test, which compares χ_m^2 with χ_{m+1}^2 to find the best value of M.[12]

(5) For the best value of M, one uses the least-square curve (B5) to compute

$$E(A/B)=gG=a_0.$$

We have described the extrapolation procedure for cross sections for which (B1) is valid, however the procedure may be applied to any cross section in which there is an isolated pole in $(\cos\theta)$, and for which (B5) is a valid approximation. In our work, we have assumed this to be true.

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Lifetimes of the Low-Energy $M1$ Transitions in La^{137} and Kr^{83}

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Using conventional time to pulse-height techniques, the lifetimes of the low-lying levels in La^{137} and Kr^{83} have been measured, despite the low γ-ray energies (10 and 9.3 keV) and the large internal conversion coefficients (130 and 11). The results of 89 ± 4 and 147 ± 4 nsec, respectively, correspond to retardation factors of 370 and 45 over the single-particle model predictions for those $M1$ transitions.

THE measurement of the lifetime of a nuclear state is useful either as a method of clarifying a tangled decay scheme or, if the decay scheme is clear, as a means of evaluating nuclear matrix elements. In the two cases considered here, the pertinent parts of the decay scheme have been established by earlier measurements.[1,2] Therefore, the lifetimes, when combined with values for the internal conversion coefficients, can be used to find the retardation factors compared to the single-particle predictions for these decays. These are essentially equal to the nuclear matrix element of the known operator (magnetic dipole) between the ground and first excited states of these nuclei. Such information is of definite value for the testing of nuclear models. The two found here are to be added to only ten previously measured $M1$ transitions for $A>20$.

A second reason for being interested in the lifetimes of low-lying states is that long lifetimes and low energy offer the possibility of using the nucleus for recoil-free nuclear resonance experiments. The recent history of the exploitation of Fe^{57} by means of the Mössbauer Effect[3] is clear testimony of the possible value of such nuclei.

EXPERIMENTAL TECHNIQUES

The main experimental problems were created by the large internal conversion coefficients and the low energy of the transitions to be explored. In the absence of a low-energy magnetic spectrometer, it was decided to attempt the measurement by a straightforward extension to lower energies of the time-to-pulse-height delayed coincidence techniques now in common use,[4] using scintillation counters as detectors. A modification of a circuit of Simms[5] was constructed for the time-to-pulse-height conversion, and 6810-A phototubes feeding into a limiter and shorted delay line were used to establish the standard pulses. A slow channel for pulse-height selection was set up for each detector—only if each pulse fell within selected values was the multichannel analyzer allowed to measure the output of the fast time-to-height converter.

Examination of the decay scheme shown in Fig. 1 shows that the distribution of time delays between the detection of a 29-keV K x ray of La^{137} and the detection of the 10-keV γ ray contains the desired information. In the case of Kr^{83}, as seen in Fig. 2, the energies are even lower; here the K x ray is only 12.6 keV and the γ ray 9.3 keV. The experimental question was whether suitable energy and time resolution was available.

Owing largely to the excellent photocathode response and low dark current emission of the 6810 A's, little difficulty was found in either regard. Using an anthracene crystal mounted directly on the phototube as a scintillator, it was found that one photoelectron was emitted for every 1000 eV dissipated in the phosphor. In addition, it was found that under dark conditions, there were less than thirty pulses per second larger than two photoelectrons. This number results from the "pile-up" of single photoelectrons emitted, mainly thermionically, at the photocathode. In the presence of a radioactive source, the number of single photoelectrons goes up, owing mainly to light emission from

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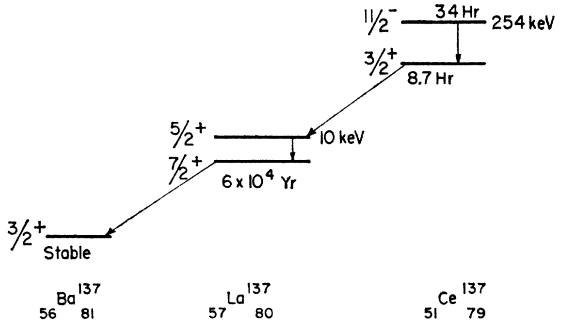

FIG. 1. Simplified energy level diagram for $A=137$. Redrawn from Nuclear Data Sheet NRC 61-2-130 (National Research Council, Washington, D. C.). We report the half-life of the 10-keV level of La^{137} as 89 ± 4 nsec.

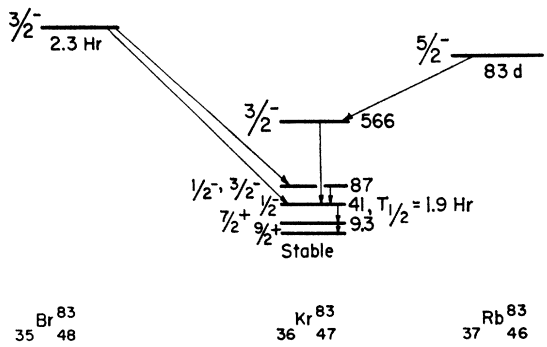

FIG. 2. Simplified energy level scheme for $A=83$. Redrawn from Nuclear Data Sheet NRC 59-1-77 (National Research Council, Washington, D. C.). We report the half-life of the 9.3-keV level of Kr^{83} as 147 ± 4 nsec.

the phosphor at long times after the pulse. This increase in "noise" is most easily seen in NaI(Tl) but is also clearly evident with anthracene. The combined effect of both kinds of noise was still small enough so that, using anthracene, the 9-keV L x rays of Ta^{181} could be clearly resolved from the noise; the spectrum was that of a broad peak (FWHM 70%) with a peak-to-valley ratio of about 3.

In order to decide such questions as which phosphor is most suited for this measurement, a simple model of the prompt response was created. Since the times of interest here are greater than a few nanoseconds, all causes of variation in response time could be neglected except those due to the statistical variation in the arrival time of the nth photoelectron. It was then assumed that each pulse passed by the single-channel analyzer contains N photoelectrons, that the probability of arrival of each photoelectron is a simple exponential function with the same lifetime as that of the phosphor (30 nsec for anthracene) and that detection corresponded to the arrival of the nth photoelectron. A simple analysis then gives for the shape of the prompt peak (more exactly, the derivative of the probability of at least n out of N luminescent centers, each of decay constant λ, having already decayed at time t):

$$f(t)=\sum_{i=0}^{n-1}\binom{N}{i}(1-e^{-\lambda t})^i e^{-\lambda t(N-i+1)} \times\left[\frac{N-i}{e^{-\lambda t}}-\frac{i}{1-e^{-\lambda t}}\right]. \quad (1)$$

The shapes found from this expression were in excellent agreement with prompt curves found experimentally, considering our only approximate knowledge of the bias level n. A typical result is that the prompt curve should be 20 nsec FWHM with a tail whose slope corresponds to an apparent half-life of 5 nsec if the limiter was set to clip 9-keV pulses at 4 keV. If the bias were set lower, as 2 photoelectrons out of 9, then the FWHM drops to 10 nsec, and the slope of the logarithmic tail to 3.5 nsec. These results indicate that lifetimes greater than about 10 nsec can be readily measured, even for γ-ray energies as low as 6 or 7 keV.[6]

For the La^{137} measurement, a NaI(Tl) crystal 6 mm thick was used to detect the 29-keV x rays. Enough photoelectrons are emitted in this case so that the slower lifetime of this phosphor is not harmful, and the improved pulse-height resolution in the slow channel helped in reducing the accidental counting rate. The source was prepared by reactor irradiation of 98.5% enriched Ce^{136} in the form of precipitated $Ce(NO_3)_3$ contained in a polyethylene bag. The bag was merely placed between, and in contact with, the two crystals.

For Kr^{83}, about 0.2 cc of ordinary krypton gas was sealed in a polyethylene bag and irradiated; the $(n\gamma)$ reaction on Kr^{82} produced a source of Kr^{83m} many times stronger than any impurity, and again the bag could be used directly as a source. In view of the nearly equal x-ray and γ-ray energies, in this experiment both crystals were anthracene, and the channels set symmetrically to cover both radiations.

Preliminary calibration of the time-to-pulse-height converter was made using oscilloscope and time marker techniques, as well as a double pulser with a variable delay. Final calibrations were made just before or after a data run by using two sources with the detectors separated and measuring the accidental coincidence rate in each time channel. Using channels of about 20 nsec width, 10^4 counts per channel could be accumulated in about 10 h using single counting rates low enough so as not to stress the electronics. This measurement of the accidental coincidence rate gives the width of each channel; these results were added together to find the over-all time delay for a count in a given channel. One advantage of this technique is that nonuniformities in channel widths are fully taken into account. A final check was made by remeasuring the well-known Fe^{57}

[6] While the present paper was in press, we were informed that Eq. (1) had already been published [M. A. El-Wahab and J. V. Kane, Nucl. Instr. Methods **15**, 15 (1962)] as part of a more general calculation of scintillation counter time resolution. They also give graphs displaying many features of the pulse shape, from which results identical to ours can be readily deduced.

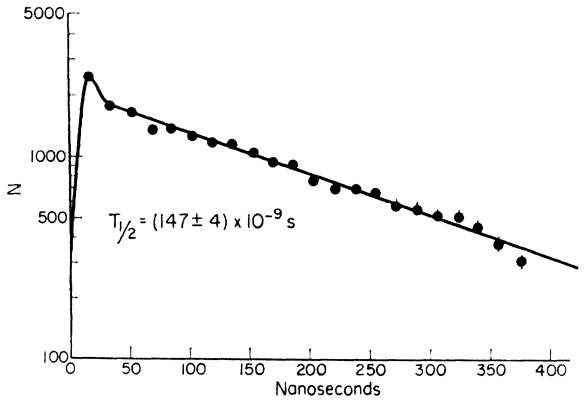

FIG. 3. A typical experiment, after subtraction of accidental coincidences, on the lifetime of the first excited state of Kr^{83}.

lifetime; our result was 98±4 nsec in agreement with recent measurements.[7]

It was thought desirable to verify the internal conversion coefficients. In the case of La^{137}, it was possible for us to make an estimate for α using the measured coincidence rate divided by the singles rate of the K x-ray detector. This result is not very precise since both the fraction of the singles count due to background and the efficiency of the γ-ray detector were not measured, but only estimated. In the case of Kr^{83}, an argon-methane proportional counter with a thin Mylar window was available which could easily resolve the 9.3-keV γ ray and the 12.6-keV x ray. In this case α can be determined without knowing the absolute efficiency of the counter for the γ ray; it is only necessary to know the ratio of efficiencies for the two energies. This ratio was determined using the dimensions of the counter and mass absorption coefficients.

RESULTS

La^{137} measurements were made on three dates, and each date consisted of three separate experiments, conducted sequentially during the decay of the source. The computed accidental coincidences were subtracted; they never accounted for more than $\frac{1}{3}$ of the counts in any channel. The data were treated by the methods of Peierls[8] to find the half-life and each separate run was in close agreement with the others. Our final result is 89±4 nsec, where the standard deviation resulting from statistics is ±2 nsec. Our estimate for α is 130±65, in agreement with Barrett,[2] who states "$\alpha=140$ within a factor of two either way."

For Kr^{83}, measurements were made on two occasions, and again each run was subdivided into three separate experiments. Figure 3 shows a typical result. All experiments were consistent with each other, and our final result is 147±4 nsec with statistics accounting for a standard deviation of ±2 nsec. For the internal conversion coefficient, our result is $\alpha=11\pm2$, in agreement with Barrett,[2] who found 10±5. It should be mentioned that both results for α are in excellent agreement with predictions made by extrapolation from the L-shell conversion coefficients of Sliv and Band.[9]

To find the retardation factors, we shall use the Weisskopf estimate for radiation width of $M1$ transitions, as given by Wilkinson[10]:

$$\Gamma_\gamma = 2.1\times10^{-2}E_\gamma^3 \text{ eV},$$

where E_γ is measured in MeV. To this is compared the actual radiation width for γ decay, $\Gamma_\gamma(\text{exp})=\hbar/\tau_\gamma=\hbar/\tau_{\text{exp}}(1+\alpha)$, where τ_γ is the mean life for γ decay alone, τ_{exp} is the experimentally observed quantity, and α is the internal conversion coefficient. The retardation factors of 370 and 45 are quite typical of $M1$ transitions[10] as can also be seen in a plot of the reduced half-lives vs mass number.[11]

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[11] D. Alburger, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 42, p. 92, Fig. 99.