Inelastic Scattering of Monochromatic Photons from the 7.64-MeV Level of Ni^{62}†

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The nuclear resonant scattering of the monochromatic iron capture gamma rays from natural nickel was studied with a single NaI crystal and a three-crystal pair spectrometer. The spectrum of the scattered photons exhibits three photon groups of 7.64, 6.47, and 5.38 MeV with relative intensities 0.69, 0.08, and 0.23, respectively. The spectrum of the low-energy cascade photons in coincidence with the scattered photons identifies these groups with the transitions from the 7.64-MeV resonant level to the 0^+ ground state and the first (2^+, 1.17 MeV) and second (0^+, 2.05 MeV) vibrational levels in Ni^{62}. Angular distribution measurements of the elastically scattered photons show that the 7.64-MeV level in Ni^{62} has angular momentum 1. The elastic-scattering cross section averaged over the incident gamma rays was determined to be $\langle\sigma_{\gamma\gamma}\rangle = 190\pm40$ mb.

I. INTRODUCTION

THE thermal neutron capture process is a source of extremely monochromatic photons. The gamma rays emitted following the thermal neutron absorption have energies in the range of 6–10 MeV with the energy resolution of a few electron volts. Therefore, the neutron capture gamma rays are suitable to study the properties of an individual nuclear level near the neutron-binding energies provided that there is an appreciable overlap between the incident capture gamma rays and the nuclear level to be studied. The nuclear resonance fluorescence of the capture gamma rays has now been observed for about 50 nuclei.[1–3] In most experiments of this type, the spectrum of the resonantly scattered photons was studied using a single NaI spectrometer. In several cases the spectrum was found to be quite complex, suggesting inelastic scattering leading to low-lying excited levels.[3] Since the excitation energy which can be reached by the neutron capture gamma rays is in the range of 6–10 MeV, the detailed study of the spectrum of the inelastically scattered photons can yield information about the structure of the lower lying levels, which may not be easily excited in other reactions. In this work, the inelastic scattering of the iron capture gamma radiation from the 7.64-MeV level[2,3] in nickel was studied by observing the low-energy cascade photons in coincidence with the resonantly scattered photons. The 7.64-MeV level is to be attributed to a specific Ni isotope by comparing the coincidence spectrum with the known low-lying levels of the nickel isotopes.

† Supported by the National Science Foundation.

[1] B. Arad (Huebschmann), G. Ben-David (Davis), I. Pelah, and Y. Schlesinger, Phys. Rev. **133**, B684 (1964).

[2] C. S. Young and D. J. Donahue, Phys. Rev. **132**, 1724 (1963).

[3] M. Giannini *et al.*, Nuovo Cimento **34**, 1116 (1964).

II. EXPERIMENTAL PROCEDURE

A. Production of Iron Capture Gamma Rays

The capture gamma-ray source was about 1 kg of natural iron placed near the core of the University of Virginia 1-MW reactor. The geometrical arrangements of the capture target, filters, and collimators remained the same as given in a previous report.[4] To reduce the fission gamma background originating from the reactor

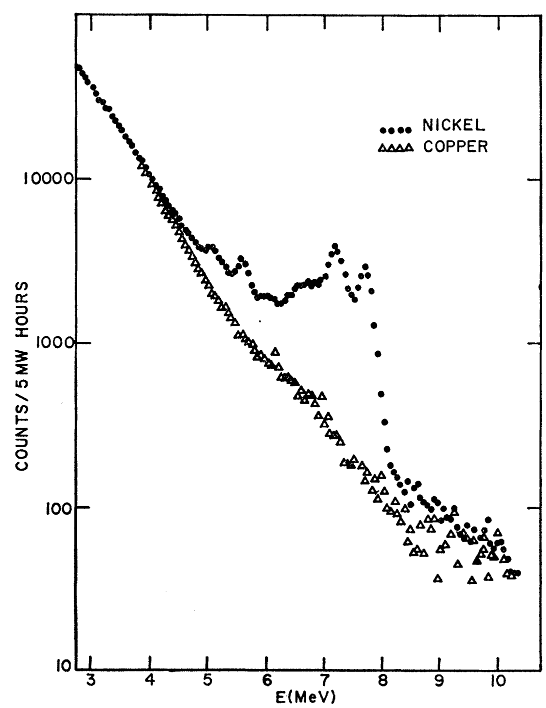

FIG. 1. Spectrum of scattered photons from nickel.

[4] K. Min, Phys. Rev. **152**, 1062 (1966).

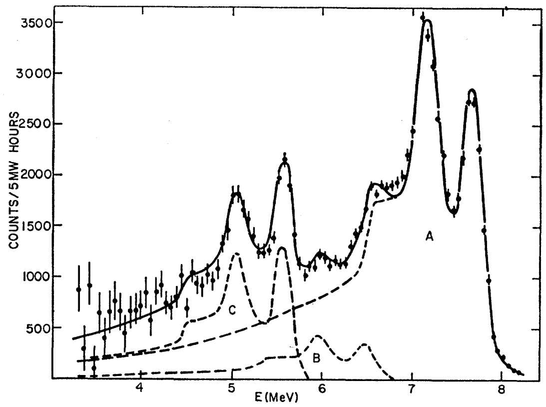

FIG. 2. Decomposition of the scattered-photon spectrum after the background subtraction. The solid line is the sum of the three components A, B, and C.

core, the iron capture target was placed behind a bismuth plate of thickness 1 in. The capture gamma rays then passed through a boron polyethylene neutron filter of thickness $1\frac{1}{2}$ in., and 20 in. of graphite beam hardener. A series of lead collimators along the beam direction collimated the capture gamma rays to a diameter of 2 in. at the scattering target position. An important feature of the experimental geometry was that the direction of the capture gamma-ray beam was tangential to the reactor core, so that the scattering target was prevented from "seeing" the core directly. With the above arrangements, the signal-to-background ratio was about 20 for the nickel scattering target of thickness 1.25 cm (Fig. 1).

B. Scattering Geometry

The scattering target was a natural nickel plate of thickness 1.25 cm. It was placed along the beam direction 2m away from the reactor shielding wall. The scattered photons were detected by a 5×4-in. NaI spectrometer placed on a rotating table with its axis of rotation fixed at the center of the scattering target. The spectrum of the scattered photons was recorded in a 400 channel RIDL pulse-height analyzer. The scatterer to detector distance was 20 cm during the normal scattering run. During the angular distribution measurements, the distance was lengthened to 50 cm from the scatterer to obtain an angular resolution of about 14°.

In the coincidence measurements, a 3×3-in. NaI crystal was used to detect the low-energy cascade photons ($E<3$ MeV) in coincidence with the scattered photons detected by the 5×4-in. crystal. During the coincidence measurements, the target face was oriented perpendicular to the incident beam, and the two detectors were placed symmetrically about the beam direction both at 135°. The target-detector distance was 14 cm.

III. RESULTS

A. Spectrum of the Scattered Photons

The spectrum of the scattered photons from the nickel target at the scattering angle 135° is shown in Fig. 1. The background due to the nonresonant processes was determined by replacing the nickel target with a copper target of matched electronic absorption. The spectrum of the scattered photons after the background is subtracted is shown in Fig. 2. The complexity of the spectrum clearly indicates the existence of inelastic scattering in addition to the 7.64-MeV elastic peak. In order to decompose the spectrum, the following procedures were used. First, a response function of the 5×4-in. crystal in the same scattering geometry was determined in an auxiliary scattering experiment in which the iron capture gamma rays were scattered from the known 7.28-MeV level in Pb^{208}.[1–3] The relative heights of the three peaks (the photopeak and the two annihilation escape peaks) were then adjusted for the energy variation using the Monte Carlo calculations of Snow and Miller.[5] The NaI crystal and the source height used in these calculations (5×5 in. and 10 cm) were not exactly the same as in the present experiment. Nevertheless, the calculated energy variation of the response function seems to be quite applicable to the scattering data as shown in Fig. 2. The solid line through the data points is the superposition of the three photon groups A, B, and C indicated by the dashed lines. The energies (E_i; $i=A$, B or C) and the relative intensities of the three components are given in Table I. In the third column of Table I, the energy differences (ϵ_i) between the elastic peak ($E_A=7.64$ MeV) and the three components are given. These energy differences correspond to the excitation energies of the lower levels to which the 7.64-MeV resonant level decays via given inelastic photon groups.

The spectrum of the scattered photons was also studied with a three-crystal pair spectrometer. The scattered photons were detected by a 2×2-in. center crystal in triple coincidence with the two 0.51-MeV annihilation photons detected by 5×4-in. side crystals. The spectrum at the scattering angle 105° is shown in Fig. 3. The background below channel 150 had a good

TABLE I. Energies and relative intensities of the resonantly scattered photon groups. The third column gives the energies of the lower lying levels populated by the scattered photons.

Component	Energy E_i (MeV)	$\epsilon_i=E_A-E_i$ (MeV)	Relative intensity (%)
A	7.64±0.05	0.00±0.07	69±8
B	6.47±0.05	1.17±0.07	8±2
C	5.58±0.05	2.06±0.07	23±8

[5] W. F. Miller and William J. Snow, Argonne National Laboratory Report No. ANL-6318, 1961 (unpublished).

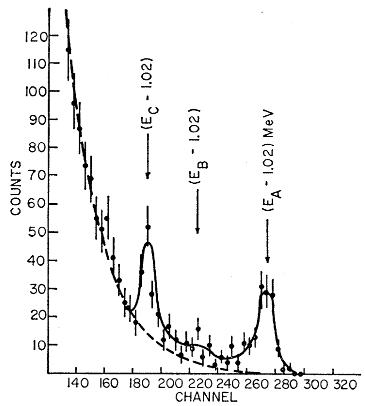

FIG. 3. Spectrum of scattered photons from nickel observed with the three-crystal pair spectrometer. Each datum is the sum of four channels.

fit with an exponential curve. As an estimate of the higher channel background, this exponential curve was extrapolated as indicated by the dashed line in Fig. 3. In spite of the low counts, the spectrum clearly shows the three photon groups A, B, and C, and their energies coincide with the values given in Table I.

B. Coincidence Spectrum of Low-Energy Photons

The spectra shown in Figs. 2 and 3 indicate that the 7.64-MeV resonant level decays to the ground state ($\epsilon_A=0$), and the two excited levels ($\epsilon_B=1.17$ MeV and $\epsilon_C=2.06$ MeV). This was further checked by looking for the cascade photons from the 1.17- and 2.06-MeV levels. The cascade photons were detected by a 3×3-in.

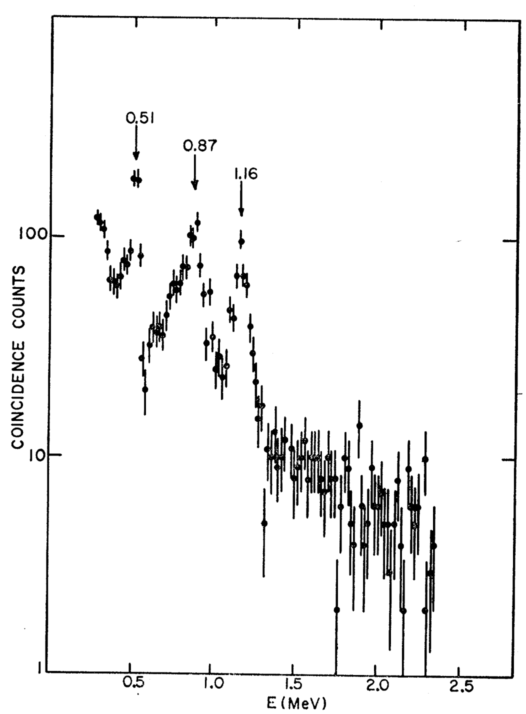

FIG. 4. Spectrum of cascade photons in coincidence with the scattered photons.

NaI crystal in coincidence ($2\tau=50$ nsec) with the scattered photons ($E>4$ MeV) detected by a 5×4-in. crystal. The coincidence spectrum is shown in Fig. 4. The peak at 0.51 MeV is due to the annihilation radiation produced in the target and the shielding materials of the detectors. Two other peaks are observed at

$$E_{\gamma 1}=(1.16\pm0.02)\text{ MeV},$$
$$E_{\gamma 2}=(0.87\pm0.02)\text{ MeV}.$$

The energy of $E_{\gamma 1}$ agrees well with $\epsilon_B=(1.17\pm0.07)$ MeV given in Table I. However, its relative intensity is much larger than expected from Table I. It must be that the 1.16-MeV photons are emitted not only in the decay of the 1.16-MeV level but also in the decay of the 2.06-MeV level. The sum

$$E_{\gamma 1}+E_{\gamma 2}=(2.03\pm0.03)\text{ MeV}$$

should then be compared with $\epsilon_C=(2.06\pm0.07)$ MeV given in Table I. There seems to be little evidence for the 2.03-MeV crossover transition in Fig. 4.

C. Identification of the Resonant Ni Isotope

The energies of the two excited levels populated by the inelastic photon groups B and C will be taken to be the average of the two sets of values obtained in Secs. III A and III B: (1.17±0.04) MeV and (2.05±0.04) MeV. These values are in good agreement with the energies of the first two vibrational levels in Ni^{62} (3.7% abundance) at 1.172 MeV ($J^\pi=2^+$) and 2.048 MeV ($J^\pi=0^+$ or 2^+).[6] The resonant scattering observed in this experiment is then attributed to the 7.64-MeV level in Ni^{62}. The nuclear levels in Ni^{62} and the photon transitions observed in this experiment are shown in Fig. 5. The energies and the spin assignments given on the right are the values obtained in other reactions.[6] The $J=1$ assignment for the 7.64-MeV level is discussed below.

D. Properties of the 7.64-MeV Resonant Level

1. *Angular Momentum*

In order to determine the angular momentum of the 7.64-MeV resonant level, the angular distribution of

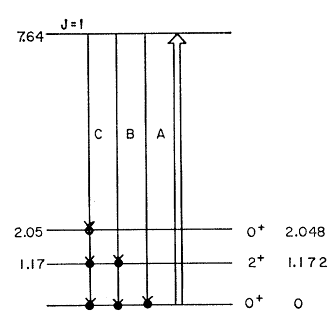

FIG. 5. Energy levels (MeV) and photon transitions observed in this experiment. The energies on the left and the $J=1$ assignment for the 7.64-MeV level were determined in this experiment. For comparison, the energies and the angular momenta determined in other reactions (Ref. 6) are given on the right.

[6] D. M. Van Patter, Nucl. Phys. 14, 42 (1959).

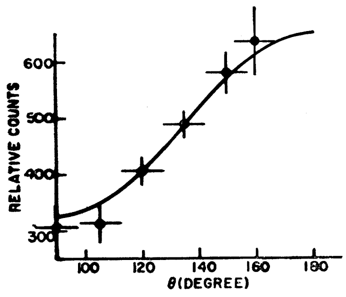

FIG. 6. Angular distribution of the elastically scattered photons. The solid line is the theoretical curve for $J=1$, $W(\theta)=C(1+\cos^2\theta)$ normalized at 135°.

the elastically scattered photons (group A) was measured at six angles. The result is shown in Fig. 6. The solid line drawn through the data points is the theoretical curve $W(\theta)=(1+\cos^2\theta)$ for 0(1)1(1)0 transition normalized at the 135° point. For $J=2$, the angular distribution is given by $W(\theta)=C(1-3\cos^2\theta+4\cos^4\theta)$ which has a pronounced minimum about 130°. It was not possible to fit this distribution through the experimental points. It is concluded that the 7.64-MeV level has angular momentum $J=1$. This agrees with the angular momentum assignment by B Arad *et al.*,[1] based on the angular distribution measurements at 90° and 135°.

2. *Elastic-Scattering Cross Section*

The differential scattering cross section at 135° was obtained using the integrated counts under the response curve A (Fig. 2) in the energy interval 6–8 MeV. In this energy interval, the iron capture gamma radiation is known to contain 7.28-, 6.40-, and 6.02-MeV components in addition to the 7.64-MeV line,[7] some of which are not resolved in the NaI spectrum. Therefore, the intensity of the 7.64-MeV line was obtained from the direct spectrum of the iron capture gamma rays at the target position, and using the average of the two available values[7] of the relative intensity of the 7.64-MeV line, $I_{7.64}/I_{7.64}+I_{7.28}+I_{6.40}+I_{6.02}=(74.4\pm4.8)\%$. The intensity thus obtained was further reduced by a factor of two, based on the recent evidence that the 7.64-MeV line is a doublet of equal intensities.[8] The differential elastic scattering cross section averaged over the incident photon spectrum was

$$\langle(d\sigma_{\gamma\gamma}/d\Omega)_{135°}\rangle=(16.8\pm3.4)\text{ mb/sr.}$$

For the angular distribution $W(\theta)=C(1+\cos^2\theta)$ determined in Sec. III D1, the total elastic-scattering cross section is 11.2 times the 135° differential cross section. Thus,

$$\langle\sigma_{\gamma\gamma}\rangle=(190\pm40)\text{ mb.}$$

This value is smaller than the result by Giannini,[3] $\langle\sigma_{\gamma\gamma}\rangle=375$ mb by almost a factor of 2, but agrees well with the result obtained by Ben-David *et al.*[9] In Ref. 9, the resonant Ni isotope was not determined, and therefore the given effective cross section $\langle\sigma_{\gamma\gamma}\rangle=7$ mb is a value averaged over *all* Ni isotopes. Since the present experiment identifies the resonant isotope to be the 3.7% abundant Ni^{62}, the value $\langle\sigma_{\gamma\gamma}\rangle=7$ mb (average over all Ni isotopes) of Ref. 9 should be corrected to $\langle\sigma_{\gamma\gamma}\rangle(Ni^{62})=7\text{ mb}\times(100/3.7)=189$ mb. This corrected value is in excellent agreement with our value, (190±40) mb.

3. *Branching Ratios for the Decay of the 7.64-MeV Level*

The relative intensities given in Table I would give the branching ratios if the three photon groups have the same angular distributions. The experiment[10] $(p,p'\gamma\text{-}\gamma)$ on Ni^{62} established $J^\pi=0^+$ assignment to the 2.05-MeV level. In this case, the two photon groups A and C have the same angular distribution $W(\theta)\propto1+\cos^2\theta$, appropriate for the 0(1)1(1)0 transitions. The photon transition B leading to the 2^+ 1.17-MeV level is either dipole, quadrupole, or a mixture of both. In either case, because of its weak intensity, the correction for the angular distribution of group B would introduce little change in the values of the branching ratios as given in Table I. The 135° spectrum on which Table I is based was taken with a 5-in.-diam crystal at 20 cm from the target subtending an angle of about 40°. The angular correlation effects discussed above are expected to have been weakened to an appreciable extent in this geometry. The branching ratio for the ground-state transition $\Gamma_0/\Gamma=(69\pm8)\%$ agrees well with the value of Giannini,[2] (71±7)%. For the inelastic transitions, however, the present experiment shows 8% branching to the 1.17-MeV (2^+) level, and 23% branching to the 2.05 MeV (0^+) level, while in Ref. 3, only one inelastic transition to a 2.09 MeV was observed.

4. *The Radiation Width*

The measured average elastic-scattering cross section obtained in Sec. III D2 is in general a function of the total radiation width Γ, the partial radiation width for the ground-state transition Γ_0, and the energy difference δ between the peak energy of the incident beam and the resonant line in the scattering target.[1] In the pure Doppler approximation,[11] the measured values of the average elastic-scattering cross section $\langle\sigma_{\gamma\gamma}\rangle=190$ mb, and the branching ratio $\Gamma_0/\Gamma=0.69$, and the spin factor $g=(2J+1)/(2J_0+1)=3$, give the following relation between Γ_0 and δ:

$$(0.026\pm0.005)=\Gamma_0 e^{-(0.093\delta)^2}.$$

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[7] L. V. Groshev *et al.*, *Atlas of Gamma-Ray Spectra from Radiative Capture of Thermal Neutrons* (Pergamon Press, Inc., New York, 1959).

[8] G. T. Ewan and A. J. Tavendale, Nucl. Instr. Methods **26**, 182 (1964).

[9] G. Ben-David, B. Arad, J. Balderman, and Y. Schlesinger, Phys. Rev. **146**, 852 (1966); the original value $\langle\sigma_{\gamma\gamma}\rangle=5.25$ mb reported by the same group in Ref. 1 has been corrected to $\langle\sigma_{\gamma\gamma}\rangle=7$ mb.

[10] A. K. Sen Gupta and D. V. Van Patter, Phys. Rev. **131**, 318 (1963).

[11] F. R. Metzger, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Pergamon Press, Inc., New York, 1959), Vol. 7.

In order to determine Γ_0 and δ separately, a self-absorption experiment was attempted. However, the resonant absorption was too small to make statistically significant measurements. Using a nickel absorber (natural abundance) of thickness 1.25 cm, the upper limit of the self-absorption ratio was estimated to be about 2%. In the experiment of Ref. 3, the temperature variation of the scattering cross section was measured to determine $\delta=11$ eV. Combining this value with their elastic-scattering cross section $\langle\sigma_{\gamma\gamma}\rangle=375$ mb, Giannini *et al.* obtained $\Gamma_0=(150\pm20)$ mV. On the other hand, if $\delta=11$ eV is used together with our measured cross section, $\langle\sigma_{\gamma\gamma}\rangle=190$ mb, $\Gamma_0=74$ mV is obtained. This value of the radiation width is consistent with the fact that the value of $\langle\sigma_{\gamma\gamma}\rangle$ of this experiment is smaller than the value of Ref. 3 by a factor of 2, while the two values of the branching ratio, Γ_0/Γ are in good agreement. (See Secs. III D2 and III D3.) With $\delta=11$ eV and $\langle\sigma_{\gamma\gamma}\rangle=190$ mb of this experiment, one would expect a self-absorption ratio of less than 1%.

III. DISCUSSION

The results have shown the feasibility of studying the spectrum of the cascade photons coincident with inelastically scattered photons from a highly excited nuclear level. By studying the spectrum of the cascade photons, the isotope responsible for the resonant scattering can be identified even when the separated isotopes are not used as targets. Furthermore, the coincidence spectrum yields information about the structure of lower lying levels. In this work, the resonant scattering of the iron capture gamma radiation is attributed to the 7.64-MeV $J=1$ level in Ni^{62}. In addition to the dominant elastic scattering, two inelastically scattered photons populate the 1.17-MeV and 2.05-MeV levels. The 2.05-MeV level is known to be a member of the two phonon vibrational triplet. It is interesting to note that the other two members of the triplet, the 2^+ and 4^+ levels observed at 2.302 MeV and 2.336 MeV, respectively in other reactions,[6] are not observed in this experiment, even though the energies are well separated from the 2.05-MeV level. It is not difficult to understand why the 4^+ level was not seen. Since the 7.64-MeV resonant level has $J=1$, the transition to the 4^+ level requires either $E3$ or $M3$, while all three observed transitions are most likely dipole. Therefore, it would have been difficult to observe the transition to the 4^+ level. However, no such restriction exists for the transition to the 2^+ level. The absence of this transition seems to indicate that the wave functions of the 2.05-MeV and 2.302-MeV levels have different admixtures of the component which can couple to the 7.64-MeV $J=1$ level through the dipole operator.

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Activation Cross Sections of Germanium for 14.4-MeV Neutrons*

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$Ge^{69,75}$, $Ga^{72,73,74}$, and $Zn^{69m,71m}$ were produced by irradiating natural germanium with 14.4±0.3-MeV neutrons. Two mixtures of powders containing GeO_2+Al+Fe and GeO_2+Al+Cu also were irradiated. The activities were identified from gamma spectra taken with a Ge(Li) detector and the cross sections were measured using the improved technique described by Rao and Fink. The reactions for which cross sections were measured are: $Ge^{70}(n,2n)Ge^{69}$, 447±45 mb; $Ge^{76}(n,2n)Ge^{75}$, 1236±120 mb; $Ge^{72}(n,p)Ga^{72}$, 47.4±4.7 mb; $Ge^{73}(n,p)Ga^{73}$, 26.4±2.6 mb; $Ge^{74}(n,p)Ga^{74}$, 13.2±1.3 mb; $Ge^{72}(n,\alpha)Zn^{69m+g}$, 15.2±1.5 mb; and $Ge^{74}(n,\alpha)Zn^{71m+g}$, 13.3±1.3 mb. For all cases where isomers exist, the cross-section value is total for $m+g$. The $Ge^{76}(n,2n)Ge^{75}$ (82-min) cross section also was checked by beta counting, which is independent of decay-scheme assumptions. The results are compared with the systematics of $(n,2n)$, (n,p), and (n,α) cross sections at 14–15 MeV.

INTRODUCTION

NEUTRON-ACTIVATION cross sections of germanium have been measured at 14.4±0.3 MeV as part of a systematic study being carried out for comparision with cross-section systematics for 14–15-MeV neutron reactions. In view of the increasing use of Ge(Li) detectors for prompt-gamma studies in fast-neutron reactions, a knowledge of the cross sections for neutron reactions in germanium is also of interest. A comparison of the present results with earlier studies appears in the discussion section.

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EXPERIMENTAL

Monoenergetic neutrons are produced by the $H^3(d,n)He^4$ reaction in thick titanium-tritium targets on the Georgia Tech 200 kV accelerator. Cross sections were measured using an improved technique developed