Polarization of γ Rays in Pb^{207}

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Polarization-direction measurements have been made on the γ-ray transitions in Pb^{207} resulting from the decay of Bi^{207}. These measurements were made to obtain additional information on both the spin of the level at 2.34 Mev and the multipole character of the decay γ ray. The observed polarization eliminates the possible spin assignment 9/2. It is concluded that the spin assignment is 7/2 and that the 1.77-Mev γ ray is predominantly $M1$.

INTRODUCTION

THE decay of Bi^{207} to levels in Pb^{207} has been of special interest because of the successful shell-model interpretation of the low-lying states of Pb^{207}.[1,2] A level diagram of Pb^{207} is given in Fig. 1. About 8% of the time the decay of Bi^{207} populates the state at 2.34 Mev.[3,4] This state decays predominantly by a 1.77-Mev γ ray to the first excited state at 0.57 Mev. There has been some question as to whether the state at 2.34 Mev should be designated as the $f_{7/2}$ or the $h_{9/2}$ state.[5] Lazar and Klema[3] made an accurate measurement of the angular correlation of the 1.77–0.57 Mev decay to obtain information on the spin of this state and the character of the 1.77-Mev γ ray. The values obtained for A_2 and A_4 (the coefficients of the Legendre functions P_2 and P_4) are given in Table I. The observed correlation did not give a unique assignment. The observed value for A_2 selects the four possibilities listed in Table I. On the basis of a comparison of the observed value for A_4 with the values expected for the different possibilities, one concludes that the most likely assignment is 1, although 3 is a possible assignment. The possibilities 2 and 4 give increasingly strong disagreement for the value of A_4.

From a careful study of the decay of Bi^{207}, Alburger and Sunyar[4] found convincing evidence for assigning the 2.34-Mev state as $f_{7/2}$. In addition, from a comparison of the observed K-shell conversion coefficient with possible theoretical values, they concluded that the 1.77-Mev transition was predominantly $E2$. This was in strong conflict with the results of Lazar and Klema since it required the extremely unlikely assignment 4 (with $\delta=-4.2$). However, the interpretation of the internal conversion measurement by Alburger and Sunyar was made before Sliv's important "finite nuclear size" correction to $M1$ K-shell internal conversion was generally recognized.[6] When the new value for the theoretical K-shell $M1$ conversion coefficient of 3.4×10^{-3} is compared to the experimental value of $(2.5\pm0.5)\times10^{-3}$ it seems possible that the 1.77-Mev γ ray could be mostly $M1$. In that case, one would have the much more likely assignment 3 of Lazar and Klema which requires spin $_{7/2}$ and mostly $M1$ radiation.

We have previously found that linear polarization-

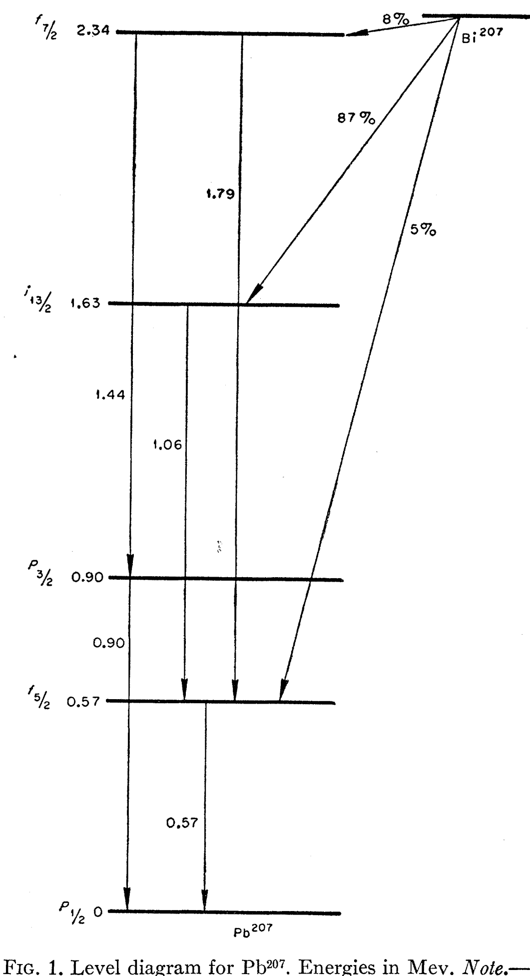

FIG. 1. Level diagram for Pb^{207}. Energies in Mev. *Note.*—The number 1.79 should read 1.77.

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[1] M. H. L. Pryce, Proc. Phys. Soc. (London) **A65**, 773 (1952).
[2] D. E. Alburger and M. H. L. Pryce, Phys. Rev. **95**, 1482 (1954).
[3] N. H. Lazar and E. D. Klema, Phys. Rev. **98**, 710 (1955).
[4] D. E. Alburger and A. W. Sunyar, Phys. Rev. **99**, 695 (1955).
[5] See references 3 and 4 for additional references to the extensive earlier experimental work on this decay scheme.
[6] L. A. Sliv, Zhur. Eksptl. i Teoret. Fiz. **21**, 77 (1951); L. A. Sliv and M. A. Listengarten, Zhur. Eksptl. i Teoret. Fiz. **22**, 29 (1952); and L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57 ICCK1, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].

TABLE I. Possible angular correlation coefficients. The first column contains the number which identifies the possible assignment of the 1.77—0.57 Mev cascade based on the angular correlation measurement of Lazar and Klema. These assignments are listed in columns 2 and 3. The expected values for A_2 and A_4 (the coefficients of the Legendre functions P_2 and P_4) are given in columns 4 and 5. The experimental values of A_2 and A_4 are given at the bottom of the table.

Assignment	Spin sequence	δ	A_2	A_4
1	$9/2(E2+M3)5/2(E2)1/2$	+0.184	−0.0087	+0.0315
2	$9/2(E2+M3)5/2(E2)1/2$	−2.8	−0.0087	−0.014
3	$7/2(E2+M1)5/2(E2)1/2$	−0.085	−0.0087	−0.0002
4	$7/2(E2+M1)5/2(E2)1/2$	−4.2	−0.0087	−0.068
	Experimental		−0.0087±0.0089	+(0.029±0.014)

direction correlation measurements were useful in resolving ambiguous assignments resulting from angular correlation measurements.[7,8] We therefore calculated the expected polarizations of the γ rays for the possibilities listed in Table I. These are given in Column 4 of Table II. It is seen that the expected polarizations are quite large and are sufficiently different to allow a unique assignment of the spin and character of the decay of the 2.34-Mev state. We wish to report this additional information obtained from some linear polarization-direction correlation measurements.

METHOD AND APPARATUS

Biedenharn and Rose[9] have given convenient formulas for the expected linear polarization-direction correlations. For the case of a γ-γ cascade with one pure multipole radiation (L_1) and one mixed multipole radiation (L_2, L_2+1), one has $W(\theta,\phi)=W_{\rm I}+\delta^2W_{\rm II}+2\delta W_{\rm III}$, where δ^2 is the ratio of the intensities of L_2+1 to L_2 multipoles in the mixed transition. $W_{\rm I}$, $W_{\rm II}$, and $W_{\rm II}$ are the linear polarization-direction correlation functions for pure 2^{L_1} pole-pure 2^{L_2} pole, pure 2^{L_1} pole-pure 2^{L_2+1} pole, and the interference term, respectively, Here θ is the angle between the directions of propagation of the two γ rays and ϕ is the angle between the direction of polarization and the normal to the plane defined by the directions of propagation of the two γ rays.

Our polarimeter, which is based on the Compton scattering mechanism, has previously been described.[7] The polarimeter is arranged so that $\theta=90°$. We measure $N_{\rm II}/N_\perp$, the ratio of the triple coincidence rate for the position when the detector of the Compton scattered photons is in the plane of the two γ rays to the triple coincidence rate for the perpendicular position. Therefore, the polarization, P, is given by $W(90°,90°)/W(90°,0°)$. The ratio $N_{\rm II}/N_\perp$ and P are connected through the relation

$$N_{\rm II}/N_\perp=(P+R)/(1+RP),$$

where R is the sensitivity of the polarimeter. For ideal geometry, R is simply the ratio of the differential Compton cross section averaged over the polarizations of the scattered photon, i.e.,

$$R=(d\sigma/d\Omega)_{\beta=\pi/2}/(d\sigma/d\Omega)_{\beta=0},$$

and β is the angle between direction of polarization of the incident photon and the plane of scattering. The finite extent of the detectors will reduce the value of the asymmetry ratio R. The actual values for R have been measured for γ-ray energies of 200 to 800 kev by

TABLE II. Expected and observed γ-ray polarizations. Columns 1 and 2 identify the possible spin sequence. Column 3 lists the γ-γ cascade. The γ ray whose polarization is measured is designated by italicizing the γ-ray energy. The expected value for the polarization, $P=W(90°,90°)/W(90°,0°)$, is given in column 4. Column 5 lists the polarization to be expected when one takes into account the finite geometry of the detector which detects the γ ray whose polarization is not measured. Column 6 shows the observed values for the polarization.

(1) Spin sequence	(2) δ	(3) γ rays (Mev)	(4) Theoretical polarization	(5) Theor pol with finite geom	(6) Observed polarization
$13/2(M4)5/2(E2)1/2$		*1.06*−0.57	0.616	0.635	0.62±0.04
(1) $9/2(E2+M3)5/2(E2)1/2$	+0.184	*1.77*−0.57	1.18±0.02	1.12±0.02	0.68±0.11
(2) $9/2(E2+M3)5/2(E2)1/2$	−2.8	*1.77*−0.57	2.40±0.03	2.23±0.03	
(3) $7/2(E2+M1)5/2(E2)1/2$	−0.085	*1.77*−0.57	0.74±0.04	0.76±0.04	
(4) $7/2(E2+M1)5/2(E2)1/2$	−4.2	*1.77*−0.57	0.44±0.02	0.47±0.02	
(1) $9/2(E2+M3)5/2(E2)1/2$	+0.184	1.77−*0.57*	1.02±0.02	1.02±0.02	1.00±0.11
(2) $9/2(E2+M3)5/2(E2)1/2$	−2.8	1.77−*0.57*	1.28±0.03	1.26±0.03	
(3) $7/2(E2+M1)5/2(E2)1/2$	−0.085	1.77−*0.57*	0.98±0.03	0.98±0.03	
(4) $7/2(E2+M1)5/2(E2)1/2$	−4.2	1.77−*0.57*	0.91±0.04	0.92±0.04	

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[8] F. K. McGowan and P. H. Stelson, Phys. Rev. **109**, 901 (1958).
[9] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

the use of known polarizations from Coulomb excitation γ rays.[8] By comparison of these values with those for an ideal geometry, the experimental curve has been extrapolated to 1.77-Mev γ-ray energy. For the three γ rays of interest here, *viz.*, 0.57, 1.061, and 1.77 Mev, we have taken the following values of R, respectively; 3.5 ± 0.2, 2.1 ± 0.1, and 1.57 ± 0.07.

The polarization of either γ ray in a cascade can be measured. In the case of the 1.061–0.57 Mev cascade, only the polarization of the 1.061-Mev γ ray was measured. The polarizations of both γ rays in the 1.77–0.57 Mev cascade were measured. The expected polarizations for the different possible spin assignments given in columns 1 and 2 are listed in column 4. The γ ray whose polarization is measured is designated by italicizing the x-ray energy.

The finite extent of the γ-ray detector which detects the γ ray whose polarization is not measured attenuates to some extent the coefficients which enter into the calculation of the expected polarization. When these attenuation factors are introduced, one obtains the values of P expected for the finite geometry and these are given in column 5 of Table II.

The general arrangement of the electronic gear has previously been described. The only change for the present experiment was that for some of the measurements a reduction was made in the resolving time to $2\tau=0.10$ microsecond.

The source for these measurements was bismuth nitrate dissolved in water.

RESULTS AND DISCUSSION

1.06–0.57 Mev Cascade

The main decay of Bi^{207} is to the metastable state at 1.63 Mev which in turn decays by a $1.061-0.57$ Mev γ-ray cascade. The nature of this cascade is well-established as $13/2(M4)5/2(E2)1/2$. We have measured the polarization of the 1.061-Mev γ ray in this case to check out our apparatus. The measured value of $N_{\parallel}/N_{\perp}$ is 1.184 ± 0.020. The random coincidence rate, which has been removed, amounted to 15% of the total coincidence rate. This value for $N_{\parallel}/N_{\perp}$ leads to an experimental value for P of 0.62 ± 0.04 and this compares with the expected theoretical value of 0.635.

1.77–0.57 Mev Cascade

An inspection of the expected theoretical values of P for the $1.77-0.57$ Mev cascade shows that the measurement of the polarization of the 1.77-Mev γ ray offers a better chance of making a unique assignment than does the measurement of the polarization of the 0.57-Mev γ ray. Polarization measurements were made on both γ rays but considerably more counting time was devoted to the polarization of the 1.77-Mev γ ray.

The result of the measurement of the polarization of the 0.57-Mev γ ray is $N_{\parallel}/N_{\perp}=1.00\pm0.07$ and this leads to an experimental value for P of 1.00 ± 0.11. This result is consistent with assignments 1, 3, or 4 but makes assignment 2 unlikely since the difference is greater than two standard deviations.

The coincidence counting rate during the determination of the polarization of the 1.77-Mev γ ray was about 7 counts/hr. The random coincidence rate was 12% of the total coincidence rate. The observed value for $N_{\parallel}/N_{\perp}$, corrected for the random rate, is 1.086 ± 0.037. The corresponding value for P is 0.68 ± 0.11. This result clearly eliminates assignments 1 and 2 both of which have spin 9/2. It also makes assignment 4 unlikely since this differs by two standard deviations. The observed polarization agrees reasonably well with assignment 3 which requires $7/2(E2+M1)5/2(E2)1/2$ and $\delta=-0.085$.

The observed result that the 1.77-Mev γ-ray transition between the $f_{7/2}$ and the $f_{5/2}$ states is 99.3% $M1$ and 0.7% ($E2$) agrees with the following theoretical estimate of this mixture. It is known that the decay of the first excited state of Pb^{207} by a pure $E2$ transition is much faster than that expected for a shell-model neutron[10] and this indicates the importance of collective motion for $E2$ transitions in Pb^{207}. From this evidence it is reasonable to assume that the $B(E2)_d$ for the 1.77-Mev transition also results from collective motion. If one takes the $B(E2)_d$ equal to that observed for the 0.57-Mev transition one obtains a partial half-life for $E2$ decay of 4×10^{-13} sec. On the other hand, one expects the $M1$ decay rate to be given reasonably well by the shell model transition rate. This estimate gives a partial half-life for $M1$ decay of 5×10^{-15} sec. The estimated ratio of 80 for $M1$ to $E2$ intensities agrees well with the observed value.

[10] P. H. Stelson and F. K. McGowan, Phys. Rev. **99**, 112 (1955).