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J. M. Hollander

May 1965

THE USE OF SEMICONDUCTOR DETECTORS FOR
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The recent availability of semiconductor detectors sensitive to both electrons and photons with moderate efficiency and energy resolution has provided for nuclear spectroscopy of tool of remarkable power and versatility. This advance in instrumentation may be compared, in its eventual impact, to the development of other important research tools as the scintillation detector, the double-focusing spectrometer, and the multichannel analyzer.

Already the new lithium-drifted germanium gamma-ray detector is finding use in many areas of nuclear structure physics, for example, radioactive decay scheme studies, in-beam gamma-ray spectroscopy, Coulomb excitation studies, Mössbauer absorption studies, fission studies, and others.

To place the merits of these detectors in perspective with respect to their application to the determination of internal conversion coefficients, it is useful to review some of the techniques presently employed for this problem. In Table I several methods are listed, together with their chief advantages and drawbacks. It is probably reasonably accurate to state that the previously available methods required either 1) a very simple decay scheme or 2) a very strong source. When the decay scheme is simple, measurements could be made with use of the efficient scintillation detectors in spite of their low resolving power for gamma rays. Or, alternatively, for beta emitters with only

one or two gamma rays, it was possible to determine the relative integrals of the beta spectrum and conversion line with good accuracy. When a very strong source was available, advantage could be taken of precise but indirect methods of low efficiency, such as the "internal-external conversion" technique, that provide the possibility of very accurate determinations.

Thus, much effort applied in these special cases has resulted in a good knowledge of a small number of conversion coefficients, but a technique that is widely applicable to nuclear spectroscopic investigations has been lacking. The use of Si and Ge detectors now provides such a technique, and makes it possible to measure internal-conversion coefficients with a facility not previously attainable.

Several variations on a basic technique are possible, all of which make use of lithium-drifted germanium detectors for recording the gamma-ray spectra. As an illustration of the general features of these detectors, we show here a photograph and drawing (Figs. 1 and 2) of a standard Ge(Li) assembly used at the Lawrence Radiation Laboratory in Berkeley. The resolving power of this system is illustrated by the spectrum of Co^{57} shown in Fig. 3, in which a line width of 2.3 keV is obtained.

The most general application of the semiconductor detectors for conversion-coefficient determinations involves the use of lithium-drifted silicon and germanium crystals for the recording of the electron and gamma-ray spectra, respectively. Because of the multichannel nature of both counters the full electron and gamma-ray spectra can be recorded simultaneously and no decay corrections on individual peaks are necessary; therefore, the method can be used for the study of short-lived activities.

In Fig. 4 a picture of the first design of such a "conversion-coefficient spectrometer" is shown, and in Fig. 5 a scale drawing is reproduced to show the various component parts. This device, which has been fully described elsewhere,¹ is essentially a small vacuum chamber in which silicon and germanium detectors are mounted in 180° fixed geometry, and into which active sources can be introduced through a conventional spectrometer-type air-lock. In this design, both the Si and Ge crystals were located within a common vacuum system. However, because the surface layer of uncovered germanium detectors can so easily be damaged by the condensation of moisture, etc. caused by the inadvertent admission of air into the system (which occasionally happens when inexperienced operators use the apparatus), the design was subsequently changed so that the germanium crystal was enclosed in a separate conventional vacuum chamber, as shown in Figs. 6 and 7. In this design, the germanium detector assembly fits reproducibly into a "well", machined into the vacuum chamber of the Si detector system.

An example of the electron and photon spectra taken with the conversion-coefficient apparatus is shown in Fig. 8. Here, the K, L, and M electron lines of the 279-keV transition in Hg^{203} decay are resolved, with line width 4.2 keV. The 279-keV photon line width is 4.6 keV.

The internal-conversion coefficient may be expressed as:

$$\epsilon = \frac{A_e}{\eta_e(E_e)} \cdot \frac{\eta_\gamma(E_\gamma)}{A_\gamma} \quad (1)$$

where:

A_e is the area under the conversion electron peak.

A_γ is the area under the corresponding gamma-ray peak.

$\eta_e(E_e)$ is the detection efficiency of the Si(Li) system for electrons in the full-energy peak (including solid-angle factor).

$\eta_\gamma(E_\gamma)$ is the detection efficiency of the Ge(Li) system for gamma-rays in the full-energy peak (including solid-angle factor).

Calibration of the instrument was done in the following way: First, a determination was made of the relative photopeak efficiency, $\eta_\gamma(E_\gamma)$, of the Ge(Li) detector as a function of gamma-ray energy E_γ , by use of a number of isotopes with well-measured photon-relative intensities. The experimental gamma efficiency function is shown in Fig. 9. A suitably normalized electron efficiency function $\eta_e(E_e)$ was then determined, with use of Eq. (1), by measuring the areas under the electron and gamma-ray lines from transitions with known conversion coefficients. All solid-angle factors are constant and need not be considered explicitly. The normalized electron efficiency function so obtained is shown in Fig. 10.

This method is being applied in studies of neutron-deficient cyclotron produced activities in the Pt, Au, Hg region. Spectra recorded of 40-hour $\text{Hg}^{195\text{m}}$ are shown in Figs. 11, 12, and 13. From these spectra, recorded over a period of only 2 days, as many as 18 conversion coefficients can be determined.

A case of particular interest was the 191-keV transition in the decay of Pt^{197} , for which there were a number of widely deviating K-conversion coefficient measurements in the literature, ranging from 0.65 to 2.5. Portions of the Pt^{197} and $\text{Pt}^{197\text{m}}$ electron and gamma-ray spectrum, taken with the conversion-coefficient spectrometer, are shown in Fig. 14. From this spectrum the value $\epsilon_k = 0.69 \pm 0.07$ was obtained.

The ultimate accuracy obtainable with this technique depends on several factors. Among these are:

(1) Care and extent of calibration of the efficiencies of the gamma and electron detectors. With use of a number of isotopes that have accurately-known gamma and electron relative intensities, the relative efficiency curves can in principle be well established, at least up to ~ 1.5 MeV. At least three absolute conversion coefficients are well known (Hg^{203} , Au^{198} , and Cs^{137}) thus the normalization of the electron and gamma efficiency scales can be effected to an accuracy of a few percent. It should thus be possible to achieve at least a $\pm 10\%$ overall calibration accuracy.

(2) Knowledge of the spectral response of the detectors. With more extensive studies of the response functions and peak shapes of individual detectors, the accuracy of peak area measurement will be much improved over the present situation. It will be possible eventually to achieve the sophistication that presently characterizes the analysis of scintillation spectra, although the methods will remain largely empirical rather than analytic, because of variability from detector to detector.

(3) As in all measurements, the complexity of the individual spectrum must be considered, as well as the peak-to-background ratio. The presence of a beta spectrum constitutes an unavoidable source of background in a singles spectrum, although in some situations this may be improved by coincidence measurements. Background due to the registration of Compton scattered gamma rays in both Si and Ge detectors is severe in present-day detectors, but this problem can be lessened by better design of the detector assemblies and also by the application of Compton-rejection anti-coincidence shields. Then also, the development of Ge detectors of larger volume will markedly improve the full-energy peak/Compton ratio.

At the present time, in cases that are not particularly unfavorable, conversion coefficients can probably be measured by the Si-Ge technique with an accuracy of ± 15 -20%. While not sufficiently accurate in its present development for making sensitive tests of conversion coefficient theory, this technique will facilitate the measurement of large numbers of conversion coefficients, from which it will be possible to assign many nuclear spins and parities in level-scheme studies.

In situations where the experimental problem demands higher accuracy of the conversion-coefficient determinations than can be achieved by the technique described above, it is possible (if time is not a critical factor) to combine the advantages of high-resolution electron spectrometers with those of lithium-drifted germanium detectors. The following are illustrative examples of how this has been done: 1) Internal calibration - the mixed-source technique. Brown and Ewan² have measured internal-conversion coefficients in the decay of Cs^{134} by studying a single mixed source containing both Cs^{134} and the calibration standard Cs^{137} . The relative gamma-ray intensities were measured with a Ge(Li) spectrometer and the relative K-conversion lines with a $\pi\sqrt{2}$ beta spectrometer. Portions of the spectrum are reproduced in Fig. 15, showing the photons and K-conversion lines of the 605 and 796 keV transitions of Cs^{134} and the 662 keV transition of the internal standard, Cs^{137} . From the measured intensity ratios, the absolute conversion coefficients are deduced as follows:

$$\alpha_K(602) = \frac{I_{K-602}}{I_{K-662}} \cdot \frac{I_{\gamma-662}}{I_{\gamma-602}} \cdot \alpha_K(662)$$

The value so obtained for the 605 keV E2 transition, $(4.85 \pm 0.2) \times 10^{-3}$, is in close agreement with other recently measured values for this transition.

2) External calibration - Yamazaki and Hollander³ have measured the K- and L-conversion coefficients of the 80 keV transition of Ho^{166} by use of the 279-keV transition of Hg^{203} as a conversion-coefficient standard. The mixed-source technique could not be used in this case because of interference in the gamma-ray spectrum between the Ho^{166} 80-keV photon and the Hg^{203} K x-rays, which lie in the same energy region. Separate sources of Ho^{166} and Hg^{203} were therefore used for the comparative measurements of the K-conversion lines in a $\pi\sqrt{2}$ spectrometer, subsequent to which the same sources were used for measurements of the gamma spectrum. In both measurements, the source geometry was carefully fixed and reproducible. The relevant portions of the Ge(Li) gamma-ray spectra are shown in Fig. 16.

A requirement for the successful use of Ge(Li) detectors for conversion-coefficient determinations is that the shape of the full-energy peak efficiency curve be very well known. In this measurement on Ho^{166} the efficiency of the detector at ~80 keV relative to that at 279 keV was determined from the area of the Hg K-x-ray peak relative to the 279 keV area, with knowledge of the fluorescence yield and 279 keV conversion coefficient. It was found, in fact, that the detection efficiency is slightly lower at 80 keV, for the particular detector used, than at 279 keV. The decrease in efficiency at very low energies is presumably due to a "window", or dead layer, at the surface of the lithium-drifted germanium crystal.

An improvement on this technique is illustrated schematically in Fig. 17, which shows a Ge(Li) detector mounted as a fixed part of the source chamber of an iron-free $\pi\sqrt{2}$ spectrometer. With this system, gamma spectra can be recorded

simultaneously with the scanning of selected regions of the internal-conversion spectrum so that decay corrections are minimized. In addition, the geometry of such a system can be fixed and reproducible so that, in principle, a single calibration is sufficient for a series of precision measurements. (This should, of course, be checked periodically, but the calibration activity need not be run at the same time as the source being studied.) 3) Internal calibration with a known transition - Hamilton and vanNooijen⁴ have measured internal-conversion coefficients of a number of transitions in the decay of Y^{86} . Relative intensity measurements were made of the gamma rays with a Ge(Li) spectrometer and of the electrons with a $\pi\sqrt{2}$ spectrometer. Normalization of the intensity scales was made with respect to the 1078-keV E2 transition in the same decay whose conversion coefficient had previously been determined by the internal-external technique. The accuracy obtained in these measurements is believed to be 8-10%.

It is apparent that in the field of internal-conversion coefficient measurement, we are at the beginning of a new era, ushered in by the semiconductor detector. The measurement of an internal-conversion coefficient is no longer an experimental "tour de force", but has become almost a routine laboratory measurement. The result of this new simplicity will be a tremendous proliferation in the number of conversion-coefficient values that will be known. Still, for very accurate measurements of the various conversion coefficients (absolute, K/L ratios, L and M subshell ratios, etc.) the elegant and often indirect methods will continue to be used. The main impact of the semiconductor detector will be to provide large quantities of reliable data--from which a true systematics of internal-conversion will eventually emerge.

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2. R. A. Brown and G. T. Ewan, private communication.
3. T. Yamazaki and J. M. Hollander, unpublished data.
4. J. H. Hamilton and R. van Nooijen, private communication.

FIGURE CAPTIONS

- Fig. 1. Photograph of a standard Ge(Li) gamma-ray detector assembly used at Lawrence Radiation Laboratory, Berkeley.
- Fig. 2. Cross-sectional view of Ge(Li) assembly of Fig. 1.
- Fig. 3. Gamma-ray spectrum of Co^{57} .
- Fig. 4. Original version of conversion-coefficient spectrometer.
- Fig. 5. Cross-sectional view of spectrometer of Fig. 4.
- Fig. 6. Photograph of revised conversion-coefficient spectrometer.
- Fig. 7. Drawing of revised conversion-coefficient spectrometer.
- Fig. 8. Electron and gamma spectra of the 279-keV transition in Hg^{203} recorded with conversion-coefficient spectrometer.
- Fig. 9. Experimental photopeak efficiency function for Ge(Li) detector of the conversion-coefficient spectrometer.
- Fig. 10. Normalized electron efficiency function for Si(Li) detector of the conversion-coefficient spectrometer.
- Fig. 11. Electron and gamma spectra of Hg^{195} and $\text{Hg}^{195\text{m}}$.
- Fig. 12. Electron and gamma spectra of Hg^{195} and $\text{Hg}^{195\text{m}}$.
- Fig. 13. Electron and gamma spectra of Hg^{195} and $\text{Hg}^{195\text{m}}$.
- Fig. 14. Partial electron and gamma spectra of Pt^{197} and $\text{Pt}^{197\text{m}}$.
- Fig. 15. Portion of electron and gamma spectra of Cs^{134} and Cs^{137} , from Brown and Ewan.²
- Fig. 16. Portion of gamma spectra of Ho^{166} and Hg^{203} , from Yamazaki and Hollander.³
- Fig. 17. Representation of proposed installation of Ge(Li) detector near source position in an iron-free electron spectrometer.

ZN-4854

Fig. 1.

MUB-5549

Fig. 2.

MUB-3715

Fig. 3.

ZN-4437

Fig. 4.

MUB-3714

Fig. 5.

(a)

(b)

ZN-4764

Fig. 6.

MUS-6029

Fig. 7.

MUB-3717

Fig. 8.

MUB-5335

Fig. 9.

MUB-6023

Fig. 10.

MUB-5603

Fig. 11.

MUB-6026

Fig. 12.

MUB-6027

Fig. 13.

MUB-7535

Fig. 14.

A.E.C.L. Ref. # A-3078-G

MUB-7278

Fig. 15.

MUB-6028

Fig. 16.

MUB-6024

Fig. 17.

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