error would be of some significance. Comparisons between neighboring "reduced" radial wave functions[5] suggest that it is not a large effect although perhaps it is one that warrants further study after more Hartree functions become available in this region. The greatest opportunity to account for any differences between theoretical and experimental results probably lies in consideration of the limitations of the Hartree approximation itself, particularly when applied to a problem of this type.

In conclusion it might be remarked that the possibility explored here of carrying out shakeoff calculations to the outermost occupied states suggests that it might be worthwhile to design experiments which would test detailed predictions embodied in this type of calculation. It might also be noted that analytical wave functions developed in this study have convenient properties for the calculation of various expectation values and it would appear that they might profitably be applied to other types of atomic or nuclear calculations.

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Absolute Intensities of Resonance Neutron Capture Gamma Rays from Cd, Te, and Sm†

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The absolute intensities of gamma rays having energies between 200 and 650 kev, emitted after resonant neutron capture in Cd^{113}, Te^{123}, Sm^{147}, Sm^{149}, and Sm^{152} have been measured. The instrumentation involved a combination of time-of-flight technique and multichannel pulse-height analysis using a NaI(Tl) scintillation counter. The even-even compound nuclei studied appear to emit intense low-energy gamma rays, while the even-odd nucleus Sm^{153} shows no correspondingly intense low-energy transitions.

I. INTRODUCTION

PREVIOUS work on the high-energy gamma radiation following thermal neutron capture has shown wide variations from element to element in both the number and intensities of resolved transitions as well as in the overall spectrum shape. These variations may be related to shell structure and odd-even characteristics of nuclei.[1,2]

Studies of the most prominent low-energy transitions with scintillation spectrometers have not been extensive enough to reveal any such systematics.[3–5] The present investigation obtains the absolute intensities of the most prominent low-energy transitions following resonant neutron capture in several nuclei with the aim of extending the data in this field.

II. METHOD

The geometry of the experiment is shown in Fig. 1. The Yale linear electron accelerator[6] was employed as a pulsed neutron source utilizing the (γ,n) reaction in the beryllium target. The neutrons were collimated by a 3-in. aperture through 8 feet of concrete. Additional lead shielding, shown in the figure, reduced the effect of the x-ray flash on the scintillation spectrometer. Selection of resonant-energy neutron-capture gamma rays was accomplished by the time gating of pulses

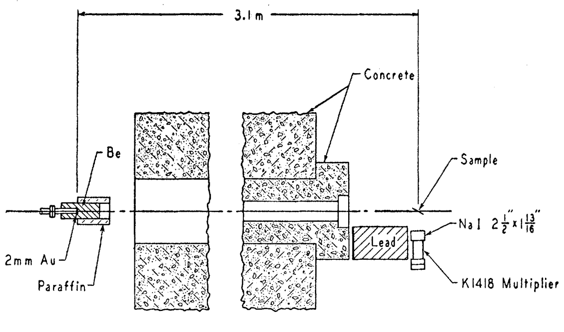

FIG. 1. Geometry of the experiment.

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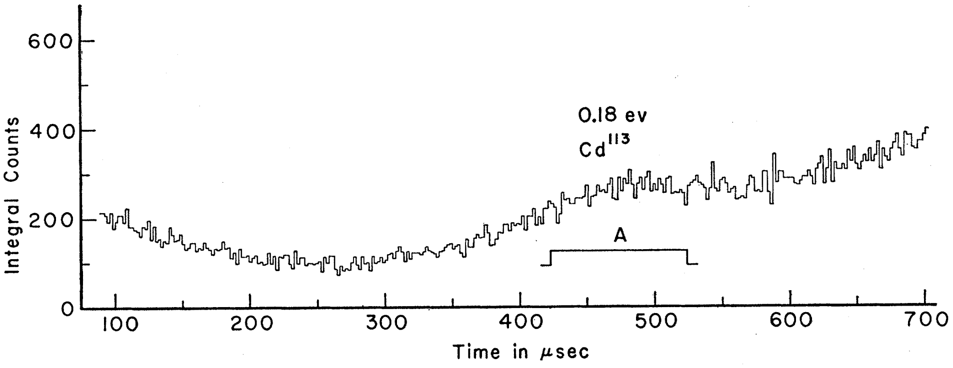

FIG. 2. Time-of-flight spectrum of cadmium using integral capture gamma-ray detection. Each horizontal segment represents a 2-μsec channel. The interval A indicates the position of the time gate during which gamma-ray counts were accepted for pulse-height analysis.

from the scintillation spectrometer. The position of the time gate was determined by using the 500-channel time analyzer[7] and pulse-height analysis was carried out using the associated 160 channel pulse-height analyzer.

The neutron production occurred during a 1-μsec interval and the channel width was 2 μsec. These conditions coupled with the comparatively short 3.1-m flight path and the 8-in. length of the paraffin moderator imply relatively poor time-of-flight resolution. However, in the present experiment, it is only necessary to ensure that the neutron resonances are sufficiently separated in time so that the capture gamma rays observed are specific to a single resonance. For the resonances encountered here, this condition was clearly established.

The detector employed was a $2\frac{1}{2}$ in.$\times 1\frac{13}{16}$ in. NaI(Tl) crystal coupled to a K-1418 photomultiplier. The gamma-ray energy calibration was afforded by radioactive sources of Cs^{137} and Hg^{203} in addition to the 478-kev gamma ray from the decay of the Li^7 excited state formed in the $B^{10}(n,\alpha)$ reaction. The system had a resolution of 10% measured at 661 kev. Absolute intensity measurements of the low-energy gamma-ray transitions were made by an extension of a method applied in earlier work[8] concerned with thermal neutron capture. The pulse-height spectrum associated with capture in a particular resonance is compared with that obtained when the sample under study is replaced with a thick B^{10} sample of the same area which absorbs all incident neutrons in the energy range of the resonance. The B^{10} pulse-height spectrum consists of a 478-kev gamma ray which is emitted in 93.5% of thermal neutron captures.[9] This absolute intensity is assumed to remain constant over the neutron energy range studied.

To obtain the number of gamma rays emitted per neutron capture, the area under the photopeak associated with the gamma ray of interest is compared with the area of the 478-kev photopeak of B^{10}, both pulse-height analyses being taken through the same time gate. The comparison involves a determination of the ratio of the number of neutrons captured in the resonance to the number captured in the B^{10} sample, and a correction of the measured photopeak areas for the energy variation of the photopeak efficiency of the NaI crystal. Normalization for the two runs is furnished by a BF_3 monitor.

The observed time-of-flight spectrum is used as a measure of the fraction of the neutrons captured within the time gate. The spectrum may be normalized to the incident flux using known resonance parameters and knowledge of the resolution function. Alternatively, a transmission experiment allows direct measurement since the areas in the transmission "dips" represent the fractional neutron capture if it can be assumed that all neutrons removed from the beam are captured. For the very thick samples used, this assumption leads to negligible error.

The variation of photopeak efficiency with energy for the NaI(Tl) scintillation counter was determined from a calculation of the total efficiency and measurements of the photopeak fraction after the method described by Lazar *et al.*[10] It was necessary to include in the calculation results of supplementary measurements which accounted for the fact that the neutron capture gamma rays were emitted from sources of finite size. For gamma-ray energies between 280 kev and 1 Mev, the error in the determination of the ratio of photopeak efficiencies is estimated to be 10%. The absorption

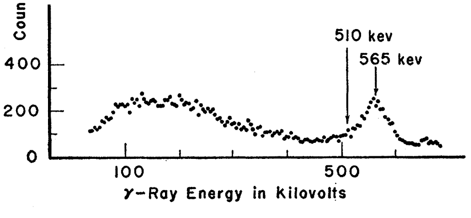

FIG. 3. Pulse-height spectrum of gamma-ray transitions in Cd^{114} following resonant neutron capture. Resonance energy is 0.18 ev. The arrow at 510 kev indicates the position expected for a photopeak associated with annihilation radiation.

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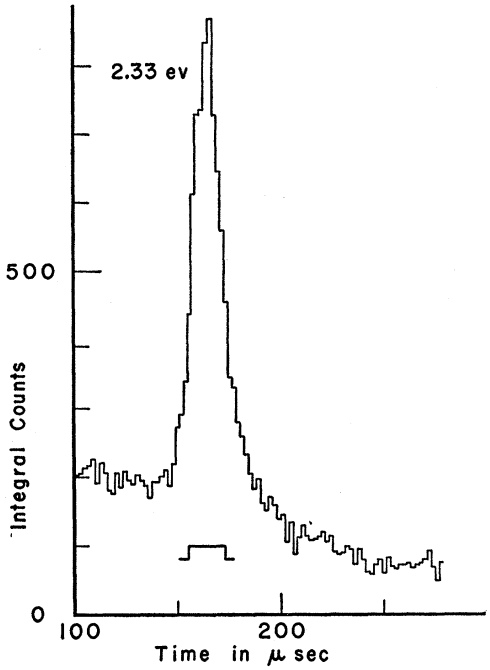

FIG. 4. Time-of-flight spectrum obtained from tellurium target. The position of the time gate is indicated.

of the gamma rays studied in the samples used was less than 10%.

The samples used were in the form of $2\frac{1}{2}$ in. squares of varying thicknesses. The Cd and Te samples were metallic foils while the Sm sample consisted of Sm_2O_3 powder uniformly packed between sheets of 3-mil aluminum foil. No measurable gamma radiation was emitted from the aluminum sample holder.

III. RESULTS

(1) Cadmium

The sample used consisted of a foil of thickness 0.249 g/cm^2. The resonance at 0.178 ev is due to Cd^{113} and dominates thermal capture. The measured time-of-flight spectrum is shown in Fig. 2 and the resulting pulse-height spectrum of gamma rays when the time gate was set at A is shown in Fig. 3.

FIG. 5. Pulse-height spectrum of gamma-ray transitions in Te^{124} following resonant neutron capture. Resonance energy is 2.33 ev.

The intense gamma ray at 565±10 kev is presumed to be the same transition observed in thermal capture measurements.[3,5,11–13]

It has also been observed[14,15] in the decay of In^{114}, and has been identified in Coulomb excitation experiments[16,17] as a 2^+ to 0^+ transition from the first excited state to the ground state.

A line at 510 kev appears to some degree in most of the spectra, and is probably annihilation radiation resulting from pair production in the nearby lead shielding or in the sample itself by high-energy neutron capture gamma rays. The energy resolution of the pulse-height equipment was adequate to allow sufficient separation of an annihilation peak from the 565-kev photopeak to ensure that the former would not materially affect the computed absolute intensity value of 52±9 photons per 100 neutrons captured. The absolute intensity obtained is taken to be in agreement with that obtained by the Russian group[12] who report an intensity of 42 photons per 100 neutrons captured with no error given.

Motz[13] has also measured the intensity of this gamma ray using thermal neutron capture and reports the higher value of 85±10 photons per 100 neutrons captured.

(2) Tellurium

The neutron resonance at 2.33 ev in Te is attributed to the isotope Te^{123}. The time-of-flight spectrum showing the time-gate position for the 2.33-ev resonance is shown in Fig. 4. The pulse-height spectrum taken through this gate is plotted in Fig. 5. The 625±10 kev gamma ray is attributed to resonance neutron capture. A transition of approximately this energy has been seen in thermal neutron capture,[3] in the decay[18,19] of Sb^{124}, and in inelastic alpha scattering.[20] All these experiments agree in the interpretation of the gamma ray as a transition between the 2^+ first excited state and the ground state of Te^{124}. The Te^{124} 625-kev gamma ray was emitted in 56±14% of the neutron captures.

(3) Samarium

The sample was in the form of Sm_2O_3 powder having an effective thickness of natural samarium of 0.427

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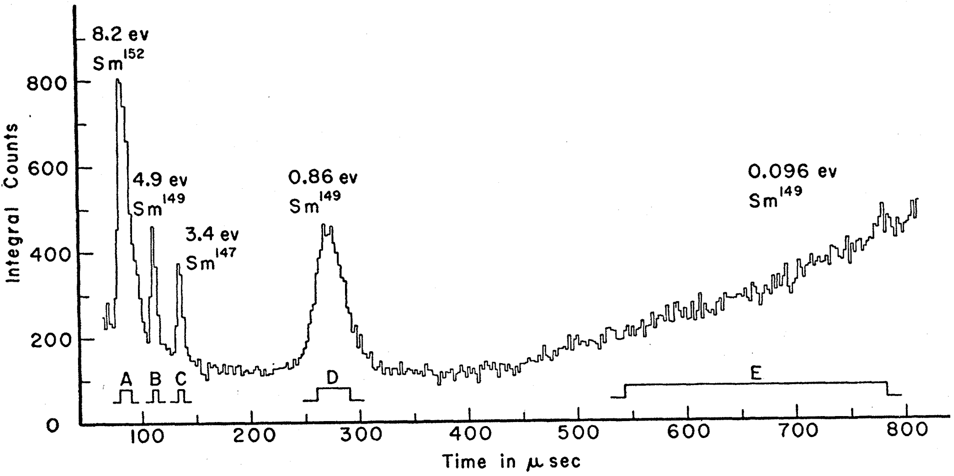

FIG. 6. Neutron time-of-flight spectrum obtained from samarium oxide target.

g/cm^2. Natural samarium has seven isotopes. The resonances at 0.096 ev, 0.86 ev, and 4.9 ev have been identified with capture by Sm^{149}. The resonances at 3.4 ev and 8.2 ev are due to Sm^{147} and Sm^{152}, respectively. Figure 6 shows the neutron time-of-flight spectrum obtained. Pulse-height spectra of transitions in Sm^{150} were taken with the time gate in positions *B*, *D*, and *E*. The results are shown in Figs. 7, 8, and 9. In each case transitions of 340 ± 10 kev and 440 ± 10 kev were present. The broad maximum at 150 kev is attributed to backscattering of these radiations. The 340-kev line is probably the gamma ray observed in several Coulomb excitation experiments[21–23] as well as in the decay[24] of Pm^{150}, and has been identified as a transition from a 2^+ first excited state to ground state. The two gamma rays together with many of higher energy, have been reported by Ad'yesavitch *et al.*[12] in thermal neutron capture, which is dominated by Sm^{149}. Internal conversion electrons from these gamma rays following capture of thermal neutrons have been observed.[11] The latter data suggest an *E*2 character for both gamma rays.

The detector time gate was set in position *C*, Fig. 6, to detect transitions in Sm^{148}. The pulse-height spectrum, given in Fig. 10, shows a prominent photopeak corresponding to a 565 ± 10 kev gamma ray. The 565-kev transition agrees in energy with that of a 2^+ to 0^+

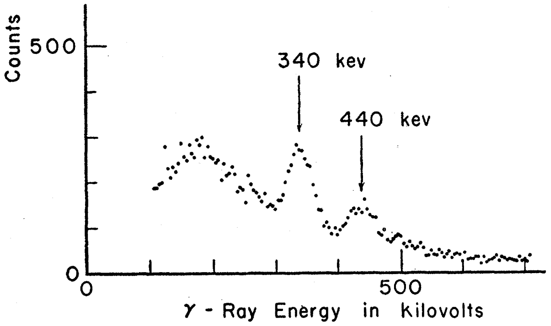

FIG. 7. Pulse-height spectrum of gamma-ray transitions following neutron capture in Sm^{149} at resonance energy 4.9 ev.

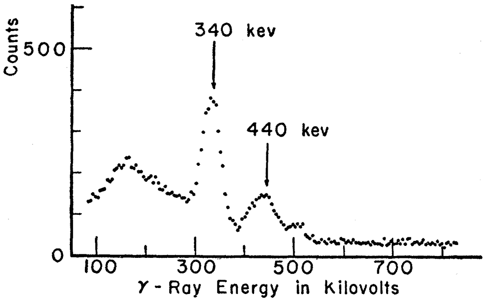

FIG. 8. Pulse-height spectrum of gamma-ray transitions following neutron capture in Sm^{149} at resonance energy 0.86 ev. The maximum at about 150-kev pulse height is attributed to backscattering of the 340- and 440-kev gamma rays by the surroundings.

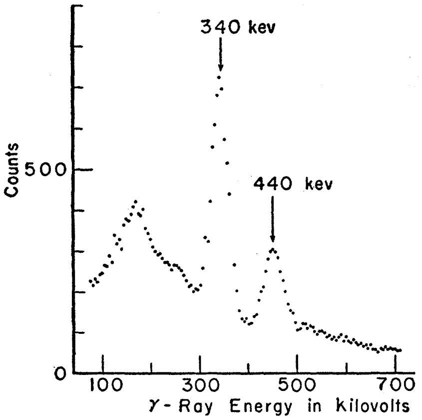

FIG. 9. Pulse-height spectrum of gamma-ray transitions following neutron capture in Sm^{149} at resonance energy 0.096 ev. The maximum at about 150-kev pulse height is attributed to backscattering of the 340- and 440-kev gamma rays by the surroundings.

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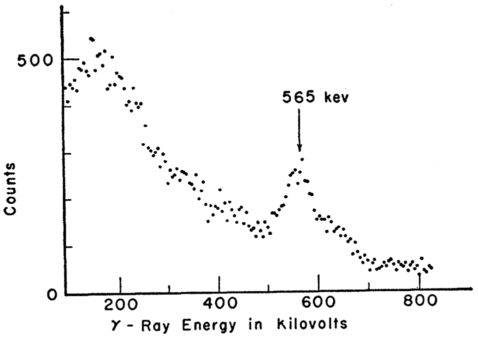

FIG. 10. Pulse-height spectrum of gamma-ray transitions following resonant neutron capture in Sm^{147}. Resonance energy is 3.4 ev.

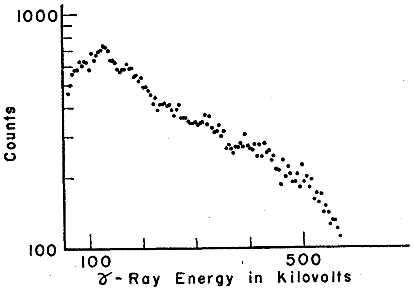

FIG. 11. Pulse-height spectrum of gamma-ray transitions following resonant neutron capture in Sm^{152} at 8.2 ev.

TABLE I.

Final nucleus	Resonance energy (ev)	γ-ray energy (kev)	γ's per 100 neutrons captured
Z even, N even			
${}_{48}$Cd^{114}	0.18	565	52±9
${}_{52}$Te^{124}	2.33	625	56±14
${}_{62}$Sm^{148}	3.4	565	62±25
${}_{62}$Sm^{150}	0.096	340 440	77±8 42±5
${}_{62}$Sm^{150}	0.86	340 440	75±10 41±9
${}_{62}$Sm^{150}	4.9	340 440	70±25 40±15
Z even, N odd			
${}_{62}$Sm^{153}	8.2	no distinct lines observed, 200 kev $<E$ <600 kev	<10 for $E_\gamma = 600$ kev

first excited state to ground-state gamma ray emitted after Coulomb excitation.[21–23] The shape of the high-energy side of this photopeak suggests the presence of unresolved gamma rays of lower intensity.

Results of the intensity measurements of the individual Sm capture gamma rays are given in Table I. Ad'yasevitch *et al.*[12] list the intensities of the 340- and 440-kev gamma rays observed in thermal capture as 38 and 33 photons per 100 neutrons captured, respectively. The present measurement is in good agreement for the 440-kev gamma ray. For the 340-kev line the present result is higher by a factor of two. Larger errors are assigned to the intensities measured at the 4.9-ev resonance because of difficulty in ascertaining the contribution of the 8.2-ev resonance.

Figure 11 shows the pulse-height spectrum obtained with the time gate in position A, Fig. 6. No clearly resolved gamma rays from Sm^{153} with energies between 200 kev and 600 kev were observed. The maximum at about 130 kev is too broad to be interpreted as a single photopeak. It may correspond to several unresolved gamma rays. Experimental conditions were such that at 200 kev, transitions of intensities greater than 5 photons per 100 neutrons captured would have been observed, while at 600 kev the corresponding intensity would have been 10 photons per 100 neutrons captured.

IV. DISCUSSION

Upon examination of the results listed in Table I, the following statements can be made. For four even-even final nuclei, gamma rays of high intensity (~50 per 100 neutron captures) are present. For the even-odd nucleus, Sm^{153}, no resolved transitions were observed in the region 200 to 600 kev.

V. ACKNOWLEDGMENTS

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