try to visualize an $l_n=3$ distribution buried in the "background" of Fig. 5, we conclude that, at best, this hypothetical proton group cannot amount to more than about 3 percent of the $Q=8.14$-Mev group in intensity. Even so, this may represent the proper identification of the proton groups from Ti^{47}, since it is difficult to gainsay the evidence for a ground-state Q greater than 8.14 Mev. We can find no reason to distrust the mass data, and so, in Table I, two alternatives have been listed in the column headed "excitation energy of final nucleus," one of which assumes $Q=8.14$ Mev is the ground state while the other assumes that it is the first excited state, with a very uncertain excitation energy of about 1.27 Mev. If $Q=8.14$ Mev is not the ground-state transition, we can only speculate about the failure to observe the true ground-state reaction. One argument, which can lead only to qualitative conclusions, has to do with the peculiar nature of Ti^{47}. By the independent-particle shell model, the Ti^{47} spin should be 7/2 instead of 5/2. Presumably spin 5/2 is the result of an unusual coupling of five neutrons in $f_{7/2}$ orbits. If another neutron is to be captured directly into an $f_{7/2}$ orbit to form ground state Ti^{48} with six $f_{7/2}$ neutrons and zero spin, some rearrangement of the angular momenta of the five original neutrons will be necessary in order to conserve total angular momentum. It is undoubtedly true that this necessity for rearrangement will reduce the cross section for the reaction, but it is not obvious that it can account for our complete failure to observe the corresponding proton group.

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Two-Step Cascades in Chlorine-36 and Cadmium-114 Neutron-Capture Gamma-Ray Spectra*

ARTHUR L. RECKSIEDLER AND BERNARD HAMERMESH
Argonne National Laboratory, Lemont, Illinois

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Two NaI(Tl) crystals were used in conjunction with a twenty- and a single-channel pulse-height analyzer and a 5-microsecond coincidence circuit to determine cascade branches in the neutron-capture gamma-ray emission from Cl^{36} and Cd^{114}. Several two-step cascades in Cl^{36} and one in Cd^{114} have been verified by the present methods.

INTRODUCTION

THE use of NaI(Tl) crystals has provided a method of measuring photon energy values in the lower range of neutron-capture gamma-ray energies. The most prominent capture gamma energies in several elements have been determined by the use of such crystals.[1] Higher-energy photons have been measured accurately by the use of a pair spectrometer.[2]

A single neutron capture by an element X^A forms the isotope X^{A+1} in an excited state corresponding to the neutron binding energy for the element. In decaying to the ground state, intermediate states may be involved and the energy difference between each state then corresponds to the energy of the capture gamma rays emitted by the isotope. In a time on the order of 10^{-13} second the new nucleus is at the ground state unless an isomer is formed. In chlorine-36 several two-step cascades had been predicted according to the data collected by the use of NaI(Tl) crystals by Hamermesh and Hummel, and a pair spectrometer by Kinsey *et al.* The sum of the two gamma rays constituting each supposed cascade branch is in agreement with the neutron binding energy as shown in Table I.

The cadmium high-energy spectrum has been investigated by Kinsey *et al.*, and the neutron binding energy reported as corresponding to the highest-energy gamma ray of 9.046±0.008 Mev. Several other gamma rays have been determined including one at 8.48 Mev. The lower (50 kev to 5 Mev) energy range of the spectrum has been investigated in noncoincident runs with the NaI(Tl) crystal. The spectrum was found to be complicated and no lines other than the 0.558-Mev gamma ray were resolved. The sum of the 8.48-Mev and 0.558-Mev gamma rays equals the neutron binding energy, and a two-step cascade branch was also predicted here.

TABLE I. Combined pair-spectrometer and scintillation-spectrometer data on the capture γ rays from chlorine-36. Energies in Mev.

	Kinsey	Hamermesh	Sum (Neutron binding energy)
A	8.56±0.03	···	8.56±0.03
B	7.77±0.03	0.784±0.010	8.55±0.03
C	7.42±0.03	1.15 ±0.010	8.57±0.03
D	6.98±0.03	1.59 ±0.013	8.57±0.03
E	6.62±0.06	2.00 ±0.025	8.62±0.06

* Part of a thesis submitted by A. L. Recksiedler as a requirement for the Master's Degree in Engineering Physics from the Michigan College of Mining and Technology. Work performed under the Participating Institution Program of the Argonne National Laboratory.

[1] B. Hamermesh and V. Hummel, Phys. Rev. 88, 916 (1952).

[2] Kinsey, Bartholomew, and Walker, Phys. Rev. 85, 1012 (1952).

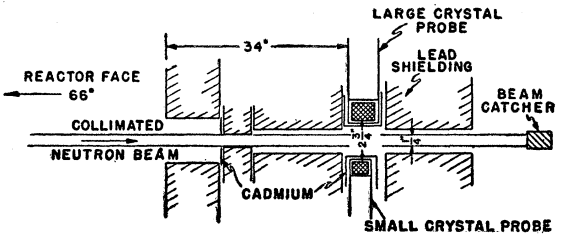

FIG. 1. Schematic diagram of coincident capture gamma-ray detectors (top view).

APPARATUS

The reactor CP3 at the Argonne National Laboratory was used as a source from which a collimated neutron beam was taken. The sample was placed in the beam approximately 100 inches from the reactor face. For the chlorine runs, a sample of C_2Cl_6 (hexachlorethane) was used as target material. Although there was no attempt made to separate isotopes, chlorine-35 is present to 75 percent in natural chlorine, with a neutron capture cross section of 32 barns. The remaining 25 percent is chlorine-37 with a cross section of 0.14 barn. Carbon in the sample also has a low capture cross section, so that the spectrum found is chiefly due to neutron capture processes by Cl^{35} nuclei. A target of metallic cadmium was placed in the beam to obtain the cadmium-114 spectrum. Although present to only 12.3 percent, the large capture cross section, on the order of several thousand barns, is sufficient to effectively minimize the contributions to the spectrum of the other cadmium isotopes.

A large NaI(Tl) crystal ($3\frac{1}{2}\times3\frac{1}{2}$ inch right circular cylinder) was placed 90° from the direct beam in a horizontal plane while a similar smaller crystal (1-inch height by $1\frac{3}{8}$-inch diameter) was placed approximately $2\frac{3}{4}$ inches apart from and opposing the larger crystal as shown in Fig. 1. Two-inch bismuth blocks were used as lining around the crystals and lead blocks were used for further shielding. Cadmium sheets were then placed over the lead shielding. The smallest shielding thickness was 4 inches, except at the face of the crystals. Only a sheet of cadmium separated the probe face from the sample. Background was further cut by means of cadmium and lead jaws placed about 18 inches from the crystals. The crystals were packaged by a method devised by Swank and Moenich.[3] The crystal arrangement was chosen for the best geometry available with a minimum of loss in effective shielding and in resolution.

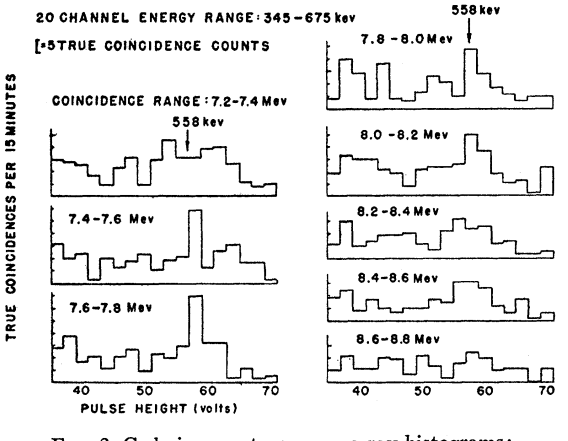

FIG. 2. Cadmium capture gamma-ray histograms; 0.558–8.48 Mev cascade; Method A.

A bank of three RCA 5819 photomultipliers was placed behind the large crystal with the output fed to a two-stage preamplifier. The small crystal was backed by a single 5819 and a similar preamplifier. The output from either probe could be connected to a single- or twenty-channel pulse-height analyzer. A coincidence circuit with a resolving time of 5 microseconds was connected so that the pulses from the single-channel analyzer would trigger the gate and the twenty-channel coincident pulses would be recorded. All single-channel pulses would also be recorded. Noncoincident trials were necessary to determine the noncoincident 20-channel counting rates.

METHOD

Increased background at lower energies combined with a greater crystal efficiency determined that the large crystal be used only in the high-energy region being investigated. At approximately 4 Mev the background represented 40 percent of the noncoincident counting rates. The large crystal was placed on the high-energy region while the smaller crystal recorded the low-energy region of the spectrum. The background did not arise as a major problem with the smaller crystal. The ratio of true coincident counts to accidental counts was between $1\frac{1}{2}$ and 2 at the expected coincident energies. True coincident counts are considered to be the total recorded counts less the accidental counts. Calibration was obtained from known gamma-ray energies in Au^{198} (0.411 Mev), Cs^{137} (0.662 Mev), Na^{24} (1.38 Mev and 2.76 Mev), and a PoBe source (4.5 Mev).

By exchanging the large and small crystal probes between the single- and twenty-channel analyzers, two methods of obtaining data were available. The first, Method A, was to set the twenty-channel analyzer on the low-energy range containing the full-energy peak and its maximum Compton energy. The range was varied on repeated trials to account for any individual channel variations. A channel width of approximately 20 kev was used below 1 Mev and 50 kev above 1 Mev. The single-channel analyzer was then varied over the energy range corresponding to the high-energy step in the cascade in widths of 200 kev. Due to the effects of pair production, it is possible for the high-energy gamma-ray to produce pulses in an energy range corresponding to approximately 1.2 Mev. Thus, six 200-kev intervals cover the energy range in which coincident

[3] R. K. Swank and J. S. Moenich, Rev. Sci. Instr. **23**, 512 (1952).

pulses caused by the cascade can be expected. The high-energy counting rate decreased gradually with increasing energy, and no actual peaking effects were observed. A series of histograms may be made showing the true coincidence counts in each energy interval for the length of the run (15 minutes per interval), as shown for cadmium in Fig. 2. The low photoelectric peak is shown to appear as the high-energy ranges corresponding to the high-energy gamma-ray minus one and two annihilation quanta appear in the single-channel analyzer. The peak dies out after the full high-energy peak is passed. By adding the actual counts in the proper energy range and subtracting accidental counts, a curve of the low-energy region in coincidence with a high-energy range is obtained with fair statistics.

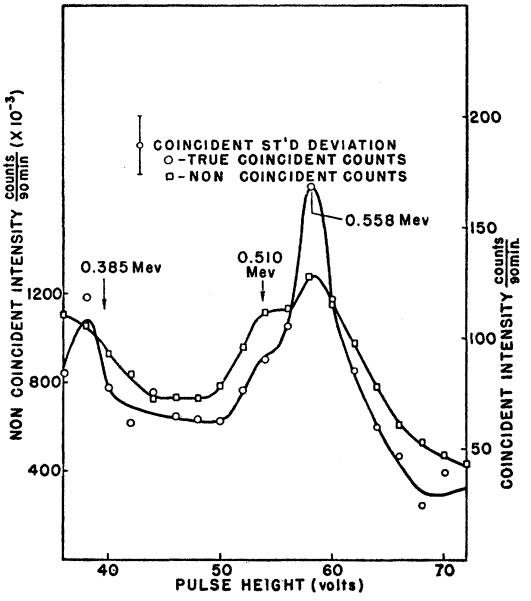

FIG. 3. Cadmium capture gamma-ray spectra, Method A; 0.558–8.48 Mev cascade, 7.4–8.6 Mev coincident range; calibration 9.62 kev/v.

Method B consisted of placing the large crystal's pulses on the twenty-channel analyzer and the small crystal's output on the single-channel analyzer. The low-energy range was then covered in successive 20- or 50-kev intervals. Due to the multiplicity of cascade possibilities the direct results of the run provided little useful information. As the full low-energy peak appeared in the single-channel analyzer, increased counts in the proper range seemed to appear in coincidence counting, but results were indefinite. Assuming the low-energy peak is sitting on a background of Compton distributions from slightly higher-energy gamma rays, which also form cascades within the high-energy range, the energy interval containing the low-energy photopeak will provide coincidences over a greater range than the 1.2-Mev range of the cascade being checked. To evaluate the Compton background on which the low-energy

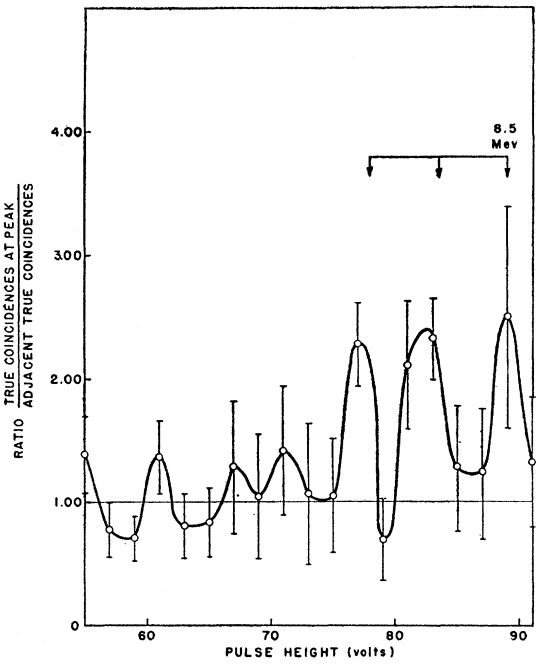

FIG. 4. Cadmium capture gamma-ray spectrum, Method B, 0.558–8.48 Mev cascade; calibration 91 kev/v.

gamma ray is sitting, an average was taken of the true coincident rates on either side of the photopeak, and the result was then divided into the true coincidences at the photopeak. Lines actually forming cascades should then have large ratios, while all other ratios are essentially one. The method, although yielding poor statistics, essentially has confirmed the results of Method A.

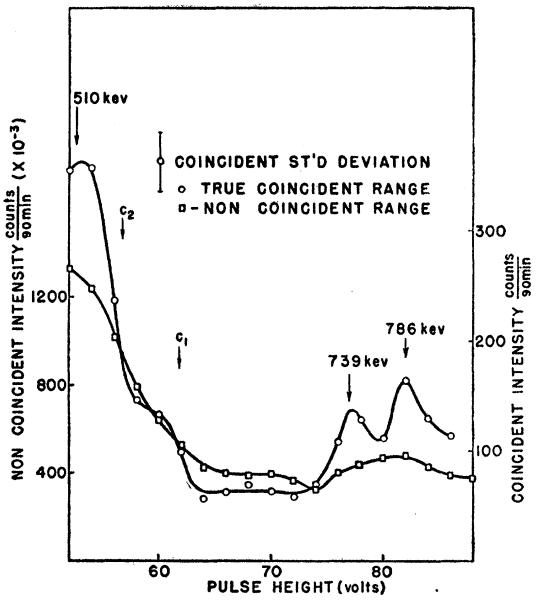

FIG. 5. Chlorine-36 capture gamma-ray spectra, Method A, 0.784–7.77 Mev cascade, 6.6–7.8 Mev coincident range; calibration 9.60 kev/v.

RESULTS

The coincident curve obtained by Method A on the cadmium cascade (Fig. 3) indicates the full-energy peak and the Compton maximum energy of 0.385 Mev. There is also a rise in the curve corresponding to an energy of 0.510 Mev, or the annihilation quantum, and this is coincident with the entire high-energy range. That the coincident curve does not reach zero in the other energy regions is attributed largely to Compton distributions from other cascades in the energy ranges considered. The noncoincident energy distribution without a background correction is also shown in the figures of data obtained by Method A.

The ratios obtained by Method B on the cadmium 0.558–8.48 Mev cascade (Fig. 4) indicate that the full 8.5-Mev energy peak along with the peak minus one and two annihilation quanta have ratios above two, while all other ratios are within statistics equal to the value of one. From the curve it is concluded that no other gamma rays down to 5.00 Mev are in coincidence with the 0.558-Mev gamma ray.

In chlorine the 0.784–7.77-Mev cascade curve obtained by Method A (Fig. 5) indicated another possible coincident gamma ray at 0.735 Mev, along with the expected photopeak at 0.784 Mev and its Compton edge (C_1). The Compton maximum (C_2) of the second gamma ray should also appear, but is obscured by the 0.510-Mev annihilation radiation. The extra peak has been found on repeated coincident runs, but noncoincident trials have failed to separate two distinct lines.

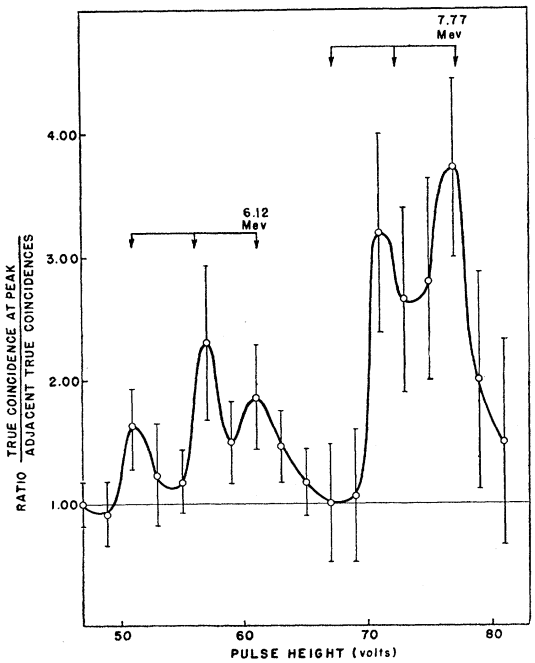

FIG. 6. Chlorine-36 capture gamma-ray spectrum, Method B, 0.784–7.77 Mev cascade; calibration 100 kev/v.

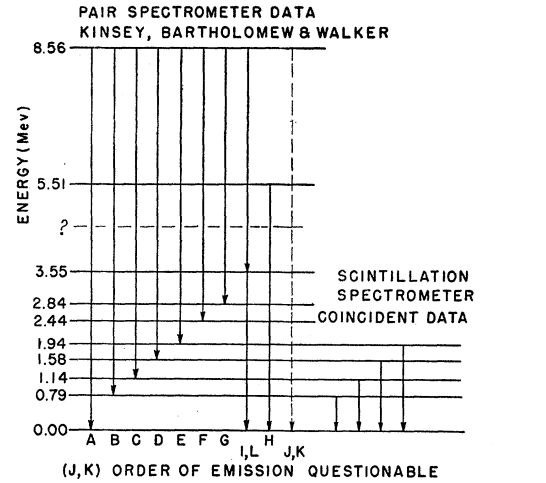

FIG. 7. Level scheme, chlorine-36 capture gamma-ray spectrum.

In the curve obtained by Method B (Fig. 6), the 7.77-Mev full energy peak appears along with the peak minus one annihilation quantum. The third peak definitely does not appear, and the reason for this is unclear. In trials on the other predicted cascades, the region around 6.5 Mev has shown lower ratios than would be expected for the method. There are also three peaks which seem to indicate the gamma ray of 6.12 Mev, reported by Kinsey *et al.*, also forms a cascade with the 0.784-Mev gamma-ray. The energy discrepancy between the neutron binding energy and the sum of these gamma rays is about 1.58 Mev, which could be emitted in one or more steps. The present information indicates the two gamma rays mentioned are a portion of a more complex cascade branch.

The curves on the other cascade branches in chlorine indicate only the predicted results, i.e., that the 1.15-Mev and 7.42-Mev gamma rays form a two-step cascade branch, and that the 1.59-Mev with the 6.98-Mev, and the 2.00-Mev with the 6.62-Mev gamma rays form similar two-step cascades.

CONCLUSIONS

The cascade branches of chlorine-36 which have been confirmed by the present study are indicated in the capture gamma-ray level scheme as shown in Fig. 7. There is yet to be resolved the significance of the 0.735-Mev gamma ray, and the reason for the apparent interference in the present methods of determining coincident energies around 6.5 Mev. A portion of a more complex cascade branch containing the 0.784-Mev and 6.12-Mev branch has also been found by the present methods.