be very helpful in making a critical evaluation of our photoeffect calculations.

No numerical work was done at photon energies as high as 190 Mev and so comparison with the data of Weil and McDaniel is not possible. The bremsstrahlung experiment of Johansson[31] at 65 Mev is of interest since both photoneutrons and photoprotons which had reasonably well defined laboratory energies were observed. The angular distribution of the yield of photoprotons having energies greater than 14 Mev from carbon as observed by Johansson is shown in Fig. 6. By way of comparison, there is shown also on Fig. 6, our calculated results for 13.3-Mev photoprotons from carbon irradiated by 50-Mev photons. The two curves are normalized at 60° laboratory angle. In the case of photoneutrons, Johansson obtained no data for carbon, but did notice in the cases of Be, Al, Ta, and Tb, that neutrons were emitted preferentially at 90° in the laboratory. This agrees qualitatively with our results for photoneutrons, as may be seen in Fig. 4.

As more experimental data become available, it might be of interest to test deuteron-model calculation using a variety of ground-state nucleon momentum distributions and then see if the same momentum distributions that give the best agreement in the case of the nuclear photoeffect also give the best agreement for proton scattering[7] and the "pickup" process.[9]

[31] S. A. E. Johansson, Phys. Rev. 97, 434 (1955).

ACKNOWLEDGMENTS

I wish to thank Professor L. I. Schiff for his very helpful advice in many parts of this calculation.

PHYSICAL REVIEW VOLUME 100, NUMBER 1 OCTOBER 1, 1955

Gamma-Gamma Angular Correlation in Ba^{134}

ERNEST D. KLEMA
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received May 20, 1955)

The directional angular correlation of the 1367–605 kev γ-γ cascade in Ba^{134} has been measured with a coincidence scintillation spectrometer using NaI detectors. For a dilute cesium chloride aqueous solution source, the observed correlation function, after correcting for the finite angular resolution of the detectors, is given by $W(\theta)=1+(0.090\pm0.0086)P_2(\cos\theta)-(0.004\pm0.013)P_4(\cos\theta)$. From this result it is not possible to assign unambiguously a spin and parity to the 1972-kev level in Ba^{134}, from which the cascade originates. However, the present angular correlation data taken with internal conversion coefficient data for the transitions from this level indicate that it very probably has spin 3 and odd parity.

I. EXPERIMENTAL RESULTS

THE directional angular correlation of the 1367–605 kev γ-γ cascade in Ba^{134} has been measured with a coincidence scintillation spectrometer using NaI detectors in a series of 5 experiments with a total of 1.1×10^5 coincidence counts taken at 19 angular positions. The source was a dilute aqueous solution of cesium chloride.

The data were obtained as discussed previously[1] and were analyzed following the paper of Rose.[2] The γ-ray spectrum of the cesium chloride source is shown in Fig. 1. Each point on the curve out to a pulse height of 810 units contains 4096 counts, and the points for greater pulse heights contain 1024 counts each. The windows of the differential pulse-height analyzers were placed, as shown in Fig. 1, so that one was set on the full-energy peak of the 605-kev γ ray and the other accepted only the full-energy peak of the 1367-kev γ ray. Since the latter γ ray is the highest-energy one of the source, the measurement of the angular correlation of the 1367–605 kev cascade is a clean one and needs no correction for interference by the other cascades.

The true coincidence counting rate for the present experiment was of the order of 3.5×10^{-2} count/sec and the random rate was 15% of this. The correlation function obtained, after correcting for the finite angular resolution of the detectors, is

$$W(\theta)=1+(0.090\pm0.0086)P_2(\cos\theta)-(0.004\pm0.013)P_4(\cos\theta).$$

The errors given above are the standard deviations as defined by Eq. (30) of Rose's[2] paper.

II. ANALYSIS OF RESULTS

The most recent decay scheme proposed for Cs^{134} is given in Fig. 2.[3] In contrast with the ones previously advanced, it agrees with coincidence data obtained at this laboratory and with the relative intensities of the γ rays as measured by scintillation spectrometry here.[4]

[1] E. D. Klema and F. K. McGowan, Phys. Rev. 91, 616 (1953).
[2] M. E. Rose, Phys. Rev. 91, 610 (1953).
[3] Keister, Lee, and Schmidt, Phys. Rev. 97, 451 (1955).
[4] R. C. Davis, private communication.

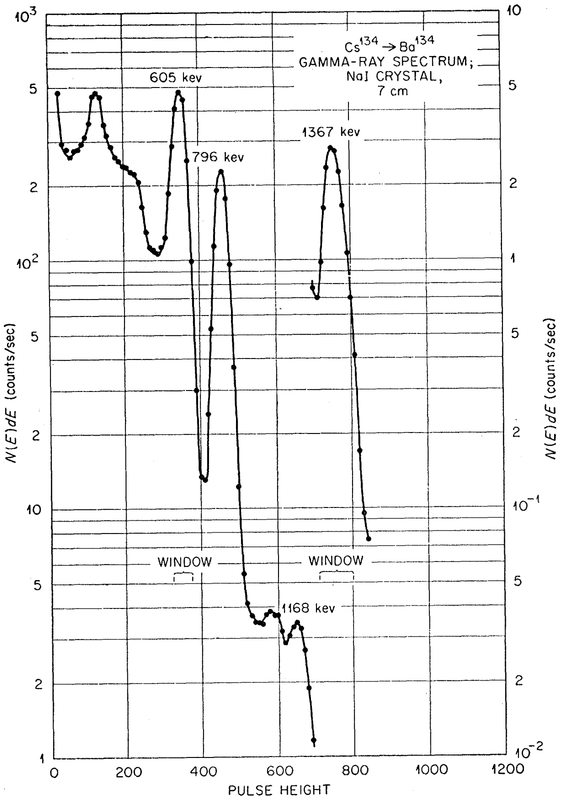

FIG. 1. Gamma-ray spectrum of the cesium chloride source. The brackets represent the positions of the windows of the differential pulse-height analyzers for the present experiment.

In the analysis of the present data, we consider spins 2, 3, 4, and 5 for the energy level at 1972 kev. We do this because there is no spin and parity assignment for this level which is consistent with all the experimental information, and we wish to point out what possible spins can be eliminated on the basis of angular correlation measurements alone. The 605-kev transition is known to be predominantly $E2$ radiation.[5] The lifetime of the 605-kev intermediate state of the cascade has been measured to be less than 3×10^{-9} sec.[6,7] Thus, it is probably a good assumption that the correlation is not affected by external fields and that the measurement yields the unperturbed correlation function.

The correlation functions expected theoretically, as calculated from the tables of Biedenharn and Rose,[8] if the 1367-kev transition is a pure multipole are shown in Table I. It is seen that the only one of these which cannot be ruled out by the present data is the one for the sequence $4(Q)2(Q)0$. If one assigns even parity to the 1972-kev level, the 1168-kev transition would be $E3$ or $E3+M4$ and the expected conversion coefficient for this transition would be far from that measured experimentally, as shown in Fig. 5 of reference 3. The 569-kev transition would be $M1$ or $E2+M1$. Its observed conversion coefficient is slightly outside the limits of those for the pure $E2$ and $M1$, but the value is nearly that to be expected for $M1$. The 1367 transition would be $E2$, and the observed conversion coefficient is somewhat different from the expected value.

The assignment of spin 4 and odd parity would make the 569-kev transition $E1$ or $E1+M2$, and its observed conversion coefficient lies between these limits. However, the 1168-kev transition would be $M3$ or $E4+M3$, and its observed coefficient is far outside of those expected for this case. Thus it is quite unlikely the above sequence is the correct one, and we next consider the

TABLE I. Angular correlation coefficients A_2 and A_4 in $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$ for the various sequences indicated.

Sequence	A_2	A_4
$2(D)2(Q)0$	0.2500	0
$2(Q)2(Q)0$	−0.0766	0.3264
$3(D)2(Q)0$	−0.0714	0
$3(Q)2(Q)0$	−0.2041	−0.0816
$4(Q)2(Q)0$	0.1020	0.0091
$4(O)2(Q)0$	−0.2678	0.0317
$5(O)2(Q)0$	0.1786	−0.0043

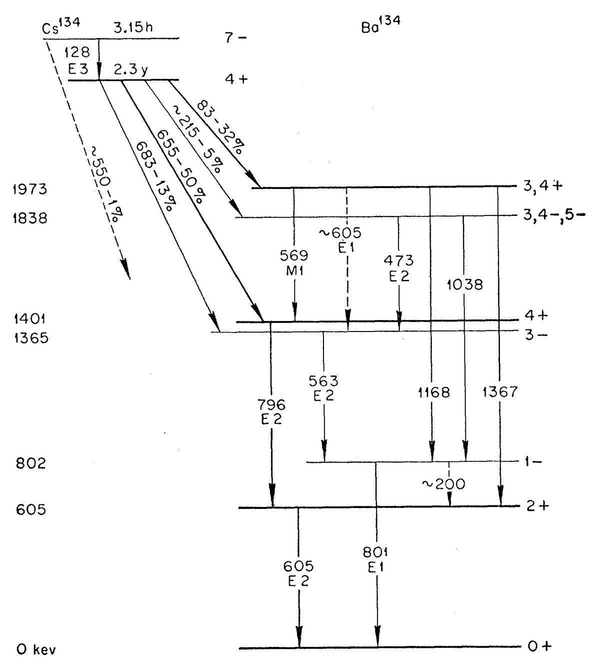

FIG. 2. Proposed decay scheme for Cs^{134} as given by Keister, Lee, and Schmidt, Phys. Rev. **97**, 451 (1955). The present data, taken with internal conversion data given in the above paper, indicate that the 1972-kev level very probably is 3^-.

[5] B. L. Robinson and L. Madansky, Phys. Rev. **84**, 604 (1951).
[6] R. E. Bell and H. E. Petch, Phys. Rev. **76**, 1409 (1949).
[7] *Note added in proof.*—A recent measurement by V. Z. Wintersteiger, [Bull. Inst. Nuclear Sci. "Boris Kidrich" (Belgrade) 4, 79 (1954)] has shown the half-life to be less than 5×10^{-10} sec.
[8] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

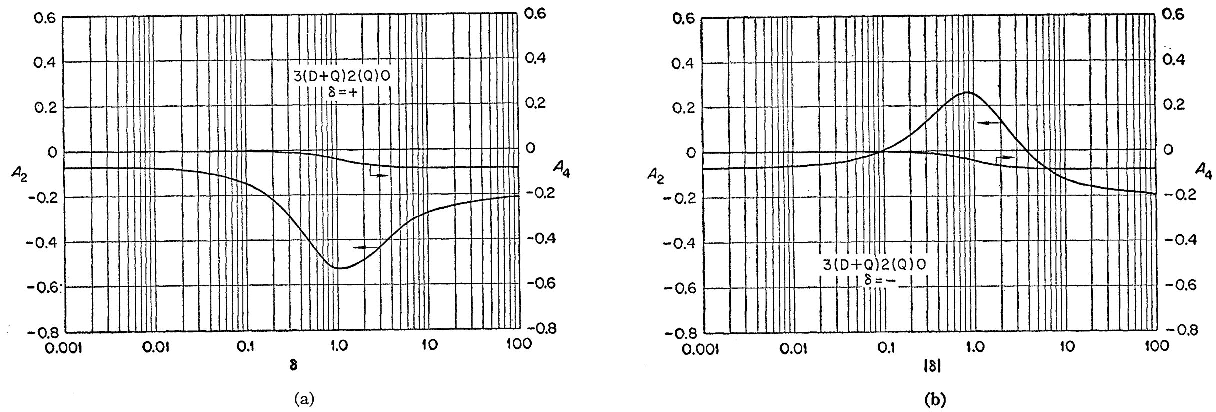

FIG. 3. Angular correlation coefficients, A_2, the coefficient of $P_2(\cos\theta)$ and A_4, the coefficient of $P_4(\cos\theta)$, as a function of δ, the mixing ratio giving the square root of the ratio of the intensity of the quadrupole radiation to that of the dipole, for the sequence $3(D+Q)2Q0$. (a) $\delta=+$; (b) $\delta=-$.

1367-kev transition to be mixed with spins 2 or 3 for the 1972-kev level.

For the sequence $2(D+Q)2(Q)0$ with δ positive, where δ^2 is the ratio of the intensity of the quadrupole radiation to the intensity of the dipole radiation, a value of A_2, the coefficient of $P_2(\cos\theta)$ in $W(\theta)$, of $+0.09$ corresponds to a value of A_4 of 0.31, and this possibility can be ruled out. For $\delta=-0.210_{-0.009}^{+0.012}$, corresponding to $A_2=0.090\pm0.0086$, we have $A_4=0.015\pm0.002$. This assignment cannot be ruled out on the basis of the angular correlation measurement. However, if we make the assignment 2^+ for the 1972-kev state, the intensity of the beta decay to it would be expected to be far lower than that which is measured experimentally, as shown in Fig. 1. If we assign 2^-, the 1168-kev transition would be $M1$ or $E2+M1$; its conversion coefficient is somewhat outside these limits. The 569-kev transition would be $M2$, and its coefficient is considerably different from that expected for this case. The 1367-kev transition would consist of $E1$ or $E1+M2$, and its coefficient falls within these limits.

We next consider the sequence $3(D+Q)2(Q)0$. The curves of A_2 and A_4 as a function of δ for this case are shown in Fig. 3. One sees that for positive δ, A_2 is never positive. For $\delta=-2.45$, $A_2=-0.090$ and $A_4=-0.070$, and again this possibility may be ruled out on the basis of the angular correlation measurements. For $\delta=-0.222_{-0.015}^{+0.011}$, corresponding to $A_2=0.090\pm0.0086$, we have $A_4=-0.004\pm0.001$. If one assigns even parity to the 1972-kev level, the conversion coefficient for the 1367-kev transition corresponding to $\delta=-0.222_{-0.015}^{+0.011}$ is $(1.1639_{-0.0076}^{+0.0071})\times10^{-3}$. The standard deviation given above includes only that of the measurement of A_2; the conversion coefficients for the pure multipoles have been interpolated from the tables of Rose, Goertzel, and Perry[9] and have been taken as exact. The difference between the above value and the measured coefficient of $(0.55\pm0.10)\times10^{-3}$ is 6 times the standard deviation of the measurement, and this assignment can be ruled out.

Finally if one assigns spin 3 and odd parity to the 1972-kev level, the sequence is given by $3^-(E1+M2)2^+(E2)0$. For this case the conversion coefficient of the 1367-kev transition corresponding to $\delta=-0.222_{-0.015}^{+0.011}$ is $(0.482_{-0.010}^{+0.012})\times10^{-3}$. This agrees with the measured value of $0.55\pm0.10\times10^{-3}$. On this assignment, the 569-kev transition is $E1$ or an $E1+M2$ mixture, and the value of δ^2 that corresponds to its observed conversion coefficient[3] of $10.5\pm1.6\times10^{-3}$ is 0.520 ± 0.093. The 1168-kev transition is $E2$ for this assignment. Its observed conversion coefficient is quite close to that expected for $E2$ radiation, the difference between the observed value and the theoretical value being less than twice the standard deviation of the measurement.

The above assignment of 3^- for the 1972-kev level and an $E1+M2$ mixture with $\delta=-0.222_{-0.015}^{+0.011}$ for the 1367-kev transition fits best all the experimental evidence, and it is concluded that it is probably correct.

III. ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance of Wilma Stair, who transcribed the data from the tapes for the least-squares fittings.

[9] Rose, Goertzel, and Perry, Oak Ridge National Laboratory Report ORNL-1023 (unpublished).