Coulomb Excitation of Second 2^+ States in Even-Even Medium Weight Nuclei

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The location of a second 2^+ state has been found for thirteen even-even medium-weight nuclei by means of Coulomb excitation produced by 8-, 9-, and 10-Mev α particles. The relatively weak excitation of these states is detected by a coincident measurement of the cascade gamma rays. From the observed gamma-ray yields, information is obtained on the $B(E2)$'s for the crossover transitions. The cross over $B(E2)$'s exhibit some uniformity and are all rather weak, being about single-particle value or a little less. For some nuclei the cascades/crossovers ratio for the second 2^+ state is known from other work, and it is then possible to extract the $B(E2)$ for the upper cascade transition. These upper cascade $B(E2)$'s exhibit enhancements comparable to those for the lower cascade transitions. Evidence is obtained for the "double $E2$" Coulomb excitation of the 4^+ state in Cd^{114} and this requires an enhanced $4\rightarrow 2$ $B(E2)$. In general, the measurements reported support a collective model interpretation, but it is as yet difficult to draw conclusions concerning the shape of the collective potential energy surface governing this motion.

I. INTRODUCTION

THE Coulomb excitation of an even-even nucleus primarily involves the excitation of the first 2^+ state. The strong excitations of the first 2^+ states of medium-weight nuclei have allowed the systematic determination of the position of the first 2^+ state together with fairly accurate measurements of the associated $B(E2)$.[1–3] The observed large enhancements of the values for $B(E2)$ over that expected for a single-particle transition naturally suggested a collective motion interpretation of these states. Several authors[3–5] have pointed out the close correlation of the enhancement of the $B(E2)$ and the associated energy of the first 2^+ state.

Several years ago Scharff-Goldhaber and Weneser[6] pointed out certain regularities exhibited by the low-lying levels of even-even medium weight nuclei. The systematic trends in the ratios of the level positions, spins of the second excited states and the relative transition rates for the competing modes of decay of the second 2^+ state led to the proposal that these excited states result from a collective motion which generates "near harmonic" spectra. They suggested a vibrational model based on the collective theory of Bohr and Mottelson[7] which might account for the observed properties of the states.

This vibrational model predicted that at roughly twice the excitation energy of the first 2^+ state there should be close-lying triplet of states of the type 0^+, 2^+, and 4^+. Essentially no information was available on the existence of these triplets. However, the lack of evidence did not necessarily contradict the model because, at the time, most of the knowledge of these states was based on excitation by beta decay with its concomitant strong selection rules. Furthermore, if in a given case, beta decay did appreciably excite a second member of the triplet, this fact might have been missed because of limited experimental resolution. Recently an example of such a case has been found (see below).[8]

The first evidence for the existence of states which could be associated with the predicted triplet was found in the nucleus Cd^{114}. This evidence came from work on the decay scheme of In^{114} and the work of Motz[9] on the γ-ray spectra following neutron capture in Cd^{113}. Four states were identified in the energy region at twice the excitation of the first 2^+ state, and three of these could be characterized as 0^+, 2^+, and 4^+.

Goldhaber and Kraushaar[10] pointed out that the second 2^+ state of vibrational type nuclei systematically exhibits a peculiar decay from the point of view of the single-particle transition rates. Both the crossover $E2$ and the cascade $M1$ transitions are highly unfavored compared to the cascade $E2$ transition. This behavior was qualitatively explained by the vibrational model. The vibrational model also made the quantitive prediction that the ratio, $R=B(E2,2'\rightarrow 2)/B(E2,2\rightarrow 0)$ should be equal to 2.[11] (Here $2'$ designates the second 2^+ state.) For medium-weight nuclei no information was available on this ratio and there were no absolute values for the crossover $B(E2)$ and the cascade $B(M1)$.

Several other types of collective motion have been proposed to account for "near harmonic" spectra. Wilets and Jeans[12] studied the case of nuclei characterized by fixed total deformation but with unstable shape

[1] The $B(E2)$ is the reduced electromagnetic quadrupole transition rate. See review article of K. Alder *et al.*, Rev. Modern Phys. **28**, 432 (1956).
[2] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).
[3] P. H. Stelson and F. K. McGowan, Phys. Rev. **110**, 489 (1958).
[4] C. F. Coleman, Nuclear Phys. **7**, 488 (1958).
[5] D. M. Van Patter, Bull. Am. Phys. Soc. 3, 360 (1958).
[6] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).
[7] A. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **26**, No. 14 (1952); A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).
[8] R. L. Robinson, F. K. McGowan, and W. G. Smith, Bull. Am. Phys. Soc. 4, 279 (1959).
[9] H. T. Motz, Phys. Rev. **104**, 1353 (1956).
[10] J. J. Kraushaar and M. Goldhaber, Phys. Rev. **89**, 1081 (1953).
[11] D. C. Choudhury, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **28**, No. 4 (1954).
[12] L. Wilets and M. Jeans, Phys. Rev. **102**, 788 (1956).

(γ-unstable nuclei). The predicted properties are quite similar to those of the weak-coupling case considered by Scharff-Goldhaber and Weneser. On this model one expects a triplet of 0^+, 2^+, and 4^+ states at roughly twice the energy of the first 2^+ state. The quantity R is again predicted to be 2. The similarities in the predictions of these two models make it difficult to find experimental evidence favoring one over the other.

Raz has reported calculations using two equivalent particles and adding surface effects to the two-body interaction.[13] The effects of increasing the strength of the surface interaction and of increasing the strength of the two-particle interaction are studied. According to these calculations, in the region of about twice the energy of the first 2^+ state there should be a doublet of 2^+ and 4^+ character. The 0^+ state is considerably higher in energy. The quantity R varies with coupling strength but never exceeds the value 1. Raz also made some quantitative calculations concerning the crossover $E2$ and the cascade $M1$ decay of the second 2^+ state.

Davydov and Filippov have suggested that "near harmonic" spectra can result from the rotation of nonaxially symmetric nuclei.[14] From the observed energy separation of the states one can obtain the value of γ for the nucleus. With this value for γ one makes quantitative predictions for R and for the ratio of cascade to crossover $B(E2)$'s for the second 2^+ state. A triplet of states is not predicted by this model; in the energy region at twice the excitation of the first 2^+ state one expects a 2^+ state and, somewhat higher, a 4^+ state.

In general, one expects that the Coulomb excitation of the second 2^+ state is quite weak compared to the excitation of the first 2^+ state, both because the cross section decreases rapidly with increasing excitation energy and because the cross section depends directly on the crossover $B(E2)$ which is expected to be small. Even under favorable conditions for excitation, we have not been able to obtain evidence for the excitation of second 2^+ states by direct examination of gamma-ray spectra. However, by making a coincidence measurement on the cascade gamma rays, one can achieve a considerable increase in sensitivity and by this method it has proved possible to measure the Coulomb excitation of the second 2^+ state.[15]

The simplest information one extracts from these Coulomb excitation measurements is the location of the second 2^+ state. The location of this state was not known for most of the nuclei studied. This information combined with available data of 0^+ and 4^+ states provides evidence on the possible existence and quality of doublets or triplets. In addition, from the measured cross section, one can extract values for $B(E2)$ and $B(M1)$ for transitions involving the second 2^+ state. The above discussion shows that such information may be useful in testing the degree of validity of the different proposed types of collective motion.

II. EXPERIMENTAL METHOD

A schematic diagram of the experimental arrangement is given in Fig. 1. The two gamma-ray detectors

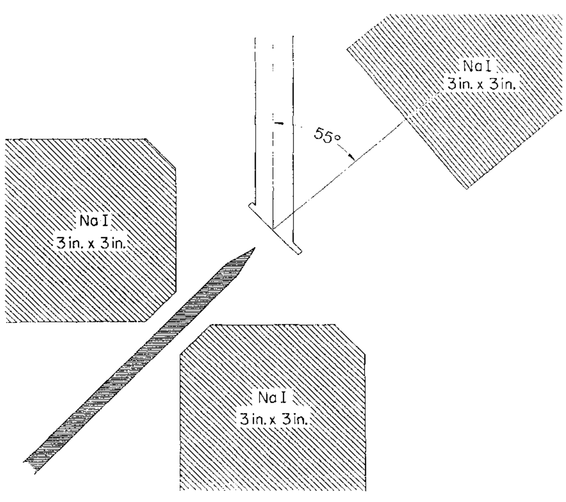

FIG. 1. Schematic diagram of the experimental arrangement. The bevelled 3-in.×3-in. NaI crystal detector located at 90° to the beam direction detected the upper cascade γ ray. The detector located at 0° detected the lower cascade γ ray. The detector located in the upper right corner was not used in this experiment.

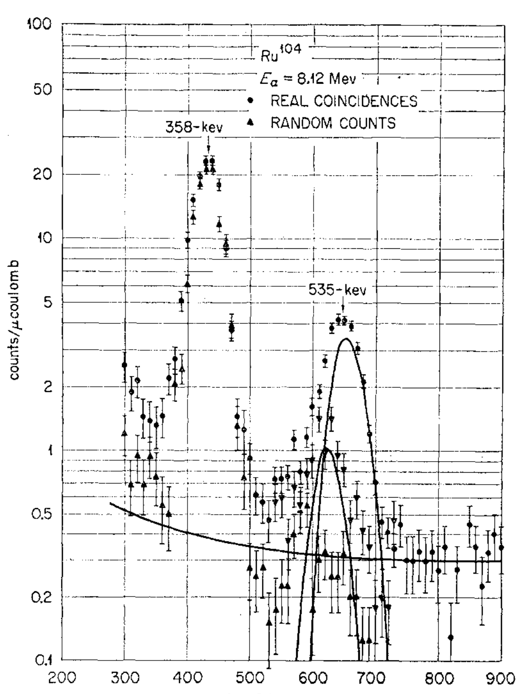

FIG. 2. Coincidence spectrum for Ru^{104}. The solid circles show the gross coincidence spectrum. The solid triangles show the random spectrum. See Sec. II-3 of text for discussion of the spectrum.

[13] B. James Raz, Phys. Rev. 114, 1116 (1959).

[14] A. S. Davydov and G. F. Filippov, Nuclear Phys. 8, 237 (1958).

[15] A preliminary report of this work is given by the authors in Bull. Am. Phys. Soc. 2, 267 (1957).

are 3×3-in. NaI(Tl) cylindrical crystals. For most of the measurements, bevelled crystals were used to obtain higher efficiencies by increasing the solid angle. The distance from the source of γ rays to the front face of the crystal is 4 cm. The tapered lead shield was placed between the crystals to reduce background coincidences resulting from Compton scattering of gamma rays from one crystal to the other.

The strong Coulomb excitation of the first 2^+ state is one of the difficulties in this experiment. A low coincidence rate results from the fact that the electronic equipment processes a maximum of 2×10^4 pulses/sec and most of these pulses result from γ rays from excitation of the first 2^+ state. To alleviate this drawback, it is desirable to choose projectiles with energies large compared to the energies of the excited states. Protons of the required high energy are not suitable because they easily penetrate the Coulomb barrier and produce troublesome compound nucleus reactions. We therefore used α particles for excitation. The ORNL 5.5-Mv Van de Graaff accelerator was used to accelerate doubly-ionized helium ions to energies of 8 to 10 Mev.

In all cases, the targets used were prepared from enriched isotopes. Most of the targets had been made previously to measure the Coulomb excitation of the first 2^+ state. The preparation of these targets has been described.[3]

A fast-slow coincidence circuit was used with resolving time, 2τ, of either 0.12 μsec or 0.06 μsec. Pulses from the detector located at 0° to the α-particle beam were fed into a single-channel analyzer whose window was placed on the full energy peak of the γ ray resulting from the decay of the first 2^+ state. The coincidence spectrum from the detector located at 90° to the beam was displayed on a multichannel analyzer. Initially a sliding 20-channel analyzer was used. Later, a considerable improvement was made when a full 120-channel analyzer became available.

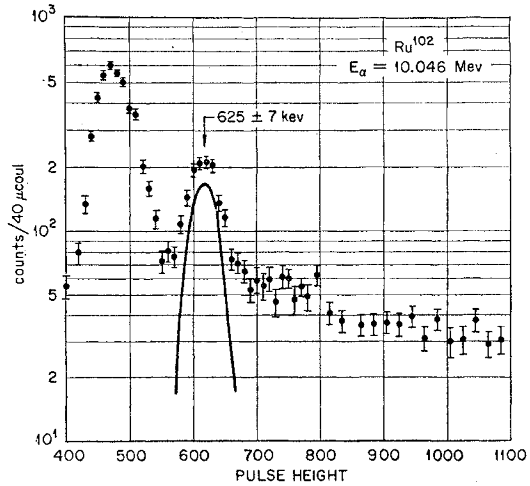

FIG. 3. Coincidence spectrum for Ru^{102}. See Sec. II-3 of text for discussion of the spectrum.

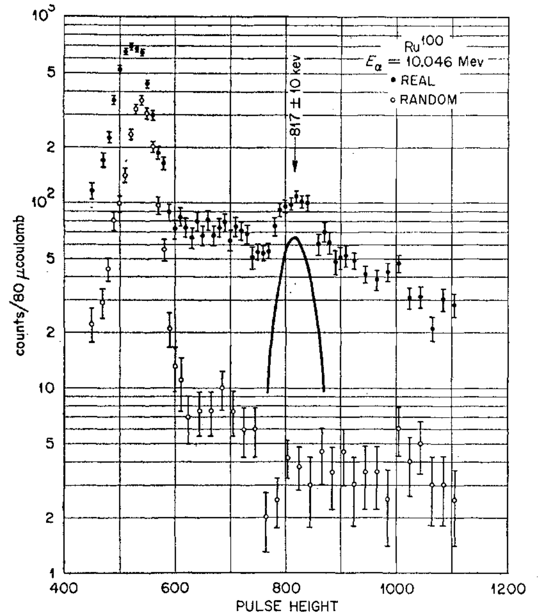

FIG. 4. Coincidence spectrum for Ru^{100}. See Sec. II-3 of text for discussion of the spectrum.

1. Gamma-Ray Spectra

Typical coincidence spectra are shown for each of the 13 nuclei studied in Figs. 2 through 13. In each case there is, in addition to the strong chance coincidence peak located at the energy of the first 2^+ state, a true coincidence peak which results from the weak excitation of the second 2^+ state. The energies of the observed

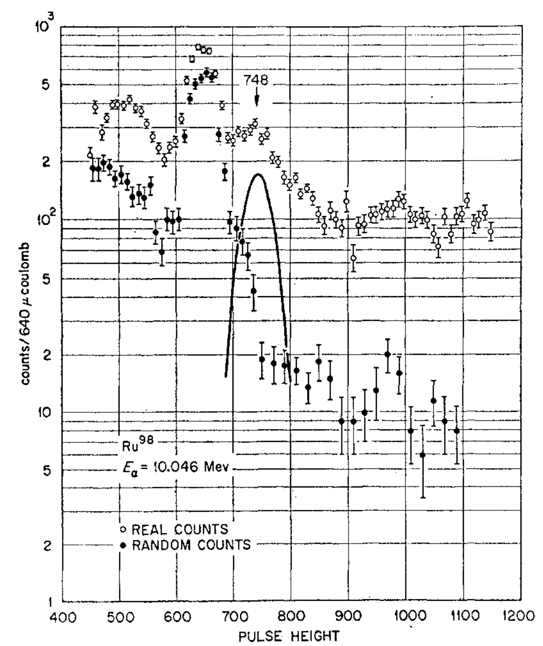

FIG. 5. Coincidence spectrum for Ru^{98}. See Sec. II-3 of text for discussion of the spectrum.

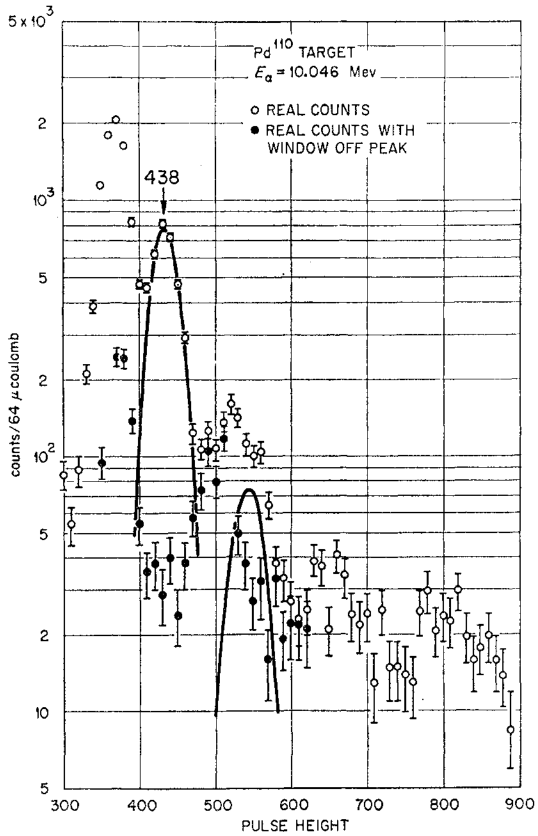

FIG. 6. Coincidence spectrum for Pd[110]. See Sec II-3 of text for discussion of the spectrum.

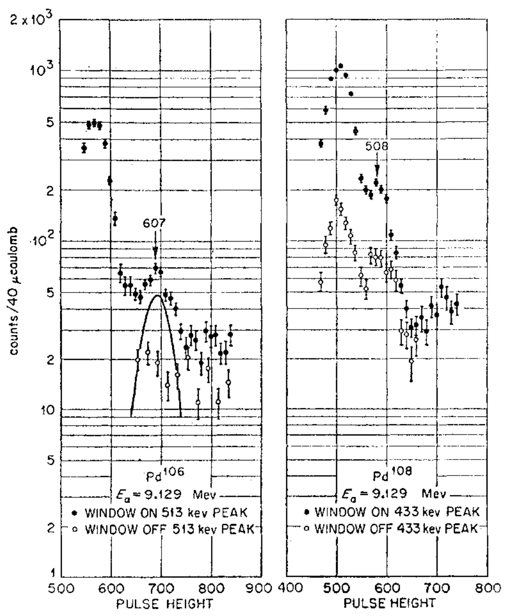

FIG. 7. Coincidence spectra for Pd[108] and Pd[106]. See Sec. II-3 of text for discussion of the spectra.

gamma rays and the associated errors (regarded as standard deviations) are listed in Table I. Cd[112] and Cd[114] exhibit two higher 2^+ states as shown in the spectra and table. The detailed discussion of each of these nuclei is deferred to Sec. II-3 on individual cases.

The observed number of Coulomb excitations of the second 2^+ state is given in Column 4 of Table II for the corresponding α-particle energy listed in Column 3. Targets were used which were thick to the incident α particles. Since the experiment does not measure the yield of the crossover gamma rays, the listed numbers are the *partial* number of excitations which result from the cascade decay of the second 2^+ state. Furthermore,

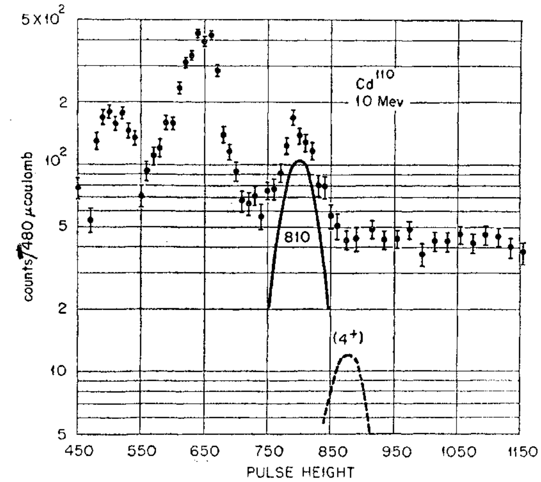

FIG. 8. Coincidence spectrum for Cd[110]. See Sec. II-3 of text for discussion of the spectrum.

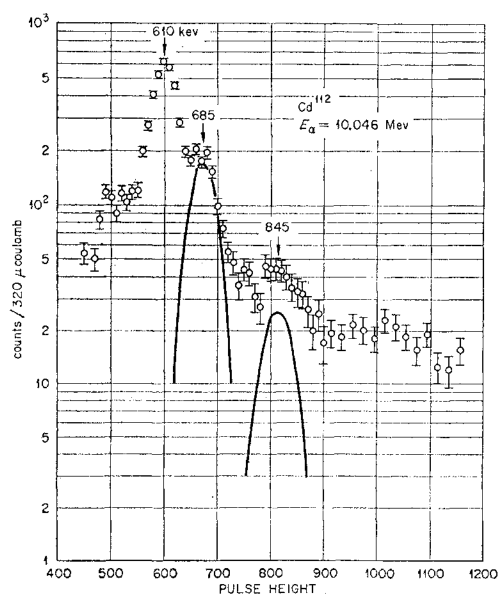

FIG. 9. Coincidence spectrum for Cd[112]. See Sec. II-3 of text for discussion of the spectrum.

an isotropic γ-ray correlation is assumed in obtaining the numbers listed. Estimates of the possible error resulting from this assumption are discussed below.

2. Extraction of $\varepsilon B(E2)_{ex}$

For most of the nuclei investigated, the γ-ray yield was measured at several α-particle energies to determine whether the yield varied correctly for the Coulomb excitation process. We shall initially assume that the excitation of the second 2+ state is caused solely by direct $E2$ excitation *via* the crossover transition. The theoretical thick-target Coulomb excitation integrals are given

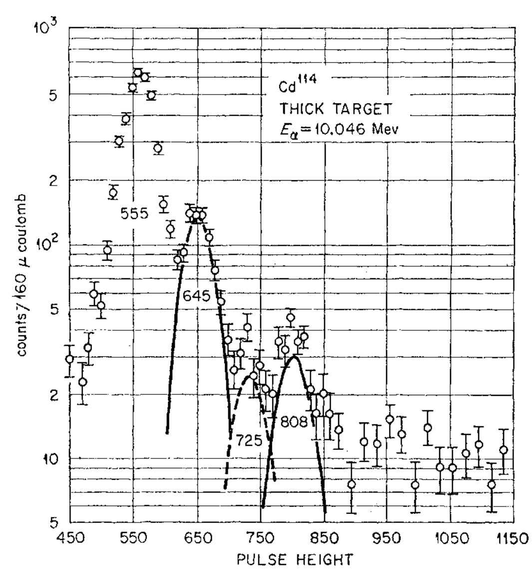

FIG. 10. Coincidence spectrum for Cd^{114}. See Sec. II-3 of text for discussion of the spectrum.

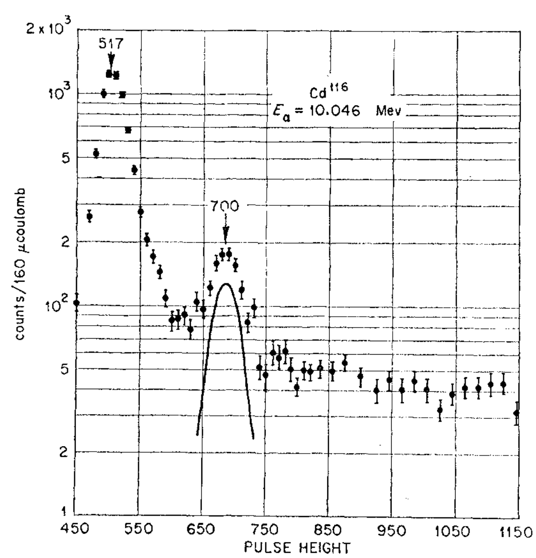

FIG. 11. Coincidence spectrum for Cd^{116}. See Sec. II-3 of text for discussion of the spectrum.

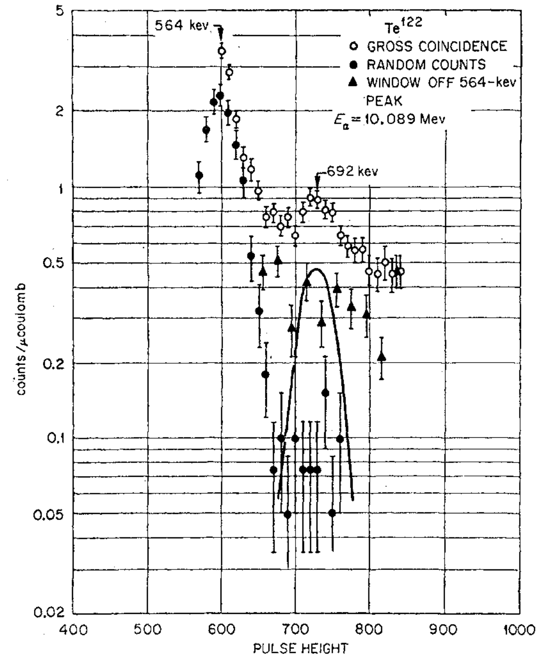

FIG. 12. Coincidence spectrum for Te^{122}. See Sec. II-3 of text for discussion of the spectrum.

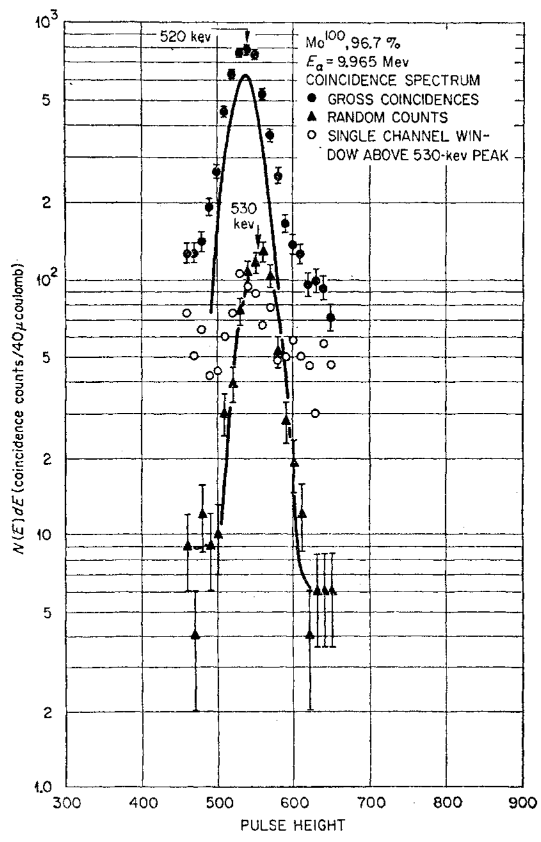

FIG. 13. Coincidence spectrum for Mo^{100}. See Sec. II-3 of text for discussion of the spectrum.

TABLE I. Summary of observed gamma-ray energies. Column 1 lists the nucleus. Column 2 gives the energy of the first 2^+ state γ ray. Column 3 gives the energy of the upper cascade γ ray. The last column lists the energy of the second (or third) 2^+ state.

(1) Nucleus	(2) E_1 (kev)	(3) E_2 (kev)	(4) (E_1+E_2) (kev)
Mo^{100}	530±5	520±5	1050±7
Ru^{98}	654±6	748±10	1402±12
Ru^{100}	540±5	817±10	1357±11
Ru^{102}	475±5	625±7	1100±9
Ru^{104}	358±3	535±6	893±7
Pd^{106}	513±5	607±7	1120±8
Pd^{108}	433±4	508±6	941±7
Pd^{110}	374±4	438±6	812±7
Cd^{110}	656±6	810±10	1466±12
Cd^{112}	610±6	685±10	1295±12
		845±12	1455±14
Cd^{114}	555±5	645±8	1200±10
		808±12	1363±13
Cd^{116}	517±5	700±10	1217±11
Te^{122}	564±5	692±10	1256±11

in Column 5 of Table II in the units [kev×mg/cm^2]. The quantity $\epsilon B(E2)_{\rm ex}$, which is essentially obtained from Columns 4 and 5, is given in the last column of Table II. The formulas used to obtain the quantities listed in Columns 5 and 6 are given in a previous paper.[3] The quantity ϵ is defined as the ratio [cascades/(cascades+crossovers)]. Since the number of crossover decays is not measured, ϵ is, in general, not known unless determined by another experiment such as radioactive decay measurements. The errors listed for $\epsilon B(E2)_{\rm ex}$ are not the absolute errors but include only the errors entering into the relative measurement at different α-particle energies since here we want to determine whether the $\epsilon B(E2)_{\rm ex}$ for a given nucleus remains constant within the relative errors at different bombarding energies. In some cases there are two entries with almost the same α-particle energies; these represent different runs separated by several months.

The observed general constancy of the $\epsilon B(E2)_{\rm ex}$ with changing α-particle energy indicates that to within the accuracy of the measurements the excitations agree with the theoretical variation for the Coulomb excitation process. In Table III we list our best values for the $\epsilon B(E2)_{\rm ex}$ for each transition. The errors given in Table III include all sources of error which enter under the assumption that the observed γ-ray yields result solely from crossover $E2$ Coulomb excitation as outlined above. However, the errors cannot be considered absolute errors because of possible uncertainties arising from an oversimplification of the interpretation of the γ-ray yields. Three possible sources of systematic errors are (1) contribution to γ-ray yield via compound nucleus inelastic scattering, (2) complications from a competing "double $E2$" mode of Coulomb excitation, and (3) neglect of the angular correlation of the cascade γ rays.

A. Compound Nucleus Contribution

A theoretical estimate of the compound nucleus cross section as a function of α-particle energy is shown in Fig. 14 for the representative nucleus Ru^{104}. This estimate is taken from the work of Igo[16] which assumes an optical model potential obtained from the analysis of elastic scattering data. Igo's cross sections are larger than the theoretical values given by Blatt and Weisskopf.[17] However, recent experimental information confirms the large values of Igo.[16,18]

The cross-section curve for the direct $E2$ Coulomb excitation of the second 2^+ state of Ru^{104} is also given in Fig. 14. It is clear that the variation with α-particle energy is quite different for the two processes; at 8 Mev the Coulomb excitation cross section is larger than $\sigma_{\rm comp}$ by a factor of 2, whereas at 10 Mev the $\sigma_{\rm comp}$ is 10 times larger than the Coulomb excitation cross section. We believe the general background level of our coincidence spectra may be evidence for the existence of compound nucleus reactions. The background level is considerably higher than the random rate. This background level rises rapidly with increasing α-particle energy; at 11 Mev the peak to background rate is less favorable than at lower energies.

However, the quantity of direct interest here is not $\sigma_{\rm comp}$ but the possible contribution to the excitation of the second 2^+ state from inelastic compound nucleus scattering. A previous theoretical estimate of this partial cross section, $(\alpha,\alpha'\gamma)$, for the excitation of the first 2^+ state in Sn^{120} indicates that this mode of decay is extremely unfavored compared to the (α,γ), (α,p) and (α,n) processes.[3] Furthermore, one expects the $(\alpha,\alpha'\gamma)$ process to vary even more rapidly with α-particle energy than does the compound nucleus reaction since this reaction essentially depends on the product of two α-particle penetrabilities rather than directly on the α-particle penetrability. Since the observed variations in γ-ray yields fit well with the much less rapidly varying Coulomb excitation cross section, this is strong evidence that the contribution via compound nucleus reactions is not a significant part of the observed γ-ray yields. To illustrate this, we point out that if one takes the cross section for the $(\alpha,\alpha'\gamma)$ to have the same shape as the compound nucleus cross section given in Fig. 14, then the number of excitations of the second 2^+ state in Ru^{104} (thick target) would have increased by over 100 times in changing the α-particle energy from 8 to 10 Mev. Actually, the yield increased a factor of 4.15±0.45 which is in good agreement with the theoretical factor of 4.6 for Coulomb excitation.

B. "Double E2" Coulomb Excitation

In addition to the direct excitation of the second 2^+ state by means of the crossover $E2$ transition, an alternative second-order Coulomb excitation mechanism known as "double $E2$" excitation may produce excita-

[16] G. Igo, Phys. Rev. **115**, 1665 (1959).
[17] J. M. Blatt and V. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, New York, 1952).
[18] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. 4, 266 (1960).

TABLE II. Summary of information on the observed number of Coulomb excitations and the corresponding $\epsilon B(E2)_{ex}$. Columns 1 and 2 list the nucleus and the observed energy of the second 2^+ state. Column 4 lists the observed number of excitations per 6.24×10^{12} incident α particles with corresponding energies listed in Column 3. The numbers given in Column 4 are for the *partial* number of excitations of the second 2^+ state which decay by cascade emission since this is the quantity measured experimentally. Column 5 lists the theoretical thick target Coulomb excitation integral in (kev×mg/cm²). Column 6 lists the quantity $\epsilon B(E2)_{ex}$ in cm⁴ (see text).

(1) Nucleus	(2) E (kev)	(3) E_α (Mev)	(4) I	(5) Y	(6) $\epsilon B(E2)_{ex}$
Mo^{100}	1050	8.013	$(1.91\pm0.19)\times10^4$	2.88×10^3	$(1.97\pm0.20)\times10^{-50}$
		8.996	$(3.72\pm0.45)\times10^4$	7.73×10^3	$(1.43\pm0.17)\times10^{-50}$
		9.965	$(1.03\pm0.09)\times10^5$	1.65×10^4	$(1.86\pm0.17)\times10^{-50}$
Ru^{104}	893	8.124	$(2.16\pm0.20)\times10^4$	5.78×10^3	$(1.29\pm0.12)\times10^{-50}$
		9.129	$(4.67\pm0.30)\times10^4$	1.35×10^4	$(1.19\pm0.08)\times10^{-50}$
		10.133	$(8.97\pm0.50)\times10^4$	2.68×10^4	$(1.15\pm0.06)\times10^{-50}$
Ru^{102}	1100	8.124	$(7.19\pm0.50)\times10^3$	2.22×10^3	$(1.12\pm0.08)\times10^{-50}$
		9.129	$(1.98\pm0.14)\times10^4$	6.40×10^3	$(1.06\pm0.08)\times10^{-50}$
		10.133	$(5.22\pm0.30)\times10^4$	1.44×10^4	$(1.25\pm0.07)\times10^{-50}$
		10.046	$(4.82\pm0.30)\times10^4$	1.35×10^4	$(1.23\pm0.07)\times10^{-50}$
Ru^{100}	1357	9.129	$(1.06\pm0.22)\times10^4$	2.33×10^3	$(1.57\pm0.33)\times10^{-50}$
		10.133	$(2.45\pm0.40)\times10^4$	6.34×10^3	$(1.33\pm0.22)\times10^{-50}$
		10.046	$(1.77\pm0.18)\times10^4$	5.85×10^3	$(1.05\pm0.10)\times10^{-50}$
Ru^{98}	1402	10.046	$(7.50\pm0.75)\times10^3$	4.96×10^3	$(0.52\pm0.05)\times10^{-50}$
Pd^{110}	812	8.124	$(1.69\pm0.20)\times10^4$	7.21×10^3	$(0.92\pm0.11)\times10^{-50}$
		9.129	$(3.74\pm0.35)\times10^4$	1.65×10^4	$(0.90\pm0.09)\times10^{-50}$
		10.133	$(7.45\pm0.90)\times10^4$	3.17×10^4	$(0.93\pm0.11)\times10^{-50}$
		10.046	$(7.33\pm0.37)\times10^4$	3.01×10^4	$(0.96\pm0.05)\times10^{-50}$
	926	10.046	$(8.10\pm1.2)\times10^3$	2.14×10^4	$(0.15\pm0.02)\times10^{-50}$
Pd^{108}	941	8.124	$(6.03\pm1.5)\times10^3$	4.03×10^3	$(0.59\pm0.15)\times10^{-50}$
		9.129	$(2.10\pm0.40)\times10^4$	1.03×10^4	$(0.80\pm0.15)\times10^{-50}$
		10.133	$(4.38\pm0.90)\times10^4$	2.14×10^4	$(0.81\pm0.17)\times10^{-50}$
Pd^{106}	1120	9.129	$(1.54\pm0.23)\times10^4$	5.19×10^3	$(1.17\pm0.28)\times10^{-50}$
		10.133	$(3.16\pm0.60)\times10^4$	1.22×10^4	$(1.03\pm0.20)\times10^{-50}$
Cd^{116}	1217	8.124	$(3.23\pm0.75)\times10^3$	8.75×10^2	$(1.68\pm0.40)\times10^{-50}$
		9.129	$(9.18\pm2.30)\times10^3$	3.04×10^3	$(1.37\pm0.25)\times10^{-50}$
		10.133	$(2.14\pm0.42)\times10^4$	7.94×10^3	$(1.22\pm0.24)\times10^{-50}$
		10.046	$(1.90\pm0.14)\times10^4$	7.37×10^3	$(1.18\pm0.09)\times10^{-50}$
Cd^{114}	1200	9.129	$(5.96\pm0.40)\times10^3$	3.83×10^3	$(0.71\pm0.05)\times10^{-50}$
		10.133	$(1.59\pm0.11)\times10^4$	8.38×10^3	$(0.86\pm0.06)\times10^{-50}$
		10.046	$(1.34\pm0.08)\times10^4$	7.76×10^3	$(0.79\pm0.05)\times10^{-50}$
	1363	10.133	$(4.38\pm0.65)\times10^3$	4.62×10^3	$(0.43\pm0.06)\times10^{-50}$
		10.046	$(4.23\pm0.42)\times10^3$	4.26×10^3	$(0.45\pm0.05)\times10^{-50}$
Cd^{112}	1295	10.133	$(1.08\pm0.25)\times10^4$	5.97×10^3	$(0.82\pm0.19)\times10^{-50}$
		10.046	$(1.14\pm0.07)\times10^4$	5.52×10^3	$(0.93\pm0.06)\times10^{-50}$
	1455	10.133	$(2.70\pm0.40)\times10^3$	3.43×10^3	$(0.36\pm0.05)\times10^{-50}$
		10.046	$(2.34\pm0.23)\times10^3$	3.13×10^3	$(0.34\pm0.03)\times10^{-50}$
Cd^{110}	1466	10.133	$(9.26\pm2.10)\times10^3$	3.06×10^3	$(1.38\pm0.31)\times10^{-50}$
		10.046	$(8.85\pm0.90)\times10^3$	2.69×10^3	$(1.49\pm0.16)\times10^{-50}$
Te^{122}	1256	9.112	$(5.34\pm1.10)\times10^3$	1.82×10^3	$(1.77\pm0.36)\times10^{-50}$
		10.089	$(1.48\pm0.30)\times10^4$	5.08×10^3	$(1.77\pm0.36)\times10^{-50}$

tions of the second 2^+ state. This mechanism is discussed by Alder *et al.*[19] An approximate theoretical expression for the cross section is

$$\sigma_{E2,E2}=0.0272a^{-2}\sigma_{E2}(0\rightarrow 2)\sigma_{E2}(2\rightarrow 2'), \qquad (1)$$

where $2a$ is the distance of closest approach in a head-on collision. The cross section $\sigma_{E2}(0\rightarrow 2)$ is that for Coulomb excitation of the first 2^+ state. The cross section $\sigma_{E2}(2\rightarrow 2')$ is that for exciting the nucleus from the first 2^+ to the second 2^+ state.

One faces two problems in trying to assess the importance of the "double $E2$" excitation; the first is the meager knowledge of the general reliability of the theoretical estimate for the process and the second arises from the circumstance that the cross sections for direct and "double $E2$" excitation directly depend on the quantities $B_{E2}(0\rightarrow 2')$ and $B_{E2}(2\rightarrow 2')$ which, at the outset, are not known and in fact are among the things

[19] K. Alder, A. Bohr, T. Huus, B. R. Mottelson, and A. Winther, Revs. Modern Phys. 28, 432 (1956).

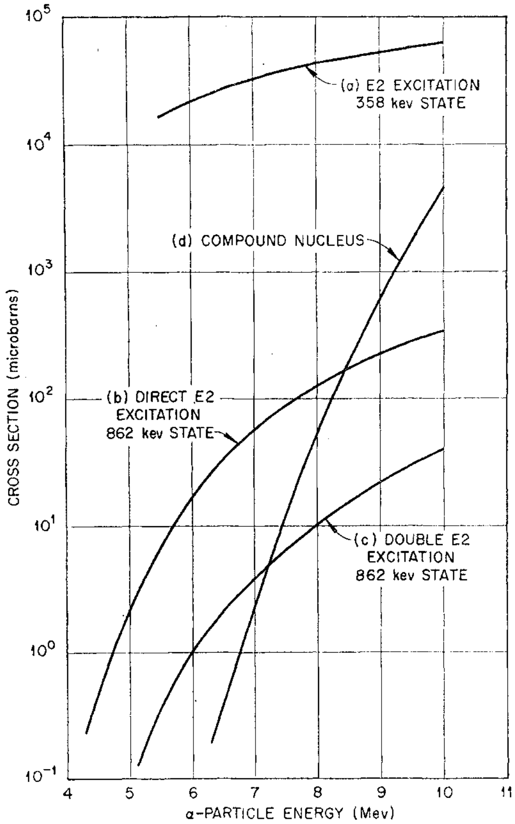

FIG. 14. Cross section curves for α-particle reactions on Ru^{104}. The curve labelled (a) is the cross section for excitation of the first 2^+ state at 358 kev. Curve (b) is the cross section for direct $E2$ excitation of the second 2^+ state at 862 kev. Curve (c) is the calculated cross section for "double $E2$" excitation of the second 2^+ state where the quantity R is taken to be 1. Curve (d) is the compound nucleus cross section obtained from Igo's calculations.

one is trying to extract from the measurements. There is one published measurement of "double $E2$" Coulomb excitation. Newton and Stephens,[20] using oxygen ions of 30 to 80 Mev, excited the 4^+ rotational state in the even-even tugnsten nuclei. By making the reasonable assumption that the value for $B_{E2}(2\rightarrow 4)$ is predicted by the theory of rotational states from the known $B_{E2}(0\rightarrow 2)$, they found that their observed yield agreed to within about $\pm 15\%$ with a calculated yield based on the cross section given in formula (1).

The coincidence spectrum for Cd^{114} shown in Fig. 10 indicates a weak peak at 725 kev. We have observed this peak in several runs on Cd^{114}. This peak corresponds to the known decay of a 4^+ state in Cd^{114} at 1280 kev. An estimate of direct $E4$ Coulomb excitation indicates that an unreasonably large $B(E4)_{ex}$ is required to account for the observed intensity. We therefore have interpreted this excitation as "double $E2$" excitation. As mentioned above, the application of Formula (1) requires the knowledge of $B(E2, 2\rightarrow 4)_{ex}$. For Cd^{114} this quantity is not known. We have therefore, tentatively, taken $B(E2, 2\rightarrow 4)_{ex}=(18/25)B(E2, 0\rightarrow 2)_{ex}$ as predicted by the model of Goldhaber and Weneser.[6,11] An alternative value predicted by the Davydov-Filippov model in $B(E2, 2\rightarrow 4)=0.50B(E2, 0\rightarrow 2)_{ex}$.[21] The calculated coincidence peak for double $E2$ excitation of the 4^+ state is shown in Fig. 10 by the dashed peak. We conclude that to within the rough accuracy of the experiment ($\pm 50\%$) the predicted yield agrees with the observed yield. Although this check of the "double $E2$" cross section lacks accuracy, it has value because the excitation conditions are essentially identical to those for "double $E2$" excitation of the second 2^+ states.

We now proceed to use formula (1) to estimate the expected number of excitations of the second 2^+ state by "double $E2$" excitation. Since the $B(E2, 2\rightarrow 2')_{ex}$ is somewhat uncertain, we have initially taken

$$B(E2, 2'\rightarrow 2)/B(E2, 2\rightarrow 0)\equiv R=1.$$

This means $B(E2, 2\rightarrow 2')_{ex}=\frac{1}{5}B(E2, 0\rightarrow 2)_{ex}$ and the values for $B(E2, 0\rightarrow 2)_{ex}$ are taken to be those previously published.[3] One can then obtain the number of "double $E2$" excitations for some other value of R simply by multiplying our values by R. We list in Table IV calculated values for the number of excitations of the second 2^+ state by "double $E2$" for representative α-particle energies corresponding to those energies actually used for the measurements (see Table II).

An estimate of the importance of "double $E2$" excitation can now be made by comparing the numbers listed in Table IV to the observed number of excitations (cascade decay only) listed in Table II. The actual ratios are somewhat lower than the ratios obtained from the numbers in the two tables since the observed

TABLE III. Best values for $\epsilon B(E2)_{ex}$. The second column lists the observed excited state for the nucleus listed in Column 1. Column 3 lists the best values for $\epsilon B(E2)_{ex}$ on the assumptions discussed in the text. Column 4 lists an absolute percentage error for $\epsilon B(E2)_{ex}$ under the restrictive assumptions mentioned in the text.

(1) Nucleus	(2) E (kev)	(3) $\epsilon B(E2)_{ex}\times 10^{50}$ (cm⁴)	(4) Percentage error
Ru^{104}	893	1.19	8
Ru^{102}	1100	1.17	8
Ru^{100}	1357	1.16	12
Ru^{98}	1402	0.52	16
Pd^{110}	812	0.94	8
Pd^{108}	941	0.74	15
Pd^{106}	1120	1.08	21
Cd^{116}	1217	1.23	11
Cd^{114}	1200	0.79	8
Cd^{114}	1363	0.44	12
Cd^{112}	1295	0.91	10
Cd^{112}	1455	0.35	12
Cd^{110}	1466	1.47	13
Te^{122}	1256	1.77	25
Mo^{100}	1050	1.75	12

[20] J. O. Newton and F. S. Stephens, Phys. Rev. Letters 1, 63 (1958).

[21] A. S. Davydov and V. S. Rostovsky, Nuclear Phys. 12, 58 (1959).

excitations do not include crossover intensities whereas the numbers in Table IV are for total number of excitations. This comparison indicates that for the excitation conditions employed (8- to 10-Mev α particles) the "double $E2$" excitation of the second 2^+ state is a few percent of the observed excitation. Therefore, our original interpretation that the excitation of these states is by the crossover transition is roughly correct.

If it were just a matter of subtracting the "double $E2$" contribution from the observed yield to obtain a better value for the crossover $B(E2)$, a rather small, unimportant correction would be required. However, one expects that the two modes of excitation, crossover and "double $E2$," would be coherent. Consequently, the actual cross section for excitation of the second 2^+ state would be of the form

$$a^2+2ab\cos\theta+b^2, \tag{2}$$

where a^2 is the crossover excitation cross section, b^2 is the "double $E2$" excitation cross section, and $2ab\cos\theta$ is an interference term. At the present time, the phase θ is an unknown quantity. This coherence of the two modes of excitation makes the small admixture of "double $E2$" excitation a much more serious source of uncertainty since it produces an unknown interference term which is considerably larger than the "double $E2$" cross section. The uncertainty introduced by this interference term constitutes one of the principal sources of error for the quantities $B(E2, 2'\rightarrow 0)_d$ and $B(E2, 2'\rightarrow 2)$ obtained from our measurements. Since our errors are considered to be standard deviations, we have taken $\frac{2}{3}$ of the maximum value for the interference term as the error to be assigned to the $B(E2)$ from this source of uncertainty.

TABLE IV. The calculated number of "double $E2$" excitations are listed in Column 3 for the nuclei and α-particle energies listed, respectively, in Columns 1 and 2. We have taken $R=1$ (see text for R).

(1) Nucleus	(2) E_α (Mev)	(3) Excitations / 6.24×10^{12} α particles	(1) Nucleus	(2) E_α (Mev)	(3) Excitations / 6.24×10^{12} α particles
Ru^{104}	8.124	1.5×10^3	Cd^{116}	8.124	1.0×10^2
	9.129	4.2×10^3		9.129	3.7×10^2
	10.133	9.7×10^3		10.046	9.5×10^2
Ru^{102}	8.124	5.2×10^2	Cd^{114}	9.129	3.4×10^2
	9.129	1.9×10^3		10.046	8.6×10^2
	10.133	4.1×10^3			
			Cd^{112}	10.046	6.5×10^2
Ru^{100}	9.129	5.4×10^2			
	10.046	1.4×10^3	Cd^{110}	10.046	3.7×10^2
Ru^{98}	10.046	8.6×10^2	Te^{122}	9.112	1.8×10^2
				10.089	5.4×10^2
Pd^{110}	8.124	1.1×10^3			
	9.129	3.0×10^3	Mo^{100}	8.013	5.2×10^2
	10.046	6.4×10^3		8.996	1.6×10^3
				9.965	3.8×10^3
Pd^{108}	8.124	5.4×10^2			
	9.129	1.9×10^3			
	10.133	4.0×10^3			
Pd^{106}	9.129	9.4×10^2			
	10.133	2.1×10^3			

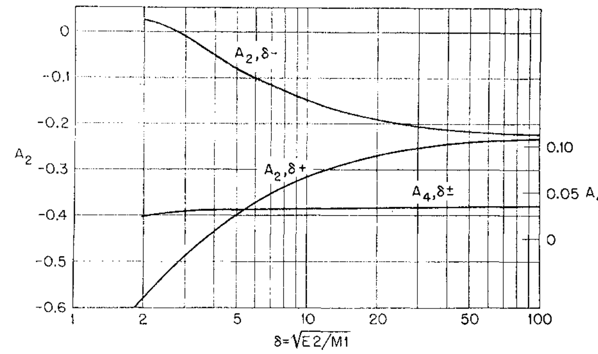

FIG. 15. Expected coefficients A_2 and A_4 as a function of $\delta[=(E2/M1)^{\frac{1}{2}}]$ for ideal geometry for the triple correlation $W(\theta)=1+A_2P_2+A_4P_4$. θ is the angle between the detector fixed at 0° and the second detector. For our case $\theta=90°$. δ refers to the upper cascade transition.

C. Angular Correlation

The coincident cascade γ rays have an angular correlation which might introduce significant errors in the values for $B(E2)$. The spin and multipole sequence of interest is

$$\overset{A}{0(E2)}\,\overset{B}{2(E2+M1)}\,\overset{C}{2(E2)}0. \tag{3}$$

Transition A is the initial $E2$ Coulomb excitation, transition B is the upper cascade γ ray (measured at 90° to the α-particle direction), and transition C is the lower cascade γ ray (measured at 0° to the α-particle direction). Fortunately, with this geometry, it is feasible to calculate the expected triple correlation by the use of the Chalk River tabulations.[22]

The initial Coulomb excitation stage of the correlation requires the introduction of the particle parameters $(a_2)_t$ and $(a_4)_t$.[23] To obtain representative numbers for these particle parameters, we have chosen the case of the thick-target Coulomb excitation of the 1200-kev state in Cd^{114} with 10-Mev α particles. For this case $(a_2)_t=+0.910$ and $(a_4)_t=-0.081$.

The triple correlation may be put into the form $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$, where θ is the angle between the detector fixed at 0° and the second detector. The coefficients A_2 and A_4 are plotted as a function of δ [$\delta=(E2/M1)^{\frac{1}{2}}$ for the mixed transition] for ideal geometry in Fig. 15. The coefficients are relatively large. The existence of a strong correlation offers the possibility of measuring δ for the upper mixed transition. However,

[22] W. T. Sharp, J. M. Kennedy, B. J. Sears, and M. G. Hoyle, Chalk River Report CRT 556 (unpublished); J. M. Kennedy, B. J. Sears, and W. T. Sharp, Chalk River Report CRT 569 (unpublished); A. J. Ferguson and A. R. Rutledge, Chalk River Report CRT 615 (unpublished).

[23] F. K. McGowan and P. H. Stelson, Phys. Rev. **106**, 522 (1957).

this treatment of the correlation ignores the "double $E2$" complication of the Coulomb excitation.

In our measurements, the detectors were placed as close to the target as possible to increase the counting rate and consequently the correlation is attenuated. The introduction of the coefficients for the finite geometry and the substitution of $\theta=90°$ gives the result $W(90°)=1.044$ for the case of pure $E2$ for the upper cascade. We have also worked out the expected correlation for two other representative cases and find results similar to the Cd^{114} case.

In conclusion, we state that although the expected angular correlation is rather strong, the detectors have been placed close enough to the target to attenuate this correlation to a large extent. From the point of view of reducing possible errors in the values for $B(E2)$ this is an advantage since the value for δ is not known for most of the transitions. For the purpose of applying a correction for the angular correlation effect, we have assumed pure $E2$ for the upper cascade transition and have applied a constant correction of -5% to the observed yields. We have taken the error associated with the angular correlation effect as $\pm3\%$.

3. Individual Cases

Ruthenium-104

Unfortunately, there is no information on the excited states of Ru^{104} from radioactive decay measurements. A coincidence spectrum for Ru^{104} is shown in Fig. 2. The real coincidence peak of 535 kev is quite strong and is somewhat too wide. This additional width is accounted for by an annihilation γ-ray peak at 511 kev. When the window of the single-channel analyzer is moved off the 358-kev peak (above it), the annihilation peak remained. This peak is probably the result of the buildup of activities produced by α-particle bombardment of light-element target impurities.

Ruthenium-102

A coincidence spectrum for Ru^{102} is given in Fig. 3. A real coincidence peak is observed at (625 ± 7) kev. Information on the excited states of Ru^{102} can be obtained from the study of the decay of Rh^{102}. This decay excites γ rays of 630 and 1100 kev which may be interpreted as the cascade and crossover of the second 2^+ state. The interpretation of this decay scheme by Hisataki and Kurbatov[24] gives a very high value for cascade/crossover. However, recent work at Oak Ridge on the decay of Rh^{102} shows that both 630- and 1100-kev γ-ray peaks are complex.[25] Coincidence and angular correlation measurements indicate that the cascade/crossover for the second 2^+ state is 1.5 ± 0.3. We have used this value to obtain the $B(E2)$'s listed in Table V. In addition, the Oak Ridge interpretation requires that a 4^+ state be placed approximately at the same energy as the second 2^+ state.

The calculation of the $B(E2)$'s listed in Table V ignores the contribution from the "double $E2$" excitation of a coincident 4^+ state. Although one does not yet know the $B(E2, 2\rightarrow4)_{ex}$, a reasonable estimate indicates that the inclusion of this contribution would reduce the values by about 10%. The $B(E2, 2'\rightarrow2)$ listed in Table V is calculated on the basis of pure $E2$ decay which is in agreement with the decay scheme results.

Ruthenium-100

A coincidence spectrum for Ru^{100} is shown in Fig. 4. A real coincidence peak is observed at (817 ± 10) kev. The peak centered at 520 pulse-height units is too broad to be attributed solely to the random peak of the 540-kev γ ray. A random spectrum is also shown in the figure. The additional width on the low-energy side is assigned to annihilation γ rays from activities produced in light element target impurities.

Information on excited states of Ru^{100} is available both from the decay of Rh^{100} and Tc^{100}. Marquez[26] has measured the beta rays and internal conversion electrons produced in the decay of Rh^{100}. From these measurements he was able to construct a level scheme for Ru^{100}. The first excited state was placed at 535 kev and a second excited state at 1358 kev. The second excited state decays by both a cascade 823-kev γ ray and a crossover 1358-kev γ ray which implies spin 2 for this state. These results agree well with what is found in our experiment. From the conversion electron intensities for the 823- and 1358-kev transition one can obtain a cascade/crossover ratio of 1.15 for the decay of the 1358-kev state. However, Marquez did not give errors on his intensity measurements so that the accuracy of this value is not known.

The decay of Tc^{100} has been studied by O'Kelly *et al.*[27] They found two strong γ rays of 542 and 600 kev and a number of less intense γ rays. The 542- and 600-kev γ rays are in coincidence. A weak γ ray of 1140 kev is observed but it is not yet clear whether this is the crossover γ ray. The level at 1140 kev is not seen in our Coulomb excitation work. This suggests either that the spin of the state is not 2 or if it is 2, then the crossover $B(E2)$ is considerably less than other observed crossover $B(E2)$ values. O'Kelley *et al.* also observed weak γ rays with energies which could correspond to the crossover and cascade decay of the 2^+ state observed in the present work. They obtained a cascades/crossover value of 2.4 ± 0.7. This value is considerably larger than the value extracted from the work of Marquez. Since errors are not given in the Marquez work, we have used the value obtained by O'Kelley *et al.* in the calculation of the $B(E2)$ decays for the second 2^+ state.

[24] K. Hisataki and J. D. Kurbatov, Bull. Am. Phys. Soc. **3**, 315 (1958).

[25] F. K. McGowan and P. H. Stelson, Bull. Am. Phys. Soc. **5**, 448 (1960).

[26] L. Marquez, Phys. Rev. **92**, 1511 (1953).

[27] G. D. O'Kelley, E. Eichler, and N. R. Johnson, Bull. Am. Phys. Soc. **3**, 62 (1958).

TABLE V. Summary of information on γ-ray transition rates for the second 2^+ state. Columns 1 and 2 list the nucleus and position of the second excited state. Columns 3 and 4 list the values for cascades/crossovers and $E2/M1$ taken from radioactive decay studies. Columns 5, 6, and 7 list the reduced electromagnetic transition rates for the second 2^+ state. The errors assigned to these transition rates are considered to be absolute errors (standard deviations), i.e., possible systematic errors as well as errors assigned in Table III are included. Column 8 lists the quantity $R=B(E2, 2'\rightarrow 2)/B(E2, 2\rightarrow 0)$. Column 9 lists the total mean life deduced from the previously listed information.

(1) Nucleus	(2) E (kev)	(3) Cascades/ crossovers	(4) $E2/M1$ $(2'\rightarrow 2)$	(5) $B(E2, 2'\rightarrow 0)_d$ (cm⁴)	(6) $B(E2, 2'\rightarrow 2)_d$ (cm⁴)	(7) $B(M1)_d$	(8) $\frac{B(E2, 2'\rightarrow 2)}{B(E2, 2\rightarrow 0)}=R$	(9) (Mean life) τ (sec)
Ru^{102}	1100	1.5 ± 0.3[a]	$\geqslant 225$[a]	$(0.36\pm0.10)\times10^{-50}$	$(0.91\pm0.27)\times10^{-49}$	$\leqslant 1.1\times10^{-4}$	0.62 ± 0.19	$(5.6\pm1.5)\times10^{-12}$
Pd^{106}	1120	2.1 ± 0.3[b]	$\geqslant 200$[b]	$(0.29\pm0.10)\times10^{-50}$	$(1.30\pm0.50)\times10^{-49}$	$\leqslant 1.7\times10^{-4}$	1.00 ± 0.37	$(5.1\pm1.9)\times10^{-12}$
Ru^{100}	1357	2.4 ± 0.7[c]		$(0.30\pm0.09)\times10^{-50}$	$(0.92\pm0.27)\times10^{-49}$		0.80 ± 0.24	$(1.7\pm0.5)\times10^{-12}$
Cd^{110}	1466	1.5 ± 0.3[d]		$(0.45\pm0.14)\times10^{-50}$	$(1.30\pm0.41)\times10^{-49}$		1.30 ± 0.42	$(1.1\pm0.3)\times10^{-12}$
Cd^{112}	1295	3.2 ± 0.8[e]		$(0.21\pm0.08)\times10^{-50}$	$(1.6\pm0.6)\times10^{-49}$		1.50 ± 0.57	$(2.6\pm1.0)\times10^{-12}$
Cd^{114}	1200	3.6 ± 0.8[f]		$(0.18\pm0.06)\times10^{-50}$	$(1.4\pm0.5)\times10^{-49}$		1.21 ± 0.42	$(4.1\pm1.4)\times10^{-12}$
Cd^{114}	1363	1.1 ± 0.2[g]		$(0.16\pm0.04)\times10^{-50}$	$\leqslant (0.24\pm0.06)\times10^{-49}$		$\leqslant 0.20\pm0.05$	
Te^{122}	1256	5.0 ± 0.8[h]	12 ± 3[h]	$(0.39\pm0.17)\times10^{-50}$	$(3.5\pm1.6)\times10^{-49}$	$(1.0\pm0.5)\times10^{-2}$	2.7 ± 1.2	$(1.1\pm0.5)\times10^{-12}$

[a] F. K. McGowan and P. H. Stelson, Bull. Am. Phys. Soc. **5**, 448 (1960).
[b] R. L. Robinson, F. K. McGowan, and W. G. Smith, Phys. Rev. **119**, 1692 (1960).
[c] G. D. O'Kelley, E. Eichler, and N. R. Johnson (private communication).
[d] B. S. Dzhelepow and N. N. Zhukovskii, Nuclear Phys. **6**, 655 (1958).
[e] R. K. Girgis and R. Van Lieshout, Physics **25**, 1200 (1959).
[f] H. T. Motz, Phys. Rev. **104**, 1353 (1956).
[g] B. P. Adyasevich, B. D. Groshev, and A. M. Demidov, *Proceedings of the Conference of the Academy of Sciences of the U.S.S.R. on the Peaceful Uses of Atomic Energy, Moscow, July, 1955* (Akademiia Nauk S.S.S.R., Moscow, 1955 [English translation by Consultants Bureau, New York: U. S. Atomic Energy Commission Report TR-2435, 1956].
[h] M. J. Glaubman, Phys. Rev. **98**, 645 (1955); B. Farrelly, L. Koerts, N. Benczer, R. Van Lieshout, and C. S. Wu, Phys. Rev. **99**, 1440 (1955).

Ruthenium-98

At 10-Mev α-particle energy a somewhat poorly defined real coincidence peak is observed which corresponds to a γ-ray energy of (748 ± 10) kev. This places a second 2^+ state at (1402 ± 12) kev. The coincidence spectrum for Ru^{98} is shown in Fig. 5.

Both the decays of Tc^{98} and Rh^{98} excite states in Ru^{98}. However, the Rh^{98} decay excites only the first 2^+ state at 654 kev. The interesting feature of the Tc^{98} decay is that β decay is not observed to the ground state or first excited state of Ru^{98} but only to a state at 1410 kev. Furthermore, the 1410-kev state only decays by cascade. O'Kelley[28] has set a limit of less than 1% for the intensity of the crossover transition. These facts suggest that the beta decay of Tc^{98} excites a 4^+ state at 1410 kev in Ru^{98}.

The observed $B(E2)_{ex}$ for the crossover transition in Ru^{98} is somewhat smaller than that for most other nuclei, and this together with the evidence from the Tc^{98} decay suggests the possibility that the observed intensity might be accounted for by "double $E2$" excitation of a 4^+ state. Assuming the unknown $B(E2, 2\rightarrow 4)_{ex}$ is given by the Goldhaber-Weneser model from the known $B(E2, 0\rightarrow 2)_{ex}$ one obtains the value 0.34×10^{-48} cm⁴. Formula (1) can then be used to estimate the expected yield and the value obtained is 3×10^3 excitations/ $6.25\times10^{12}\alpha$'s. The observed yield is 7.5×10^3 excitations/ $6.25\times10^{12}\alpha$'s, with an error of $\pm16\%$. Therefore, the "double $E2$" excitation of a 4^+ state probably makes an appreciable contribution to the observed yield. One can conclude, either (a) there exists only a 4^+ state at 1400 kev because there is sufficient uncertainty in the "double $E2$" estimate and the measured value to account for the observed difference or (b) there is a close-lying doublet of 2^+ and 4^+ states. We favor interpretation (b). However, the subtraction of the yield of the "double $E2$" excitation of the 4^+ state makes the $B(E2)$ for the crossover transition of the second 2^+ state even smaller and thus farther away from the average observed value for this type of transition.

[28] G. D. O'Kelley (private communication).

Palladium-110

No information on the excited states of Pd^{110} is available from radioactive decay measurements. A coincidence spectrum for Pd^{110} is given in Fig. 6. A relatively strong real coincidence peak is observed which corresponds to a γ ray of (438 ± 6) kev. This locates the second 2^+ state at (813 ± 7) kev. Also shown in the spectrum is the real coincidence spectrum which results

when the window of the single channel is moved below the 374-kev γ-ray peak. Under these conditions an annihilation peak remains and this is presumably the the result of activities built up in light element target impurities. There is some evidence for a second real coincidence peak at 552 kev corresponding to a level at 926 kev.

Palladium-108

The decays of both Rh^{108} and Ag^{108} excite states in Pd^{108}. At present there is only evidence for excitation of the first 2^+ state in the decay of Rh^{108}. Ag^{108} decay excites two states in Pd^{108} at 433 kev and 1040 kev. Recently, Bunker and Starner[29] have established by angular correlation measurements that the 1040-kev state is a 0^+ state.

A coincidence spectrum for Pd^{108} is given in Fig. 7. A real coincidence peak is observed which corresponds to a γ ray of (508 ± 6) kev and this places the second 2^+ state at (941 ± 7) kev. Apparently this state is not excited in radioactive decay so no further interpretation to obtain $B(E2)$ values can be made.

Palladium-106

A coincidence spectrum for Pd^{106} is shown in Fig. 7. A real coincidence peak is observed which corresponds to a γ-ray energy of (607 ± 7) kev. A second 2^+ state is therefore located at (1120 ± 8) kev.

The decays of both Rh^{106} and Ag^{106} excite many states in Pd^{106} and hence in this case a wealth of information is available. Furthermore, there is the interesting situation that the spin of Rh^{106} is probably 1 whereas the spin of the 8.3-day Ag^{106} has been measured to be 6.

It has been known for some time that the decay of Rh^{106} excites a state in Pd^{106} at 1137 kev which decays predominantly by cascade through the 513-kev state. Measurements of the angular correlation of the cascade γ rays indicated that it was close to that expected for a 0-2-0 assignment. These facts locate a 0^+ state at 1137 kev and this is quite close to the 2^+ state found in the present work. The cascade γ rays from the decay of these two states would probably not be resolved with scintillation detectors and hence a small population of the second 2^+ state would explain the observed small deviation of the angular correlation from the pure 0-2-0 case.

Recently, Robinson *et al.*[30] have re-examined the decay schemes for Rh^{106} and Ag^{106}. They have identified a crossover γ ray of 1130 kev which confirms the fact that the decay of Rh^{106} excites the second 2^+ state in Pd^{106}. The population of the second 2^+ state is about 10% of the population of the 0^+ state at 1137 kev.

In contrast to previous interpretations of the decay of Ag^{106}, Robinson *et al.* find no evidence for the excitation of the 0^+ 1137-kev state. Only the 2^+ state of 1130 kev is excited. Thus, from the decay of Ag^{106} they obtained a cascade/crossover ratio of 2.1 ± 0.3 for the second 2^+ state in Pd^{106}. An angular correlation measurement shows that the upper cascade γ ray is greater than 99.5% $E2$. With this information we can then extract values for $B(E2)$ for cascade and crossover and a limit on $B(M1)$; these quantities are listed in Table V.

Cadmium-110

A coincidence spectrum for Cd^{110} is shown in Fig. 8. A real coincidence peak is observed which corresponds to a γ-ray energy of (810 ± 10) kev. This places the second 2^+ state at (1466 ± 12) kev.

Both In^{110} and Ag^{110} activities are observed to excite states in Cd^{110}. The decay of 4.9-hr In^{110} appears to excite levels in Cd^{110} at 656, 1540, and 2475 kev. The decay of the 253-day Ag^{110} activity has been extensively studied. There is evidence for excitation of 7 states in Cd^{110}; the first 3 states are 656, 1473, and 1540 kev, according to the most recent proposed decay scheme.

Dzhelepow and Zhukovski[31] identified a γ ray of (1480 ± 4) kev which they interpreted to result from the decay of a state of this energy. It is reasonable on an energy basis to assume that this state is the same state we have observed. However, the decay scheme proposed by Dzhelepow and Zhukovski had no cascade decay for the 1480-kev state and furthermore contained a state at (1418 ± 4) kev. Funk and Wiedenbeck,[32] and Taylor and Scott[33] have proposed an alternate interpretation of the results of Dzhelepow and Zhukovski which is in agreement with the present work. This decay scheme eliminates the state at 1418 kev and provides for cascade decay of 1480-kev state. Taylor and Scott have also obtained added information for the correctness of this scheme from the study of γ-γ coincidences.

γ-γ correlations have also established that the 1540-kev state is 4^+. Accepting this decay scheme, one can then use the intensities given by Dzhelepow and Zhukovski to obtain a cascade/crossover ratio of 1.5 ± 0.3 for the decay of the second 2^+ state. The $B(E2)$ values extracted for the cascade and crossover of the second 2^+ state are given in Table V. It is assumed in obtaining the cascade $B(E2)$ that this γ ray is pure $E2$.

Cadmium-112

A coincidence spectrum for Cd^{112} is shown in Fig. 9. Two real coincidence peaks were observed for this nucleus which correspond to γ-ray energies of 685 and 845 kev. This places excited states in Cd^{112} at (1295 ± 12) and (1455 ± 14) kev.

Excited states in Cd^{112} are produced by both the decay of In^{112} (isomer) and Ag^{112}. A γ ray of 617 kev has been

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[31] B. S. Dzhelepow and N. N. Zhukovski, Nuclear Phys. **6**, 655 (1958).

[32] E. G. Funk, Jr., and M. L. Wiedenbeck, Phys. Rev. **112**, 1247 (1958).

[33] H. W. Taylor and S. A. Scott, Phys. Rev. **114**, 127 (1959).

observed in the decay of In^{112}; thus indicating excitation of the first 2^+ state. There is also some evidence for a 710-kev γ ray which might be the 685-kev γ ray we observe. A ratio of cascades/crossovers for the 1295-kev state is not yet available from the decay of In^{112}.

Although earlier work on the decay of Ag^{112} contained no evidence for the excitation of the 1295-kev state, recent work by Girgis and van Lieshout[34] has shown that this state is excited. These workers were able to obtain a cascades/crossovers value of (3.2 ± 0.8). Using this value we have computed the crossover and cascade $B(E2)$'s for the 1295-kev state and these are listed in Table V.

Girgis and van Lieshout also observed a γ ray of 855 kev which is close in energy to the 845-kev γ ray we have observed. In addition they found some evidence for a summing peak at 1460 kev. However, at this time it is not clear from decay scheme work that this is a 2^+ state since the crossover has not been identified.

If it is assumed that this state is a 2^+ state, one obtains the $\epsilon B(E2)_{\text{ex}}$ listed in Table III. This $\epsilon B(E2)_{\text{ex}}$ is the smallest listed in Table III and this fact suggests that perhaps the observed yield could be attributed to the "double $E2$" excitation of a 4^+ state. Assuming the $B(E2, 2\rightarrow 4)_{\text{ex}}$ is related to the $B(E2, 0\rightarrow 2)_{\text{ex}}$ by the Goldhaber-Weneser model, one finds that the "double $E2$" yield of a 4^+ state would account for approximately 50% of the observed yield. This result therefore favors a 2^+ assignment for the state at 1455 kev (the "double $E2$" excitation of a 0^+ state is expected to have only $\frac{1}{9}$ the intensity of that for the 4^+ state and hence 0^+ assignment is quite unlikely). The existence of two 2^+ states at this excitation energy in Cd^{112} would be similar to what is observed for Cd^{114} (see below).

Recently Cohen and Price[35] have reported evidence for 0^+ states in Cd^{112} at 1.23 and 1.43 Mev. This evidence results from the (d,p) stripping reaction on Cd^{111}.

Cadmium-114

The Cd^{114} nucleus is an unusually interesting one because there is considerable information on the low-lying states from other types of experiments. This information fits in well with what is observed in the present work.

A Coulomb excitation coincidence spectrum for Cd^{114} is shown in Fig. 10. Two real coincidence peaks are observed which correspond to γ rays of 645 and 808 kev and therefore place excited states at 1200 and 1363 kev. In addition, as observed above, there is evidence for a third coincidence peak at 725 kev corresponding to a state at 1280 kev.

The decay of an isomeric state in In^{114} excites a state in Cd^{114} at 1280 kev, which in turn decays by cascade through the first 2^+ state. Angular correlation and polarization measurements have shown that this state at 1280 kev is a 4^+ state.[36] The intensity of the weak coincidence peak at 725 kev is reasonably well accounted for by the "double $E2$" excitation of this 4^+ state.

Several groups of workers[9,37,38] have studied the γ rays in Cd^{114} which result from the strong thermal neutron capture of Cd^{113}. Motz[9] has discussed this work in the interpretation of his results and it will therefore not be discussed here. By measuring the internal conversion spectrum, Motz found a 0^+ state at 1308 ± 3 kev. In addition he observed γ rays and conversion electrons which could be interpreted to result from the following states: 559 (2^+), 1212 (2^+ or 1^+), 1286 (4^+), 1386 (2^+ or 1^+), and 1860 (4^+ or 3^+). Considering the assigned errors in energy, the states at (1212 ± 3) and (1386 ± 4) kev probably are the states found in the present work at (1200 ± 10) and (1363 ± 13) kev. Both Motz and Adyasevich *et al.* have determined cascades/crossovers values for these two states. The two sets of values agree reasonably well, and we have taken the values listed in Table V. On the assumption that the upper cascade transition is pure $E2$, one can extract values for $B(E2, 2'\rightarrow 2)$ in addition to $B(E2, 2'\rightarrow 0)$ values for these states. The values are listed in Table V. It might be mentioned that the fact that these levels are Coulomb excited eliminates a 1^+ assignment, since the "double $E2$" excitation of a spin 1 state requires an unreasonably large $B(E2, 2\rightarrow 1)_{\text{ex}}$ to account for the observed yields.

Recently, Cohen and Price[35] have reported the existence of a new 0^+ state in Cd^{114} at 1150 kev. This state is excited by the $Cd^{113}(d,p)$ reaction. They also believe that the state at 1860 kev is 0^+ instead of 3^+ or 4^+. This requires a new location for the 576-kev γ ray since it would then connect a 0^+ and 4^+ state. They point out that this γ ray would fit as an upper cascade γ ray for the new 0^+ state at 1150 kev. One peculiar feature of a 0^+ state at 1150 kev is that Motz does not observe $E0$ electrons from the decay of this state. Judging from the curve given by Motz, the $E0$ decay intensity of the 1150-kev state is at least a factor of 10 less than the $E0$ decay of the 1308-kev state. On the other hand, the cascade γ-ray intensity of the 1150-kev state would be roughly 3 times that of the 1308-kev state.[39]

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[35] B. L. Cohen and R. E. Price, Phys. Rev. **118**, 1582 (1960).
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[39] *Note added in proof.* The recently reported work of L. V. Groshev (*Proceedings of the International Conference on Nuclear Structure*, Kingston, Canada, August 29–September 3, 1960, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press), p. 568] confirms the existence of the 0^+ state at 1135 kev. The $E0$ electrons from the crossover decay of this state have been detected. The lifetimes of the two 0^+ states (1135-, 1308-kev) are not known. Groshev points out, however, that if one assumes that the cascade $E2$ decays from these two states are enhanced as predicted by the vibrational model, then the $E0$ matrix element for the 1308-kev state is unreasonably large; whereas that for the 1135-kev state is probably reasonable. This would rule out the 1308-kev state as a collective vibrational state but still leaves the possibility that the new 1135-kev state is a collective 0^+ state.

Cadmium-116

Figure 11 shows a Coulomb excitation coincidence spectrum for Cd^{116}. A real coincidence peak is observed which corresponds to a γ-ray energy of 700 kev. This places the second 2^+ state at 1217 kev. Alexander *et al.*[40] have observed two γ rays of 515 and 700 kev in the decay of 2.5-minute Ag^{116}. These energies agree well with what is observed here. Unfortunately, the crossover γ ray was not observed and therefore a value for cascades/crossovers is not available.

Tellurium-122

A Coulomb excitation coincidence spectrum for Te^{122} is given in Fig. 12. A real coincidence peak is observed which corresponds to a γ-ray energy of 692 kev. This places the second 2^+ state at 1256 kev.

The decay of Sb^{122} excites states in Te^{122} at 564 kev and 1250 kev. These energies agree with the Coulomb excitation results. Furthermore, two groups of workers[40–42] have established the value for cascades/crossovers. Angular correlation measurements[40,43] have shown that the upper cascade γ ray is $(92\pm2)\%$ $E2$ and $(8\pm2)\%$ $M1$. With this information we can extract the values for $B(E2, 2'\rightarrow 0)$, $B(E2, 2'\rightarrow 2)$, and $B(M1, 2'\rightarrow 2)$. These are listed in Table V.

Molybdenum-100

A coincidence spectrum for Mo^{100} is shown in Fig. 13. The true coincidence peak for this nucleus almost coincides with the random peak. The coincident γ ray has an energy of (520 ± 5) kev and this places the second 2^+ state at (1050 ± 7) kev.

Nothing is known about excited states of Mo^{100} from radioactive decay studies. Private communications of results obtained at the Bartol Foundation by inelastic neutron experiments indicated that the second 2^+ state of Mo^{100} was located at about 1050 kev.[44] However, a cascades/crossovers value is not available from this work, so that further interpretation for this nucleus is not yet possible.

III. CONCLUSIONS

For the class of nuclei studied, viz., medium-weight nuclei with rather strongly enhanced $2^+\rightarrow 0^+$ $E2$ transitions, it is found that a second 2^+ state systematically occurs with energy somewhere between 2 and 2.5 times that of the first 2^+ state. The plot of the observed level positions in Fig. 16 shows the general tendency of the energy ratio to remain constant even though the actual energies change considerably from nucleus to nucleus.

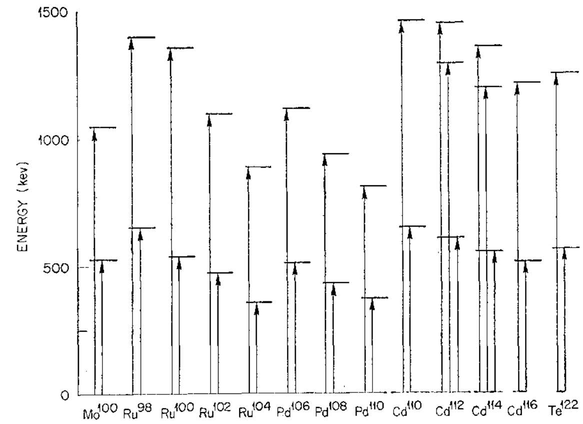

FIG. 16. Summary of the Coulomb excited 2^+ states for the 13 nuclei studied. The ratio of the energies of the first and second 2^+ states shows a tendency to remain constant even though the actual energies change considerably.

The possible systematic occurrence of 0^+ and 4^+ states with excitation energies near to that of the second 2^+ state has not yet been demonstrated. Clearly, this information would be of great value. Taking the limited amount of information on other states, as discussed in the previous section, we have plotted the positions of known states for seven nuclei in Fig. 17.

Qualitatively, all the collective models predict a strong enhancement of the $2'$ to 2 $E2$ transition. The present results confirm this expected enhancement. This information is summarized in Table V. The observed values for the ratio R are listed in the last column. These values fluctuate about unity indicating that the $2'$ to 2 $E2$ transitions have an enhancement comparable to the 2^+ to 0^+ $E2$ transition.

The $B(E2)$ values for the crossover transition from the second 2^+ state to the ground state exhibit some uniformity and are all small, being about single-particle value or a little less. This is in qualitative agreement with the predictions of all the collective models.

The 4^+ to 2^+ $E2$ transition is expected to be enhanced according to collective models. In one case this has been confirmed; the observed excitation of the known 4^+ state in Cd^{114} by the "double $E2$" process requires about the expected enhancement of the 4^+ to 2^+ $E2$ transition.

For the three nuclei Te^{122}, Pd^{106}, and Ru^{102}, information is obtained on the $B(M1)_d$ for the $2'$ to 2 transition. The $B(M1)_d$ for Te^{122} is about 1/100 of the single-particle value, and the limits set for Pd^{106} and Ru^{102} are less than 1.7×10^{-4} and 1.1×10^{-4} of the single-particle estimate, respectively. These small values are in qualitative agreement with what is expected for the different collective models.

It is concluded that the observed properties of the nuclear states generally support a collective model interpretation. Since the different proposed types of collective motion represent quite different pictures of the

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[43] T. Lindquist and I. Markland, Nuclear Phys. 4, 189 (1957).
[44] Private communications from D. M. Van Patter; and S. S. Malik, C. E. Mandeville, N. Nath, M. A. Rothman, and D. M. Van Patter, Bull. Am. Phys. Soc. 4, 259 (1959).

nuclear potential energy surface, it is of interest to try to weigh the evidence favoring each model. However, in order to illustrate some of the difficulties in such a comparison we first consider the nucleus Cd^{114}.

The positions of the known low-lying states of Cd^{114} are shown in Fig. 17 and are labelled $A, B, \cdots, G$. An interesting feature is that more states are observed than would be expected on a simple collective model interpretation. In particular, two 2^+ states, D and G are observed to be Coulomb excited. However, the $B(E2)$ values for decay of these states to the first 2^+ state, B, are quite different. The state D has an R value of 1.21 ± 0.42 whereas the upper limit for the value of R for state G is 0.20 ± 0.05. This information suggests that state D is primarily the expected collective state and that state G probably results from a different nucleon configuration. The observed enhanced decay of the state $E(4^+)$ to the state B is additional evidence indicating that state E is the expected 4^+ collective state.

It is not yet clear which, if either, of the 0^+ states, C and F, is to be associated with a collective excitation. The determination of the $E2$ transition rates for decay of these states to the first 2^+ state would be very useful.[44a]

The level scheme of Cd^{114} is quite instructive since it illustrates the problems associated with obtaining an understanding of collective motions in this type of nucleus. The collective excitation energies and possible intrinsic excitation energies are not sufficiently different to allow the rather clear-cut situation realized in the rotational collective case. As a consequence, it is, first of all, sometimes difficult to identify the primarily collective states, and, second, it is difficult to make significant comparisons with the predictions of different collective models because of the possible distortions introduced by the mixing of the two types of states.

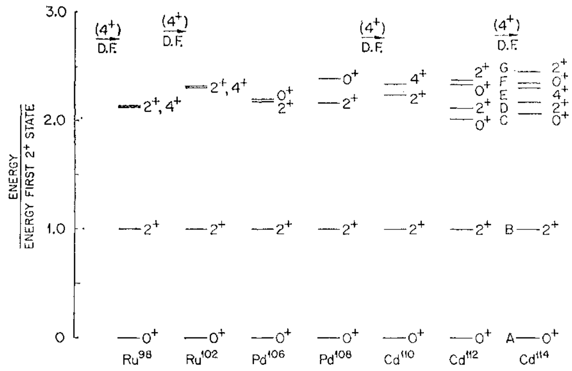

FIG. 17. Summary of the available information on the level position of seven nuclei.

Satchler[45] has considered the particular case of Cd^{114} on the assumption that there is weak coupling between collective and intrinsic excitations, As a result of this interaction, the γ-ray selection rules and the level spectrum of the harmonic vibration model are modified. There is good qualitative agreement with experiment.

An alternative interpretation of the experimental information on Cd^{114} has been given by Tamura and Komai.[46] They ignore possible interactions of intrinsic states and, instead, consider a collective model which is of the Wilets-Jean type but modified to include some γ stability. The positions of the observed collective states (taken to be A, B, D, E, and F) are well reproduced. Quantitative predictions for both the cascade and crossover $E2$ transition rates from the second 2^+ state are obtained and they agree well with what is observed.

The models of Goldhaber-Weneser and Wilets-Jean, and possible modifications of these mentioned for the Cd^{114} case, predict a triplet of states 0^+, 2^+, and 4^+. On the other hand, the Davydov-Filippov and the Raz models predict no 0^+ collective state in this energy range. Therefore, the 0^+ state offers the possibility of deciding between these models. 0^+ states at the appropriâte energy are found in Pd^{106}, Cd^{112}, Cd^{114}, and Pd^{108}. However, the strength of the evidence concerning the occurrence of a collective 0^+ state would be greatly increased if it were shown that the $E2$ decay to the first 2^+ state was in fact properly enhanced.

The Davydov-Filippov model predicts the position of the 4^+ state to be systematically higher than what is observed. The expected positions according to this model are shown in Fig. 17. The inclusion of a rotational-

TABLE VI. Comparison with Davydov-Filippov model. Column 2 lists the quantity γ (in degrees) for the nucleus listed in Column 1. γ is deduced from the positions of the first and second 2^+ states. Columns 3 and 4 show a comparison of the predicted and observed values for $B(E2, 2'\to 2)/B(E2, 2\to 0)$. Columns 5 and 6 list the predicted and observed values for the ratio $B(E2, 2'\to 0)/B(E2, 2\to 0)$.

(1)	(2)	(3)	(4)	(5)	(6)
		$B(E2, 2'\to 2)/B(E2, 2\to 0)$		$B(E2, 2'\to 0)/B(E2, 2\to 0)$	
Nucleus	γ (degrees)	Theory	Exp.	Theory	Exp.
Mo^{100}	~ 30	1.43		0	≥ 0.030
Ru^{98}	27.1	1.20		0.020	≥ 0.010
Ru^{100}	24.4	0.82	0.80 ± 0.24	0.051	0.025 ± 0.009
Ru^{102}	25.6	0.99	0.62 ± 0.19	0.038	0.025 ± 0.007
Ru^{104}	24.5	0.84		0.050	≥ 0.013
Pd^{106}	26.7	1.15	1.00 ± 0.37	0.024	0.022 ± 0.008
Pd^{108}	26.8	1.17		0.024	≥ 0.010
Pd^{110}	26.8	1.17		0.024	≥ 0.011
Cd^{110}	26.2	1.08	1.30 ± 0.42	0.030	0.045 ± 0.014
Cd^{112}	27.3	1.23	1.50 ± 0.57	0.018	0.019 ± 0.007
Cd^{114}	26.9	1.18	1.21 ± 0.42	0.023	0.015 ± 0.005
Cd^{116}	25.3	0.95		0.041	≥ 0.020
Te^{122}	26.3	1.09	$2.7\ \pm1.2$	0.029	0.033 ± 0.015

[44a] See note added in proof under Cd^{114} in Sec. II-3.

[45] G. R. Satchler, *Comptes Rendus du Congres International de Physique Nucléaire*; *Interactions Nucléaires aux Basses Energies et Structure des Noyaux, Paris, July, 1958*, edited by P. Guggenberger (Dunod, Paris, 1959), p. 786.

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vibration corrective term, which would seem to be a reasonable extension of the model, would move the 4^+ state in the right direction to agree with experiment.[47]

In the simplest approximation the models of Scharff-Goldhaber and Weneser and of Wilets and Jean predict that the quantity R should be 2. The fact that the observed values for R are mostly somewhat less than 2 is probably best interpreted as an indication that the models oversimplify the actual situation.

The model of Davydov and Filippov makes quantitative predictions for both R and the ratio of the cross-over to cascade $E2$ decay of the second 2^+ state. Van Patter[48] has collected all available information of $E2$ transition rates in nuclei and has made comparisons with the predictions of the Davydov-Filippov model. Fairly good over-all agreement is found. Preliminary values from the measurements reported here were included in this survey. In Table VI we have listed our final values and compared these to the predictions of the Davydov-Filippov model. There is generally good agreement.

It is concluded that although the available information on the type of nuclei under discussion supports a collective model interpretation, it is, at present, difficult to draw conclusions concerning the shape of the nuclear potential energy surface governing this collective motion.

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Nuclear Spins of Thulium-166 and 167†

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The spins of 7.7 hour thulium-166 and 9.6 day thulium-167 have been measured by the atomic-beam magnetic resonance method. Spin values are Tm^{166}, $I=2$; Tm^{167}, $I=\frac{1}{2}$.

INTRODUCTION

MEASUREMENTS of ground-state properties of nuclei in the region $150<A<190$ are especially interesting because of relatively large nuclear deformations with consequent collective nuclear effects. These spin measurements are the beginning of a program of investigation at this laboratory of spins and hyperfine structure in this region.

EXPERIMENTAL PROCEDURE

Thulium-166 and 167 were produced both by $(\alpha,3n)$ and $(\alpha,2n)$ reactions on 100% holmium-165 and by (p,n) reactions on 33% erbium-166 and 23% erbium-167. The bombardments of holmium were made on the Brookhaven cyclotron and the erbium bombardments were made on the Princeton cyclotron. The alpha bombardments were more successful from the standpoint of the amount of activity produced. An alpha bombardment of 13 microampere-hours at 40 Mev produces activity sufficient for thirty five-minute exposures, each with beam counting rates of about 2000 to 3000 counts per minute.

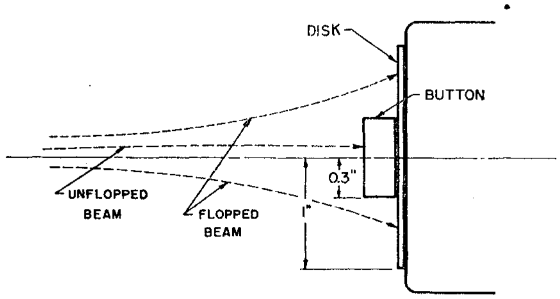

FIG. 1. Button and disk arrangement for collection of thulium atoms. Beam trajectories are schematic.

The radioactive material, either foil or metal filings, was placed in small cylindrical molybdenum ovens which were vacuum loaded and heated by electron bombardment. Beams were produced by evaporating the more volatile thulium from holmium at a brightness temperature of about 1075°C.

The atomic beam machine used was the focusing six-pole magnet apparatus described elsewhere.[1] A type of flop-in detection was used which automatically compensates for variations in beam strength. This method utilizes collection simultaneously on a copper button of 0.6-inch diameter and a copper disk of 2.0-inch diameter arranged as in Fig. 1. The atoms which have undergone appropriate $\Delta F=0$ transitions are collected on the disk, and the main beam on the center button. Designating counts per minute (total counts minus counter background) on the disk as O and counts

† This work was supported by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.

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