No coincidences between the 316- and 360-kev gamma rays were observed. Except for the possible existence of a metastable state, this precludes the possibility of these two transitions being in cascade.

The results of (gamma)-(gamma) coincidence experiments involving the 165-kev peak are inconclusive. A peak in the coincidence pulse-height distribution is observed in this region when the single-channel spectrometer is set at 150–200 kev. These coincidences are probably due to Compton scattering of the higher energy gamma rays in the detecting crystals.

Because the coincidences between the K x-ray and the 360-kev gamma ray are easily observed (the ratio of coincidence counting rate to single counting rate being approximately the geometry factor), and since conversion lines are not easily observed, the possible presence of a K capture activity was suspected. K capture in gadolinium would result in the emission of x-rays characteristic of europium; x-rays associated with internal conversion following beta decay would be characteristic of terbium. The energy resolution of the spectrometer is not good enough to permit a reliable Z assignment to the x-ray. However, by comparing the pulse-height distribution with those due to x-rays of europium and holmium (Fig. 5), it is evident that the x-ray peak is not due to europium and is probably characteristic of terbium. As an additional check, the attenuation of the peak due to absorbers of La, Ce, Pr, and Nd was observed. The relative attenuation effected by each of these absorbers was approximately the same. This also indicates that the x-ray is not the Eu x-ray, since if it were, its energy would lie between the critical edges of Ce and Pr, and a striking difference in absorption should be noted. Additional evidence indicating that no K capture activity is present was obtained from (beta)-(gamma) and (beta)-(x-ray) coincidence experiments. The results of such experiments indicate that all of the electromagnetic radiation is coincident with a beta ray of approximately 1.6 Mev.

The foregoing data may be explained by postulating the existence of a highly K converted transition of about 60 kev which is in cascade with the 360-kev transition in Tb. A careful inspection of the pulse-height distribution in the region of 60 kev failed to reveal any evidence of an unconverted gamma ray of this energy. Electrons resulting from K conversion of such a transition would have an energy below the detection limit of the conversion electron spectrometers, hence would not be observed on the photographic plates. The weak 47.4- and 53.4-kev internal conversion lines may be due to L and M conversion electrons for this transition. However, one or the other of these might also be attributed to K conversion of the $\sim$102-kev gamma ray.

The 165-kev peak in the pulse-height distribution may be interpreted either as resulting from a gamma ray of this energy or as the Compton distribution due to the 316- and 360-kev radiations. Although the former interpretation is preferred from a consideration of the line shape, the decay scheme (Fig. 6) which is proposed is consistent with all of the remaining data without inclusion of the possible 165-kev transition.

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Gamma-Gamma Directional Correlation Experiments with Mo^{93m}†

J. J. KRAUSHAAR*
Brookhaven National Laboratory, Upton, New York

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Three directional correlations have been measured involving the three successive γ rays emitted following the 7.0 hour state in Mo^{93m}. The data characterize the spins and multipoles as

$$J+8 \xrightarrow{2^4} J+4 \xrightarrow{2^2} J+2 \xrightarrow{2^2} J,$$

which is consistent with Goldhaber's postulation on the basis of "core isomerism."

THE 7.0-hour isomer of Mo has now been assigned[1–3] to Mo^{93m} and three γ rays of 0.264, 0.685, and 1.479 Mev are known[1–5] to be emitted in cascade following the decay of the isomeric state. It has been pointed out by Goldhaber[6] that the main features of the decay scheme suggest a phenomenon of "core isomerism," where the odd neutron (presumably in a $g_{7/2}$ state) couples to the even-even core which successively goes through states with spins 8+, 4+, 2+, 0+ to give a total spin to the four states involved of 23/2+, 15/2+, 11/2+, and 7/2+. As one means of establishing the spins of the four levels experimentally, directional correlation measurements

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* Now at Physics Department, Stanford University, Stanford, California.

[1] G. E. Boyd and R. A. Charpie, Phys. Rev. **88**, 681 (1952).

[2] D. E. Alburger and S. Thulin, Phys. Rev. **89**, 1146 (1953).

[3] R. Bernas and S. Beydon, Compt. rend. **236**, 194 (1953).

[4] Kundu, Holt, and Pool, Phys. Rev. **77**, 71 (1950).

[5] L. Ruby and J. R. Richardson, Phys. Rev. **83**, 698 (1951).

[6] M. Goldhaber, Phys. Rev. **89**, 1146 (1953).

have been made between the three cascade gamma rays. Stevenson and Deutsch[7] have measured the anisotropy at 180° of the γ-γ directional correlation as $+0.20$, but lack of energy discrimination prevented any definite conclusions.

Sources were prepared by bombarding Nb foil with 20-Mev deuterons in the Brookhaven 60-inch cyclotron. Mo^{93m}, formed by the $\mathrm{Nb}(d,2n)\mathrm{Mo}^{93m}$ reaction was chemically separated from Nb by an ether extraction. About 0.1 ml of an aqueous solution were used for the individual sources.

The first directional correlation studied was that between the 0.685- and 1.479-Mev γ rays which have been tentatively assigned (Fig. 1) as γ_2 and γ_3. The counters were integrally biased at just above 320 kev, and 2.5 mm of Pb placed in front of them. In this way, neither the 0.264-Mev γ ray nor back-scattered radiation were counted. The measurements are shown in Fig. 1. The lower solid curve represents the least squares fit and the dashed curve is the least squares fit corrected for the finite geometry involved. Because the three γ rays have energies considerably different from annihilation radiation, the collimated beam method[8] was employed for the geometry correction. This involved measuring the angular resolution with γ-ray beams of the appropriate energy under the various conditions of pulse-height selection.

TABLE I. The corrected least squares values of the coefficients in $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$.

Correlation	Measured values		Theoretical values	
	A_2	A_4	A_2	A_4
$\gamma_1-\gamma_2$ Basic 2^4-2^2	0.208 ± 0.103	-0.027 ± 0.028	0.2208	-0.0180
$\gamma_2-\gamma_3$ Basic 2^2-2^2	0.098 ± 0.031	0.006 ± 0.009	0.1020	0.0091
$\gamma_1-\gamma_3$ Basic 2^4-2^2 (one-three)	0.210 ± 0.096	-0.001 ± 0.027	0.2208	-0.0180

The theoretical curve in Fig. 1 (basic,[9] 2^2-2^2) can be seen to be in good agreement with the data. All other basic correlations and other reasonable assignments involving pure radiation can be excluded. For example, the spins consistent with the assignments for γ_2 and γ_3 made by Forsthoff, Goeckermann, and Naumann[10] would require a basic 2^1-2^2 cascade. This correlation has a value of -0.0714 for A_2 which is in decided disagreement with the experimental value (see Table I).

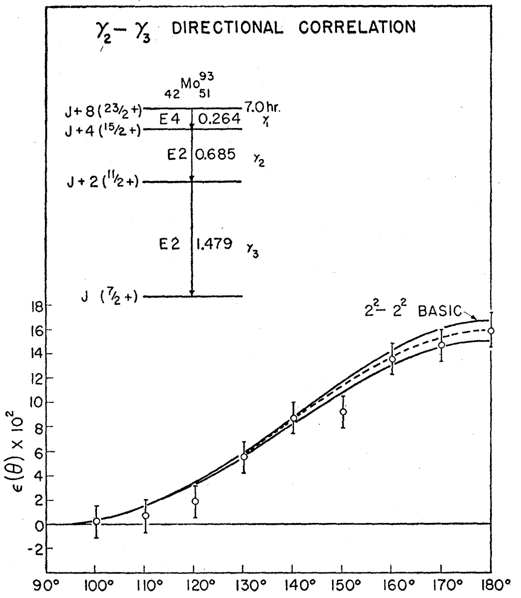

FIG. 1. The decay scheme of Mo^{93m} [See M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952)] and the directional correlation measurements between the 0.685- and 1.479-Mev γ rays. The corrected least-squares curve (dashed) is to be compared with the theoretical one.

The second correlation studied was that between γ_1 and γ_2. For this, two differential pulse-height discriminators were used in conjunction with the usual coincidence circuit. The channels were positioned to cover the appropriate photo peaks. The results are shown in Fig. 2. The experimental points have been corrected for contributions from the other possible

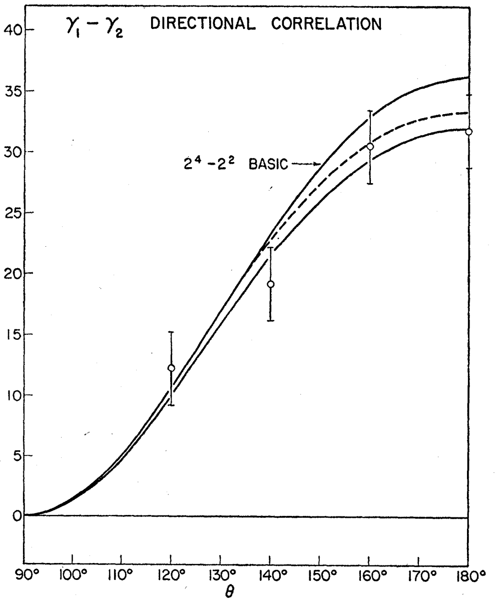

FIG. 2. The directional correlation measurements between the 0.264- and the 0.685-Mev γ rays.

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[7] D. T. Stevenson and M. Deutsch, Phys. Rev. **83**, 1202 (1951).

[8] J. S. Lawson Jr., and H. Frauenfelder Phys. Rev. **91**, 648 (1953).

[9] S. P. Lloyd, Phys. Rev. **83**, 716 (1951). As defined by Lloyd, "basic" correlations are of the type:

$$J\pm l_1 \xrightarrow{2^{l_1}} J \xrightarrow{2^{l_2}} J\mp l_2.$$

The coefficients for such correlations are independent of J.

[10] Forsthoff, Goeckermann, and Naumann, Phys. Rev. **90**, 1004 (1953).

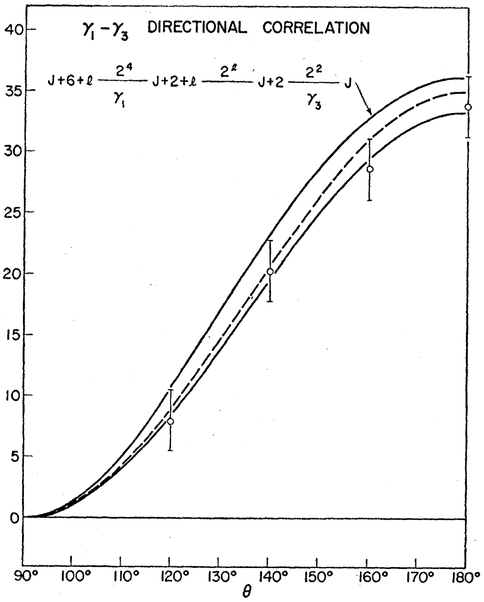

FIG. 3. The directional correlation measurements between the 0.264- and 1.479-Mev γ rays.

coincidence events due to a portion of the Compton distribution being under the photo peak of a lower energy γ ray. It will be shown later that the $\gamma_1-\gamma_3$ cascade has the identical correlation as $\gamma_1-\gamma_2$. Thus, the correction only involved the contribution from the $\gamma_2-\gamma_3$ cascade, and this amounted approximately to a six percent increase in the anisotropy.

The final dashed curve in Fig. 2 can be seen to be in agreement with the theoretical curve shown, which is that for a basic 2^4-2^2 correlation.[11] These data then characterize the spin changes and multipoles of the γ rays as

$$J+8 \xrightarrow{2^4} J+4 \xrightarrow{2^2} J+2 \xrightarrow{2^2} J,$$

which is quite consistent with the postulated assignments.[6]

As further verification of these assignments, the one-three directional correlation of γ_1 and γ_3 has been measured. For this measurement the channel for one counter was placed on the photo peak of the 0.264-Mev γ ray. The other counter was integrally biased at 0.800 Mev in addition to having 4.5 mm of Pb in front of it. The results are shown in Fig. 3. Here again the measured points have been corrected for a small contribution from the $\gamma_2-\gamma_3$ cascade. The explicit calculations of Arfken, Biedenharn, and Rose[12] for one-three correlations unfortunately do not include cases involving 2^4-pole radiation. Examination of their work indicated that basic one-three correlations were apparently not only independent of J, but when the intermediate transition is also basic, such correlations were identical to the corresponding one-two correlation.[13,‡] Thus in this case, the one-three correlation to be expected is just the basic 2^4-2^2 pole correlation as shown in Fig. 3. Such a correlation can be seen to be in agreement, within the uncertainty, with the measured points. This then is corroborative evidence for the spins indicated in Fig. 1.

In addition to demonstrating the feasibility of measuring a one-three directional correlation, it was hoped that such a measurement would establish the order of γ_2 and γ_3. There is some indirect evidence[14] that the order shown in Fig. 1 is correct and that order has been assumed in the above discussion. However, because of the basic nature of the transitions, the measurements reported here are independent of the order assumed for γ_2 and γ_3.

Internal conversion electron data[2,4,5,10] indicate that γ_1 is an $E4$ transition, which is in agreement with the directional correlation measurements. Inasmuch as the values of Z^2/E are low for γ_2 and γ_3, one must rely principally on conversion coefficients rather than the K/L ratios in determining the type of transition. The measured coefficients[10] are in satisfactory agreement with either $M1$ or $E2$ radiation.[15] The $E2$ assignment is shown in Fig. 1 because the results reported here indicate both γ rays are 2^2-pole.

A summary of the numerical results for the three directional correlation measurements is shown in Table I. The fact that the three corrected experimental curves all fall slightly below the theoretical curves is perhaps an indication that the correlations are being attenuated by extra-nuclear fields or that small amounts of mixtures of radiations are present.

In the light of Goldhaber's[6] "core isomerism" and the data reported here, a study of the energies and spins of the levels of Mo^{92} would be particularly interesting.

I am indebted to M. Goldhaber for suggesting the problem and for helpful discussions and to J. Weneser and M. Fuchs for considerations of the one-three directional correlation. Thanks are also due W. M. Harris, C. P. Baker, and the cyclotron crew for numerous irradiations and to J. Hudis for performing the equally numerous chemical separations.

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[11] Apparently the value of A_4 for this correlation in Lloyd's tables[9] is in error by a factor of 10. The correct value being -0.0180 instead of the listed value -0.0018.

[12] Arfken, Biedenharn, and Rose, U. S. Atomic Energy Commission Document ORNL 1103, 1952 (unpublished).

[13] It has been shown [J. Weneser and D. R. Hamilton, following paper, Phys. Rev. **92**, 321 (1953)] that for a series of basic transitions of any character such that the spins of the levels form a monotonic sequence, the correlation depends only on the character of the particular radiations being measured.

‡ *Note added in proof.*—It has been pointed out by M. E. Rose that numerical results for any one-three angular correlation can be obtained by using Eq. (141) in the paper of Biedenharn and Rose, Revs. Modern Phys. (to be published) in conjunction with tables of Racah coefficients.

[14] Based on the assumption of "core isomerism" and the energy expected for the first excited state of Mo^{92} [G. Scharff-Goldhaber, Phys. Rev. **90**, 587 (1953)], γ_3 should be the 1.479-Mev transition.

[15] Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **83**, 79 (1951).