# Internal Conversion of Neutron Capture $\gamma$-Rays

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Prompt internal conversion electron lines resulting from neutron capture in $_{48}Cd^{113}$, $_{62}Sm^{149}$, $_{64}Gd^{odd}$, $_{66}Dy^{164}$, and $_{80}Hg^{199}$ have been observed. Their energies were measured in a 180° focusing, constant magnetic field, film recording $\beta$-ray spectrograph. The spectrograph was placed in a neutron beam from the Argonne heavy water reactor in such a way that the source underwent bombardment during recording. In some cases $K$, $L$, and $M$ lines were observed. Each element except mercury exhibited two strongly converting capture $\gamma$-ray states from a single isotope.

## INTRODUCTION

SLOW neutron capture usually results in the emission of cascade $\gamma$-rays of average energy $\sim$2 Mev and lifetime per state $\sim 10^{-14}$ sec. In addition, however, a longer-lived ($\sim 10^{-10}$ sec) low energy state with a high internal conversion coefficient may be formed close to ground. The phenomenon of internal conversion of neutron capture $\gamma$-rays was first observed in cadmium by Hoffman and Bacher[1] and in gadolinium by Amaldi and Rasetti.[2] The latter found, for example, that in the case of thermal neutron absorption in gadolinium a prompt soft electron radiation having a half-value thickness of 2.3 mg Al/cm$^2$ was emitted. Since (1) this observation was only possible with the isotopes having the strongest absorption (odd $A$) and (2) these isotopes on capture simply form the next heavier isotopes, the radiation clearly must have been due to one or more very short-lived isomeric states in the cascade.

Goldhaber[3] and co-workers attempted to measure the lifetime of the low energy capture $\gamma$-rays from gadolinium using Geiger counters and a trigger sweep scope. They were able to show that the lifetime was $<10^{-7}$ sec.

Goldhaber and Muehlhause[4] made a limited survey of the strongly absorbing nuclei (Cd, Sm, Eu, Gd, Dy, Hg) in an attempt to establish the generality of the phenomenon of internal conversion accompanying neutron absorption. Thin films of the absorbing materials ($\sim$1 mg/cm$^2$) were placed next to a photographic plate and bombarded in the thermal column of the Argonne heavy water reactor. A dense blackening of the plates resulted which could be removed by interposing thin absorbers of either Be, Al, or Pb between the capturing material and the photographic plate. Internal conversion was indicated for all the materials examined, the electron energies ranging from $\sim$50 to $\sim$500 kev.

By an entirely different technique Wexler and Davies,[5] and Davies and Yosim[6] showed that internal conversion is associated with neutron capture in Br, In, and Au. In the experiments on indium, positive $In^{116}$ ions were found to be "emitted" from an indium surface during neutron bombardment. Since neutralization would occur if the positive ions were formed only in the surface, the conclusion of Davies and Yosim was that positive ions were formed as a result of internal conversion $\sim 10^3$A away from the surface after the $In^{116}$ nuclei recoiled from the emission of energetic capture $\gamma$-rays. This was an entirely logical observation since one would expect the short-lived isomeric state(s) responsible for conversion to be near the ground state, i.e., to be not competing with the more rapidly decaying cascade $\gamma$-ray states. This conclusion has been verified for dysprosium in the present work.

Recently the authors decided to make accurate energy measurements of a few internal conversion lines emitted promptly on neutron capture. $Cd^{113}$, $Sm^{149}$, $Gd^{odd}$, $Dy^{164}$, and $Hg^{199}$ were measured by the techniques of $\beta$-ray spectroscopy.

## APPARATUS

Neutrons from the Argonne heavy water reactor were collimated by boron to make a beam of rectangular cross section $\sim$3 mm wide and $\sim$20 mm high. This passed along the axis of an evacuated tube into a constant magnetic field $\beta$-ray spectrograph. There the beam bombarded a thin film of absorbing material ($\sim$1–3

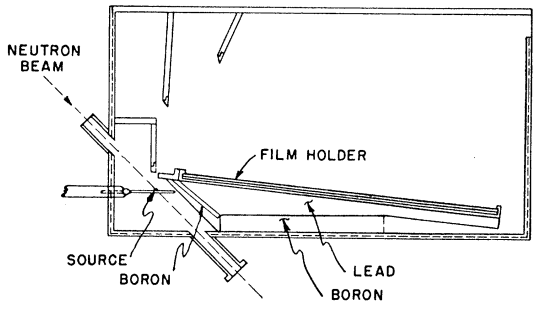


FIG. 1. Spectrograph camera.

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[3] Sala, Axel, and Goldhaber, Phys. Rev. **74**, 1249 (1948).
[4] C. O. Muehlhause, Phys. Rev. **83**, 235 (1951); C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **83**, 235 (1951).
[5] S. Wexler and T. H. Davies, Brookhaven National Laboratory Report C-7 (AECU-50) (1948).
[6] S. Yosim and T. H. Davies, J. Phys. and Colloid Chem. (to be published).

TABLE I. Line energies, work functions, and $\gamma$-ray energies.

| Compound nucleus | $E\beta$ | $K$ | $L_2$ | $L_3$ | $M$ | $E\gamma$ |
|---|---|---|---|---|---|---|
| $_{48}Cd^{114}$ | 70.1 | 26.8 | | | | 96.9 |
| | 92.8 | | | 3.5 | | 96.3 |
| | 535.1 | 26.8 | | | | 561.9 |
| $_{62}Sm^{150}$ | 290.3 | 46.9 | | | | 337.2 |
| | 329.5 | | | 6.7 | | 336.2 |
| | 393.5 | 46.9 | | | | 440.4 |
| | 433.3 | | | 6.7 | | 440.0 |
| $_{64}Gd^{even}$ | 28.9 | 50.1 | | | | 79.0 |
| | 38.4 | 50.1 | | | | 88.5 |
| | 70.7 | | 8.0 | | | 78.7 |
| | 71.3 | | | 7.3 | | 78.6 |
| | 77.0 | | | | 1.2 | 78.2 |
| | 80.4 | | | 7.3 | | 87.7 |
| | 130.4 | 50.1 | | | | 180.5 |
| $_{66}Dy^{165}$ | 73.9 | | 8.6 | | | 82.5 |
| | 74.6 | | | 7.8 | | 82.4 |
| | ~79 | | | | ~2 | ~81 |
| | 96.9 | | 9.1 $L_1$? | | | 106.0 |
| | 135.0 | 53.8 | | | | 188.8 |
| $_{80}Hg^{200}$ | ~270 | | ~14 | | | ~284 |
| | ~282 | | | | ~2 | ~284 |

percent neutron absorption) located at the normal source position of the spectrograph (see Fig. 1). The transmitted beam left the instrument through another evacuated tube and was eventually absorbed in a boron block. Internal conversion electrons resulting from neutron capture in the source moved in a 180° arc to be focused as lines on no-screen x-ray film, $K$, $L$, and $M$ lines were readily observed. Several field strengths were employed ranging from 100 to 250 gauss.

The sources studied were: enriched $Cd^{113}$ metal plated on thin aluminum (0.235 mg/cm$^2$), enriched $Sm_2{}^{149}O_3$ made to adhere to aluminum, Gd metal evaporated on aluminum, $Dy_2O_3$ made to adhere to aluminum, and enriched $Hg^{199}$ metal amalgamated with ~1 mil gold. The metal films were $\sim 5\times 10^3$A thick. These resulted in ~1–2 percent electron absorption.

## RESULTS

Table I lists line energies, work functions, and $\gamma$-ray energies for the isotopes measured. The relevant $L$ work function is not certain, the one given being that which agrees best with the total energy as inferred by other lines. In the case of gadolinium, however, the rough $K/L$ ratio observed is in agreement with the observation of $L_2$ and $L_3$ conversion lines for an $E2$ transition.[7] It will be noted that in every element except mercury it is certain that two states are to be associated with a single isotope. To make this statement true for dysprosium one must include the 1.2-min metastable state.[8] Only in the case of dysprosium was the cross-over observed.

TABLE II. Predicted and observed $K/L$ ratios.

| Compound nucleus | $E\gamma$ | $Z^2/E$ | $K/L$ ratio $M1$ Predicted | $K/L$ ratio $E2$ Predicted | $K/L$ ratio Observed | $L/M$ ratio Observed |
|---|---|---|---|---|---|---|
| $_{62}Sm^{150}$ | 336.7 | 11.4 | 7.9 | 4.2 | 4.4 | |
| | 440.2 | 8.73 | 8.0 | 5.4 | ~3 | |
| $_{64}Gd^{even}$ | 78.6 | 52.1 | 7.6 | 0.30 | ~0.3 | 2.5 |
| | 88.1 | 46.5 | 7.7 | 0.35 | | |

Table II relists a few of the state energies along with predicted[9] and observed $K/L$ ratios. It should be pointed out, however, that the observed ratios are only approximate. In the cases of samarium and gadolinium enough supplementary experiments on film density *vs* intensity were carried out to support the assignment of $E2$ (electric quadrupole).

## CONCLUSION

The technique employed is limited to materials having very large thermal absorption cross sections

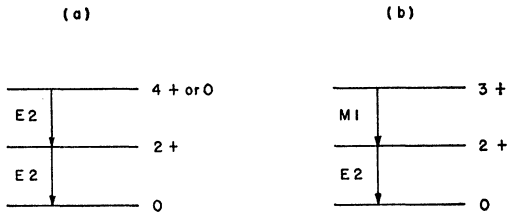


FIG. 2. Possible level schemes for the first excited states of even-even nuclei.

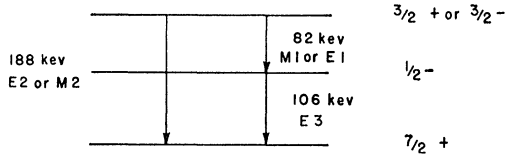


FIG. 3. Possible level scheme for the first excited states of the even-odd nucleus $_{66}Dy^{165}$.

($\gtrsim$500 b). Furthermore, the present work does not directly demonstrate that the lifetimes are less than minutes. Indirectly, however, the approximate $K/L$ ratios and the energies favor magnetic dipole or electric quadrupole transitions which would range in lifetime from $10^{-12}$–$10^{-9}$ sec.[9–11]

The "prompt" charged radiation observed has been shown to be monoenergetic electrons (i.e., lines) and to require work functions characteristic of the absorbing element. Two possible level schemes for the compound even-even nuclei are given in Fig. 2: (a) most probable, (b) possible. Figure 3 gives the level scheme near ground of the even-odd nucleus, $_{66}Dy^{165}$.

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