tion curve for the emission of x-rays in a 3-kev energy interval about 150 kev for 2 Mev protons incident on a tin target. The result given in Fig. 3 is nearly isotropic in agreement with preliminary[2] results. For angles other than 90° there will be corrections to this curve due to the dipole-quadrupole cross terms in Eq. (5), but these are expected to alter the results by less than 10 percent. The total cross section is, from Eqs. (39) and (40),

$$\sigma_{\text{tot}}(k_1,k_2,\omega)=(16\pi/3)A_0(1-3\hbar\omega/E)J_1 = 18\cdot 9\times 10^{-31}\ \text{cm}^2.$$

IV. CONCLUSION

The quantum correction to the classical orbit treatment of dipole radiation emitted by a beam of protons scattered in a coulomb field has been calculated and found to agree with experiments of Mark *et al.*[2] This correction has been expressed in terms of the inelasticity of the scattered proton, $(\hbar\omega/E)$. It serves to decrease the classical prediction by $\sim$25 percent for the experiments under discussion here. This reduction seems at first to be surprisingly large in view of the fact that the proton radiates only $\hbar\omega/E=7.5$ percent of its energy. However, we can make it reasonable by recalling that the important orbits in the classical picture are parabolic or nearly parabolic. The damping effect of the bremsstrahlung on the motion of the proton, which is neglected in the classical treatment, causes it to be slowed down and repelled further away from the Coulomb field source, thereby reducing the effective dipole moment by an appreciable amount.

Other corrections due to retardation effects, electronic shielding, and finite nuclear size can be neglected for the energies studied in this work.

We wish to thank Dr. Hans Mark for informing us of his experimental results prior to publication and thereby arousing our interest in this problem.

Note added in proof.—We have learned (private communication) that Professor L. C. Biedenharn of The Rice Institute has made the reduction to the classical orbit calculation expressed in Eq. (35) in connection with his studies on the electric excitation problem.

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Angular Correlation of the Gamma Rays of Ba^{134}

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The angular correlations have been measured between the following pairs of gamma rays from Ba^{134}: 605 kev–797 kev, 1368 kev–605 kev, and 570 kev–605 kev. These measurements indicate that the spins of the states associated with these gamma rays are 4, 4, 2, 0. The 605, 797, and 1368-kev gamma rays are pure quadrupole while the 570-kev gamma ray is a mixture of 94 percent quadrupole and 6 percent dipole.

I. INTRODUCTION

THE angular correlation of the gamma rays following the beta decay of the 2.3-year isomer of Cs^{134} has been investigated by a number of authors.[1–4] While the complete decay scheme is very complex,[5,6] the main features are shown in Fig. 1. The gamma-ray spectrum as observed is shown in Fig. 2. It should be noted that the remaining lines are too weak to be observed. The first investigators noted the similarity between the shape of the curve obtained from their measurements of the overall angular correlation and the shape of the angular correlation function obtained from the gamma rays following the beta decay of Co^{60}. The cases differed in that the asymmetry for the Ba^{134} was approximately 12 percent while that of Co^{60} was 17 percent. Since the majority of the coincidence counts were due to the 797-kev and 605-kev gamma rays, it was proposed that these two gamma rays gave rise to a basic quadrupole-quadrupole correlation. Since Ba^{134} is an even-even nucleus (56 protons-78 neutrons) the ground state is assumed to have a spin of 0 with even parity. Thus, as is in the case of Co^{60}, spins of 2 and 4 were assigned to the first and second excited states respectively with both radiations quadrupole. Robinson and Madansky[3] measured the correlation of the lower two gamma rays by demanding that they also be in coincidence with the high-energy beta ray. From this measurement and from a measurement of the over-all correlation, spins of 5, 4, 2, 0 were assigned to the important states with the radiation being dipole, quadrupole, quadrupole respectively. However because of the discrepancies between the over-all correlation and the above assignment, it was decided to reinvestigate the angular correlations in greater detail.

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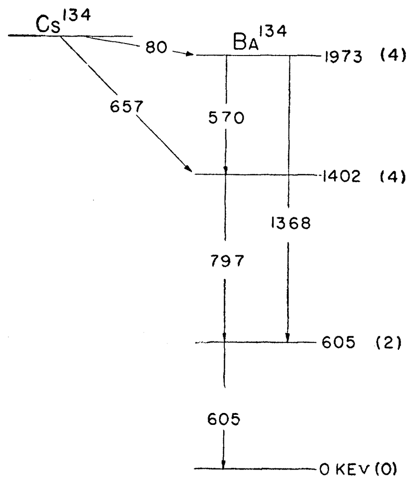

FIG. 1. Simplified decay scheme of Cs^{134}. The numbers in parenthesis are the spins of the nuclear levels.

II. APPARATUS

Scintillation counters were used as the gamma-ray detectors. They consisted of NaI(Tl) crystals mounted on RCA type 5819 photomultiplier tubes. The crystals were 1.5 in. in diameter and 1 in. thick. The source was mounted at the intersection of the axes of the cylindrical crystals and was about 5 in. above the table. The crystals were covered with $\frac{1}{16}$ in. aluminum to stop the beta rays.

Figure 3 is a block diagram of the coincidence spectrometer. It consists of two fast channels which have a resolving time of about 8 millimicroseconds in parallel with slower energy selection channels. The fast coincidence output is placed in slow triple coincidence with the two energy selection outputs. The resolving time of the slow triple coincidence circuit is about 200 millimicroseconds.

From the phototube the pulse was fed into a fast and slow channel. The fast channel consisted of Hewlett-Packard distributed amplifiers (types 460A and 460B) and a 6AU6 limiter. The resulting fast rising pulse was used to trigger a fast blocking oscillator which gave a positive output pulse of about 40 volts amplitude, 0.06 microsecond duration, and with a 0.01 microsecond rise. This was inverted and then clipped with a shorted delay line to give a fast negative pulse suitable for triggering a Garwin-type coincidence circuit.[7,8] The slow channel consisted of a Bell-Jordan A-1 type amplifier[9] and a single-channel discriminator. The output pulses from the fast coincidence circuit and the two differential discriminators were used to trigger slow blocking oscillators which in turn activated the slow coincidence circuit.

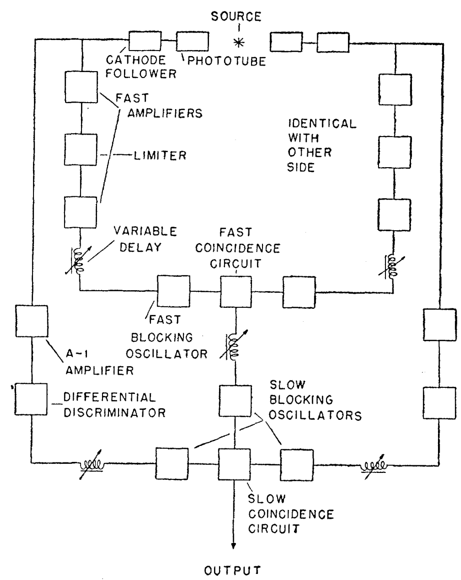

FIG. 3. Block diagram of the coincidence spectrometer.

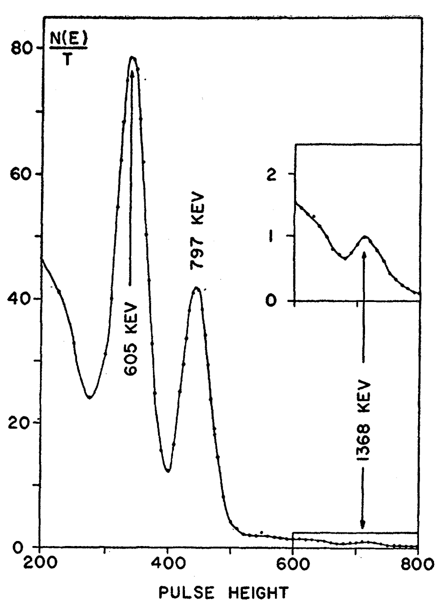

FIG. 2. Gamma-ray spectrum of Ba^{134}.

III. RESULTS

The over-all angular correlation was measured using both a solid and a liquid source. The solid source was Cs_2CO_3 and the liquid source was Cs_2CO_3 dissolved in water. The identical results of these two measurements indicate there are no perturbations of the nucleus while it is in the intermediate states. The results of the over-all correlation are shown in Fig. 4 and are in agreement with those of the previous investigators. The measured correlation will depend somewhat on the discrimination level since this will change the relative intensities of the three cascade gamma rays. A least-squares fit of

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[9] W. H. Jordan and P. R. Bell, Rev. Sci. Instr. **18**, 703 (1947).

the data to the curve

$$W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$$

was made where $P_k(\cos\theta)$ are the Legendre polynomials of degree k. Table I shows the experimental values for A_2 and A_4 along with the theoretical values for the basic quadrupole-quadrupole correlation and the basic dipole-quadrupole correlation. For the proposed assignment[3] $5(D)4(Q)2(Q)0$, the over-all correlation would be compounded from a combination of the 2^2-2^2 and 2^1-2^2 correlations. It is seen that an arbitrary combination of these correlations cannot give the observed results. Hence, it must be concluded that the assignment $5(D)4(Q)2(Q)0$ is in disagreement with the observed results.

The 797 kev–605 kev correlation was measured by setting both counters integrally on the high side of the 600-kev line. For an energy resolution of 13 percent, the 570-kev line would extend to a maximum of about 645 kev. Thus if the counters were set above 645 kev the only coincidences recorded would be between the 797 kev and the 605 kev and between the 1368-kev and the 605-kev lines. However since the 1368-kev line is very weak, this latter coincidence can be neglected. Figure 5 shows the results of this measurement. The solid curve is the theoretical curve for the basic 2^2-2^2 correlation and the dashed curve is the least squares fit to the experimental points, corrected for the finite geometry. The experimental coefficients are $A_2=0.101\pm0.008$ and $A_4=-0.002\pm0.012$. Since Ba^{134} is an even-even nucleus the ground state is assumed to have spin 0. Thus spins of 2 and 4 are assigned to the 605-kev and the 1402-kev states, respectively. Both transitions are quadrupole radiation.

TABLE I. Coefficients for the theoretical curves for the basic 2^2-2^2 correlation, the basic 2^1-2^2 correlation, and the experimental over-all correlation of Ba^{134}. The experimental coefficients have been corrected for the finite geometry.

Correlation	A_2	A_4
Experimental	0.076 ± 0.002	0.017 ± 0.003
2^2-2^2	0.102	0.009
2^1-2^2	-0.071	0

The spin of the ground state of Cs^{134} has been measured as 4[10,11] and the ΔI for the 80-kev beta transition has been measured as 0, ±1.[12] Thus the 1973-kev level in Ba^{134} must have a spin of either 3, 4, or 5.

The correlation between the 1368-kev–605-kev gamma rays was measured by setting one counter integrally at 1200 kev and the other counter integrally at about 500 kev. The results of this measurement are shown in Fig. 6. Curves 1, 2, and 3 are the theoretical curves for the basic 2^1-2^2, 2^2-2^2, and 2^3-2^2 correlations, respectively. The dashed curve is the least-squares fit to the experimental points corrected for the finite geometry. The experimental coefficients are $A_2=0.094\pm0.007$ and $A_4=-0.024\pm0.009$. It is seen that the observed correlation is in best agreement with a 2^2-2^2 correlation. If mixtures are considered, the experimental curve can be fitted with an assignment $3(D,Q)2(Q)0$. However with this assignment the 570 kev–797 kev and the 570 kev–605 kev correlations have an A_4 coefficient which is zero or negative. This is again in disagreement with the large A_4 coefficient observed in the over-all correlation. An assignment of 5 for the upper state with a mixture of 2^3–2^4 pole radiation can be ruled out on lifetime considerations. Thus the experimental data are compatible with a spin assignment of 4 for the 1973-kev level, but are not compatible with either a 3 or a 5. The 1368-kev transition is quadrupole radiation.

A measurement of the one-three angular correlation between the 570 kev and the 605-kev gamma-rays

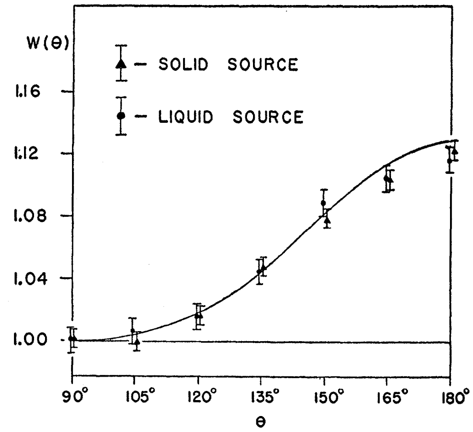

FIG. 4. Over-all angular correlation of Ba^{134}. This is composed mainly of three separate correlations; the 797–605, 570–797, and 570–605 kev correlations.

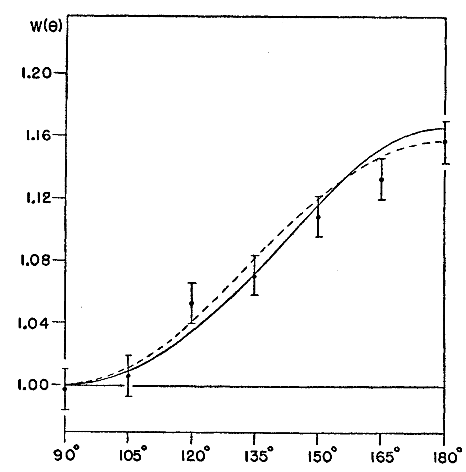

FIG. 5. Angular correlation of the 605–797 kev gamma rays. The dashed curve is the least-squares fit to the experimental points and has been corrected for finite geometry. The solid curve is the theoretical curve for a basic 2^2-2^2 correlation.

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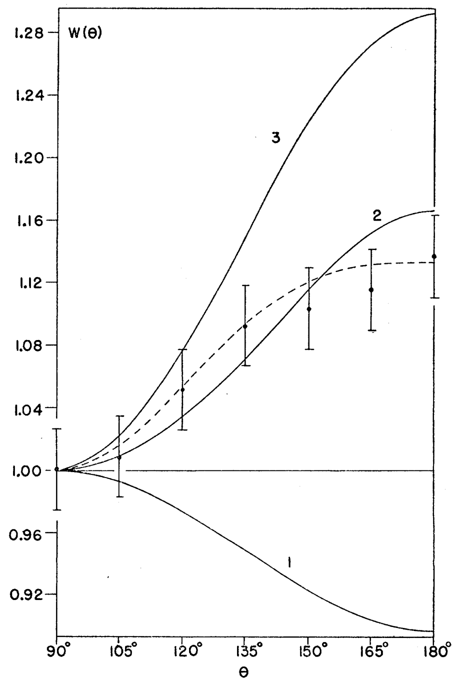

FIG. 6. Angular correlation of the 1368–605 kev gamma rays. The dashed curve is the least-squares fit to the experimental points and has been corrected for finite geometry. Curves 1, 2, and 3 are the theoretical curves for the basic 2^1-2^2, 2^2-2^2, and 2^3-2^2 correlations, respectively. The experimental curve contains a small admixture of a triple correlation due to the summing of the 570-kev and 797-kev gamma rays.

with the 797-kev transition unobserved allows a determination of the multipole order of the 570-kev gamma ray.[13,14] For this work, each counter was set at 570-kev (i.e., on the lower edge of the 605-kev line) with a 60-kev window width. In addition to the 570-kev–605-kev coincidences there will be 570-kev—797-kev and 605-kev–797-kev coincidences due to the Compton background from the 797-kev line. Hence the measured correlation will be a composite of three separate correlations. However for a spin of 4 for the uppermost state, the 570-kev–797-kev and the 570-kev–605-kev correlations will be the same for dipole, quadrupole, or a mixture of dipole and quadrupole radiation in the 570-kev transition. Thus the measured correlation will really be a composite of only two different correlations. Figure 7 shows the results of this measurement. The dashed curve is the least-squares fit to the data, corrected for the finite geometry. The coefficients are $A_2=0.019\pm0.019$ and $A_4=0.092\pm0.029$. Curve 1 is the theoretical curve for the one-three correlation for a $4(D)4(Q)2(Q)0$ cascade. Curve 2 is the basic quadrupole-quadrupole correlation. It is readily seen that the observed correlation cannot be compounded out of curves 1 and 2. However the observed correlation can be fitted by requiring the 570-kev transition to be a mixture of dipole and quadrupole radiation. Equating

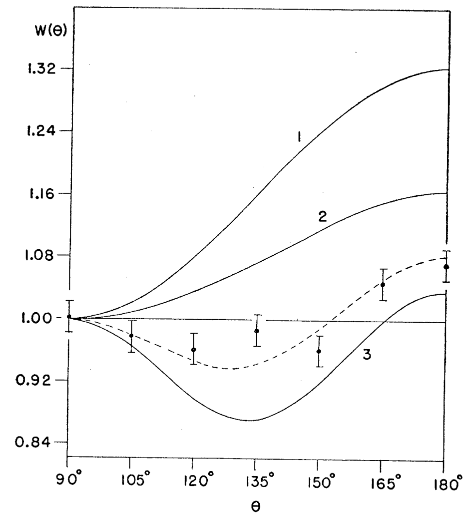

FIG. 7. Angular correlation of the 570–605 kev gamma rays. The dashed curve is the least squares fit to the experimental points and has been corrected for finite geometry. Curve 1 is the theoretical curve for the one-three correlation for a $4(D)4(Q)2(Q)0$ cascade. Curve 2 is the theoretical curve for a basic 2^2-2^2 correlation. Curve 3 is the theoretical curve for the one-three correlation for a $4(D,Q)4(Q)2(Q)0$ cascade with the first transition 94 percent quadrupole to 6 percent dipole radiation. The experimental curve is composed of 38 percent curve 2 plus 62 percent curve 3.

the observed coefficients A_2 and A_4 to the theoretical ones gives two equations with two parameters to be determined; the ratio δ of the quadrupole to the dipole nuclear matrix elements[15] and the fraction f of the basic 2^2-2^2 correlation that must be present. δ^2 gives the ratio of the intensities of the quadrupole to the dipole radiation. The required mixture is 94 percent quadrupole to 6 percent dipole with 0° phase difference. The fraction f is 0.38. Curve 3 is the correlation function for the 570-kev–605-kev cascade with the 2^2-2^2 correlation subtracted out.

IV. SUMMARY

The angular correlations of the gamma rays of Ba^{134} following the beta decay of the 2.3 year isomer of Cs^{134} were reinvestigated. The 797-kev–605-kev cascade is in agreement with a $4(Q)2(Q)0$ assignment and the 1368-kev–605-kev cascade is also best fitted by a $4(Q)2(Q)0$ assignment. The one-three correlation for the 570-kev–(797-kev)–605-kev cascade requires a mixture of 94 percent quadrupole and 6 percent dipole radiation for the 570-kev transition. For a reasonable branching ratio between the 650-kev and 80-kev beta rays, the theoretical over-all correlation is in agreement with the observed results. The large percentage of quadrupole radiation in the 4 to 4 transition may be compared to the similar cases of 2 to 2 transitions in which there are also large admixtures of quadrupole radiation.[16]

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