of Segel were not quantitative in the sense of evaluating the probabilities of various coincidence cascades. Therefore it was decided to use the sum-coincidence method to investigate quantitatively all two-step gamma-ray cascades to ground from the initial state formed in thermal neutron capture by Cl^{35}. A report of our preliminary work on Cl^{36} has already been made.[9]

EXPERIMENTAL DESCRIPTION

The experimental layout is shown in Fig. 1. The neutron source was the 6-Mev electron linear accelerator and the detectors were two NaI(Tl) crystals 4-in.

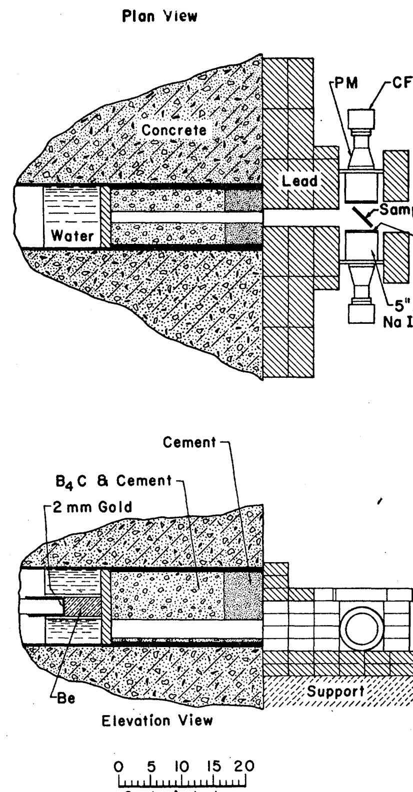

FIG. 1. Experimental geometry. The 4-in. thick by 5-in. diam NaI(Tl) scintillators are separated by 4.5 in. between faces. The 6-Mev electron beam is incident on the gold target from the left.

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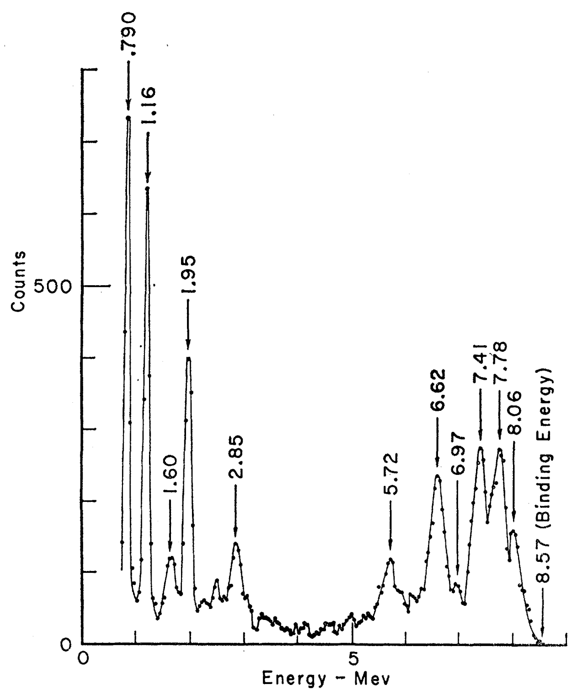

FIG. 2. Sum-coincidence spectrum (0–9 Mev) of $Cl^{35}(n,\gamma\gamma')Cl^{36}$.

thick by 5-in. diam mounted on 3-in. photomultipliers. Since the neutron source intensity was a limitation, the sample and scintillators were placed as close as possible to the electron accelerator target. The usual beam-flash effects of paralysis of electronics and gain shift of the photomultipliers were, as a result, more difficult to control. The sample was $AlCl_3$ of purity $>99.9\%$ and thickness $N\sigma=0.8$ for thermal neutrons. Thus, only 0.2% as many neutrons are captured by Al as by Cl.

The details of application and analysis of the sum-coincidence method with (n,γ) reactions have been reported.[10] Part of this is an extension of earlier work by Hoogenboom.[11] Reference 10 contains much of the details of the apparatus and procedure.

Figure 2 shows the full sum-coincidence spectrum without subtraction of background. The primary function of this curve is as an indication that the apparatus is functioning properly. The required symmetry in *areas* of pairs of peaks and the absence of counts at full energy are demonstrated. This run was taken with no lead absorbers between the scintillators, so the false peaks at 8.06 Mev and 0.51 Mev (the latter being below the analyzer threshold in this run) caused by annihilation photon transfer between scintillators[10] are abnormally large.

RESULTS

Figure 3 shows representative data taken at greater amplifier gain for improved resolution. This arrangement was used to collect data for the analysis of two-step cascades. For this run, the two lead absorbers (each 2.1 g cm^{-2}) were placed between the scintillators to reduce the backscatter and annihilation photon transfer between scintillators. The effectiveness of this procedure is analyzed in reference 10.

The vertical lines indicate the energies of difference between the neutron binding energy, 8.57 Mev, and the high-energy transitions of intensity $\geqslant 0.5\%$ observed by Groshev *et al.*[6] in the singles spectrum. The high-energy transitions are usually presumed to be initial transitions from the capturing state. It is to be expected, however, that occasionally the less energetic member of a two-step cascade is the initial transition. The lines therefore indicate the energies of possible final transitions in two-step cascades.

The direct experimental result is the product I_1b_2, where I_1 is the intensity of the initial transition and b_2 is the branching ratio to ground of the level fed by the first transition. If, in addition, I_1 is known from singles spectra,[6] the value of b_2 can be obtained. The resolution in the present work is not as great as that obtained with magnetic spectrometers, this being the price for sufficient detector efficiency for coincidence measurements. Consequently, somewhat more information can be obtained from the present experiment when the high-energy transitions located by magnetic spectrometers are used as possible members of two-step cascades and the product I_1b_2 is evaluated for each of these energies. Of course, the result $b_2=0$ will

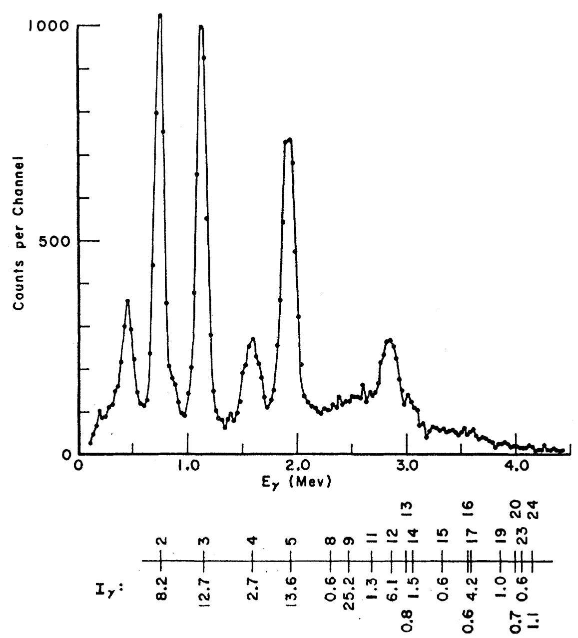

FIG. 3. Sum-coincidence spectrum (0–4.4 Mev) of $Cl^{35}(n,\gamma\gamma')Cl^{36}$. The vertical lines are located at energies of difference between 8.57 Mev and high-energy transitions observed by Groshev *et al.*[6] The numbers indicate the line designation and the intensity of their high-energy transition.

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TABLE I. Two-step ground-state cascades from $Cl^{35}(n,\gamma\gamma')Cl^{36}$.

Cascade[a]	Lower energy[a] (Mev)	Cascade energy sum[a] (Mev)	I_1b_2 (our results)	b_2 derived[a]	Upper limit of b_2 (Groshev[c])	b_2 (Segel[d])
2–63	0.792	8.578	$\equiv 8.2$	$\equiv 1$	$\equiv 1$	$\equiv 1$
3–62	1.165	8.575	11.6±1.2	0.91±0.09	1	large
4–60	1.597	8.571	2.9±0.4	1.07±0.15	1	large
5–57	1.957	8.578	12.1±1.2	0.89±0.09	0.74	0.8
55–7	2.235	8.579	0.6±0.3	≤ 0.55	0.37	...
54a–8[b]	(2.317)	(8.583)			...	
9–(53)	2.467	8.577	≤ 0.5	≤ 0.02	0.02	small
9a–51[b]	2.535	(8.58)	0.7±0.2	≤ 1	...	...
10–50[b]	2.628	8.587			1	
11–49	2.681	8.583	1.6±0.3	1.2±0.2	1	...
12–46	2.868	8.583	5.1±0.9	0.84±0.15	1	large
13–44	3.002	8.587	2.0±0.4	0.45±0.1	1	...
42–14	3.067	8.583			0.45	
15–40	3.338	8.584	≤ 0.6	≤ 1	1	exists
36–16	3.566	8.582	≤ 0.5	≤ 0.1	0.5	small
17–35	3.596	8.577			0.12	
33–18	3.822	8.579	≤ 0.3	≤ 0.16	0.17	...
20–32	3.957	8.570	≤ 0.2	≤ 0.06	1	...
31–21	3.980	8.569			0.25	
23–30	4.053	8.575			1	
24–28	4.138	8.582			0.18	
			Sum 46±6			

[a] The precise energies, designations, and intensities I_1 are taken from Groshev *et al.*[6]
[b] These cascades were not included in the decay scheme of Groshev *et al.*[6]
[c] See reference 6.
[d] See reference 7.

be obtained if there is no coincident cascade. The separate question of which of the two is the initial transition can usually be answered correctly by assigning the more energetic transition as initial. However, an unambiguous assignment requires delayed-coincidence measurements (usually very fast) or precise knowledge of the transition energy and all level energies in the region of the prospective intermediate level.

The results are summarized in Table I in which the first column identifies the members of the cascade in the presumed order of their emission. The numbering is that of Groshev *et al.*[6] The more energetic member of the cascade is listed first with six exceptions where there is insufficient evidence for a level matching the less energetic transition. Column 2 lists the energy[6] at which the cascade would appear in Fig. 3. Column 3 lists the energy sum of each cascade as measured by Groshev *et al.*, for comparison with the neutron binding energy. Column 4 lists I_1b_2, the direct result of these experiments. The units of I_1 are photons per 100 neutrons captured to form Cl^{36} and the fraction $b_2 \leq 1.0$. Column 5 lists b_2 with the assumed transition ordering of column 1 and I_1 obtained from reference 6. In the cases where several cascades in column 1 are grouped together, the number in column 5 is an average b_2 weighted in proportion to each value of I_1. Listed in column 6, for comparison, is the upper limit on b_2 set by the singles spectrum.[6] This is the ratio I_2/I_1 (or 1 if smaller) where I_2 is the intensity of *all* transitions depopulating the intermediate level, some of which may have been preceded by cascades. The extent to which the numbers in column 6 exceed those in column 5 represents the relative importance of cascades involving more than two transitions. Column 7 lists the values of b_2 reported by Segel.[7]

The preliminary report[9] of the present experiments was based primarily on the transition intensities measured earlier by Groshev *et al.*[5] Our preliminary results were not substantially different from those reported now. A 5.89–2.68-Mev cascade was included in the preliminary results, although a 5.89-Mev transition was not indicated in the earlier results of Groshev *et al.* This cascade is confirmed in their more recent results.

In evaluating I_1b_2 in the present results, the analysis of reference 10 was used. The effect of 255-kev photon transfer between scintillators was negligible because of the lead absorbers between crystals. Corrections for 510-kev photon transfer were negligible except for a 15% effect on I_1b_2 at 1.597 Mev, and a 40% contribution to the counting rate at 2.477 Mev. A comparable contribution at 2.477 Mev was produced by summing of the intense three-step cascade of 6.110–0.518–1.949 Mev reported by Segel. Consequently, after these two corrections, the value 0.06 is reduced to ≤ 0.02 for b_2 at 2.477 Mev. The threefold cascade caused a 5% correction in I_1b_2 at 1.957 Mev. There were no other corrections.

The question whether there is a real line at 0.91 Mev could not be answered with the available neutron intensity. If it were real it would require a new level in Cl^{36} at 0.91 Mev, the possibility of which cannot be eliminated with existing data. The fact that this energy is not far from the difference of 8.57 Mev and the energy of the strong 7.73-Mev $Al(n,\gamma)$ transition is

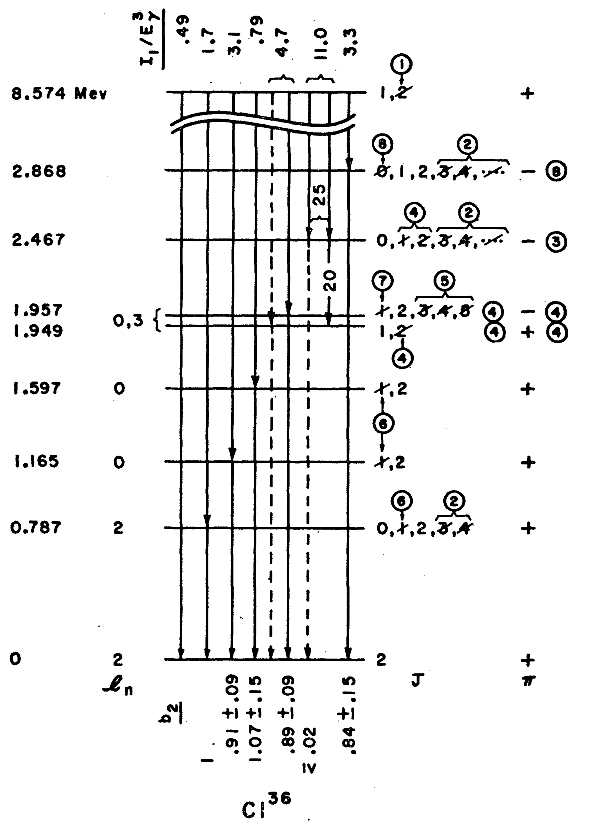

FIG. 4. Level structure of Cl^{36} with possible spin and parity assignments. The two-step cascades are the strongest ones indicated in Fig. 3. The circled numerals indicate the order of the steps taken in the analysis and are explained in the text. The quantities b_2 are those reported in Table I.

perhaps significant. However, the intensity of the structure at 0.91 Mev, about 1/30 that of the 0.79-Mev peak, is too large to be caused by chance coincidence with a transition in Al^{28}.

INTERPRETATION

The angular momentum of the ground state of $_{17}Cl^{35}$ has been measured[12] as $\frac{3}{2}$ by a microwave method. The shell model assignment[13] of the odd proton is $(d_{\frac{3}{2}})$. Thermal neutron capture then produces Cl^{36} in a 1+ or 2+ compound state. Total neutron cross-section measurements by Bruegger *et al.*[14] appear to favor the assignment of spin 2 (negative energy resonance) although the result is uncertain. The ground-state spin[12,15] of Cl^{36} is 2, with a positive parity assignment from the study[16] of the beta decay of Cl^{36}. Consequently there is reason to believe that the initial and final states in a two-step cascade in Cl^{36} are both 2+. It will be interesting, then, to compare the strength of the initial and final transitions in the cascade.

The neutron binding energy of Cl^{36} is found to be 8.57 Mev by mass measurements[17] and 8.58 Mev by measurement of the Q value of the ground state group[4] in $Cl^{35}(d,p)Cl^{36}$. The most energetic neutron-capture gamma ray from Cl^{36} observed by Groshev *et al.*[6] was 8.57 Mev.

Figure 4 shows a possible decay scheme for Cl^{36} which includes all of the strong cascades reported here and the level at 2.477 Mev with the small value of $b_2 \leqslant 0.02$. It is possible to construct a consistent set of spins and parities for the levels using the following: the values of b_2 here reported, the l_n values from the resolved (d,p) groups of Teplov,[3] the assignment by Segel[7] and by Groshev *et al.*[6] of the 0.518- and the 6.62-Mev transitions as terminating on different levels near 1.95 Mev, and the transition intensities of Groshev *et al.*,[6] particularly the indication of the nearly complete depopulation of the 2.467-Mev level by the 0.518-Mev transition. The assumption will be made that the relative probabilities of radiative transitions of various multipole orders are related approximately according to single-particle predictions—or more specifically that there are no enhancements such as are found for $E2$ transitions due to collective motion of deformed nuclei.

The numbers 1–8 in Fig. 4 indicate the order of the steps in assigning spins and parities. Step 1 eliminates $J=2$ for the capturing state. Only with different spins for the capturing state and the ground state can the very small value of $b_2 \leqslant 0.02$ for the 2.467-Mev level be explained, when the initial transition to the 2.467-Mev state has the largest reduced width of any shown in Fig. 4, and when the lowest excited states have the same parity as the ground state. Crucial to this step is the assumption that there are no collective effects and, of course, no definitive argument can be made on this point. It can only be said that a consistent scheme is possible without evoking collective effects and that Cl^{36} is only one neutron and three protons removed from closed shells. Step 1 is not in agreement with the findings of Bruegger *et al.*[14] in their measurement of the total neutron cross section. However, those authors state that they selected $J=2$ because visual shape fits to the data gave $\sigma_{\rm incoh}=10.9\pm0.9$ barns assuming $J=1$, and 7.8 ± 0.7 assuming $J=2$, while the measured value is $\sigma_{\rm incoh}=\sigma_{\rm sc}-\sigma_{\rm coh}=(16\pm3)-(12.1\pm0.8)=3.9\pm3.1$ barns. The result is not conclusive.

In Fig. 4 are shown all of the J values of excited

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[17] C. F. Giese and J. L. Benson, Phys. Rev. **110**, 712 (1958)

states which are consistent with the values of l_n. Step 2 eliminates $J \geqslant 3$ for the 2.868-, 2.467-, and 0.787-Mev levels because of the strong initial transitions to these levels which are assumed to be dipole.

Step 3 assigns odd parity to the 2.467-Mev level by assigning $E1$ to the initial transition to this level. This transition has the largest reduced width shown in Fig. 4. Unfortunately, the possibility of $M1$ cannot be discounted.

In step 4 it is assumed that the 0.518-Mev transition is virtually the sole depopulator of the 2.467-Mev level, because it is $E1$ and no other strong transitions from this level are possible. This eliminates $J=1$ and 2 for the 2.467-Mev level, since the ground state is 2^+ and $b_2 \leqslant 0.02$ for the 2.467-Mev level. In turn, this eliminates $J=2$ for the 1.949-Mev level in order that the 0.518-Mev transition be $E1$. It also provides the assignment of even parity to the level terminating the 0.518-Mev transition and consequently odd parity to the other level near 1.95 Mev in view of the values of l_n. These two assignments of l_n in turn fix the range of possible J values for these two levels at 1.957 and 1.949 Mev.

The next step, 5, is the elimination of $J=3$, 4, or 5 for the level terminating the strong 6.621 ± 0.005-Mev transition[6] on the assumption that it is dipole. There is possible a weaker $M1$-$M1$ cascade through the 1.949-Mev level to the ground state which is shown dotted. Such a cascade would not have been resolved in the present experiment. The 6.621-Mev transition has not been reported as double, but a presumably weaker transition 8 kev above the one at 6.621 Mev would appear not to be inconsistent with the data of Groshev *et al.*[6]

Step 6 eliminates $J=1$ from the possibilities for the 1.597-, 1.165-, and 0.787-Mev levels, thereby removing the possibilities of $E1$ transitions to these levels from the 2.467-Mev level. No transitions with energies 0.870, 1.302, or 1.680 Mev have been observed.[6]

In step 7, $J=2$ is preferred over $J=1$ for the 1.957-Mev level, in keeping with the shell model and the assignment $l_n=3$. In the simple picture of this state, the neutron is $f_{5/2}$ or $f_{7/2}$, but in the shell model the $f_{7/2}$ shell lies lower than the $f_{5/2}$. The $d_{3/2}$ proton and $f_{7/2}$ neutron could not couple to give $J=1$. The set of level parameters to this point is similar to one of the four sets considered by Groshev *et al.*,[6] but the approach and reasoning given here are appreciably different.

In step 8, odd parity is favored for the 2.868-Mev level in view of its large b_2. If it had even parity there would be a strong $E1$, 0.91-Mev transition to the 1.957-Mev level, while the transition to the ground state would be $M1$. No such transition is observed. The value in Table I of $b_2 = 0.84 \pm 0.15$ for the 2.868-Mev level indicates little competition with the ground state transition. This eliminates $J=0$ for the 2.868-Mev level. With the assignment of odd parity to the level, the cascade to the ground state would be $E1$-$E1$.

This set of spins and parities for some of the levels of Cl^{36} is an internally consistent one. It is further consistent with the measurements by Trumpy[8] of the circular polarization of the cascade through the 1.165-Mev level. It appears to be the most probable set which can be fitted to the data.