The residual quoted in these tables represents the difference between the measured resonance frequency and the value of the frequency predicted by the final computed atomic and nuclear constants. The weight factor is the reciprocal of the sum of the squares of the frequency uncertainties due to resonance linewidth and magnetic field uncertainty.

From the computer analysis the hyperfine-structure coupling constants for $Lu^{177}$ are: for the $^2D_{\frac{3}{2}}$ state, $a=194.84(2)$ Mc/sec, $b=1466.71(12)$ Mc/sec; and, for the $^2D_{\frac{5}{2}}$ state, $a=147.17(1)$ Mc/sec, $b=1805.93(14)$ Mc/sec. From these values of $a$ and $b$ the zero-field hyperfine-structure separations (in Mc/sec) are calculated as

$$^2D_{\frac{3}{2}} \quad \Delta\nu_{5-4}=2021.850(130),$$
$$\Delta\nu_{4-3}=360.300(85),$$
$$\Delta\nu_{3-2}=-463.130(105),$$

$$^2D_{\frac{5}{2}} \quad \Delta\nu_{6-5}=1811.784(95),$$
$$\Delta\nu_{5-4}=800.348(50),$$
$$\Delta\nu_{4-3}=175.896(50),$$
$$\Delta\nu_{3-2}=-138.968(55),$$
$$\Delta\nu_{2-1}=-221.640(45).$$

The values of $a$ corrected for configuration mixing by the procedure outlined in Sec. II are $a_0(\frac{3}{2})=242.32$ Mc/sec and $a_0(\frac{5}{2})=99.69$ Mc/sec. In the work presented here no use is made of these corrected values.

The nuclear magnetic moment sign is determined directly from the $^2D_{\frac{5}{2}}$ resonances in Table III and the Hamiltonian [(Eq. 1).] The value of the uncorrected moment obtained in this manner is $\mu_I=+1.9(8)$ nm. Similarly the $^2D_{\frac{3}{2}}$ state yields a nominal positive moment $+2.9(3.7)$ nm, but the error is considerably larger and does not exclude the possibility that the moment is negative. Although the $^2D_{\frac{5}{2}}$ results establish the sign of the moment, the magnitude is best obtained by comparison with the NMR value for $Lu^{175}$. With the known constants for $Lu^{175}$ listed above and no hyperfine-structure anomaly, Eq. (7) results in an uncorrected magnetic moment of $\mu_{I\text{uncorr}}=+2.217(10)$ nm for $Lu^{177}$. The diamagnetically corrected moment is then $\mu_{I\text{corr}}=+2.235(10)$ nm if the correction factor 1.00827 is used.[3] This procedure using Eq. (8) gives $Q=+5.51(6)$ b for the uncorrected quadrupole moment. In addition to having the same spin, both $Lu^{175}$ and $Lu^{177}$ have very similar magnetic dipole and electric quadrupole moments.

ACKNOWLEDGMENTS

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# Coulomb Excitation of Second 2+ States in $Ge^{74}$, $Ge^{76}$, $Se^{76}$, $Se^{78}$, and $Se^{80}$

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The location of a second 2+ state has been established for five even-even nuclei by means of Coulomb excitation produced by 6-, 7-, and 8-Mev $\alpha$ particles. The relatively weak excitation of these states is detected by a coincident measurement of the cascade gamma rays. The $B(E2)$'s for decay of the second 2+ state to the ground state by the crossover transition are rather small, being about single-particle value or a little less. For $Ge^{74}$, $Se^{76}$, and $Se^{78}$, the cascade/crossover ratio for the decay of the second 2+ state is known from radioactive decay measurements. The upper cascade $B(E2, 2'\rightarrow 2)$'s exhibit enhancements comparable to those for the lower cascade $B(E2, 2\rightarrow 0)$'s. The ratios of the $B(E2)$'s for the decay of the first and second 2+ states are compared to the predictions of several collective models. The $B(M1, 2'\rightarrow 2)$ values for $Ge^{74}$ and $Se^{76}$ are small, being about $10^{-3}$ times the single-particle estimate. This result is in qualitative agreement with the collective models for vibrational excitations.

## I. INTRODUCTION

In a previous report[1] the location of a second 2+ state was observed for 13 even-even medium-weight ($A=98$ to 122) nuclei by means of Coulomb excitation produced by 8-, 9-, and 10-Mev $\alpha$ particles. The relatively weak excitation of these states was detected by a coincident measurement of the cascade gamma rays. The crossover $B(E2)$'s, deduced from the observed gamma-ray yields, exhibited some uniformity and were all rather weak, being about single-particle value or a little less. For several of those nuclei the cascade/crossover ratio for the second 2+ state was known from

[1] P. H. Stelson and F. K. McGowan, Phys. Rev. **121**, 209 (1961).

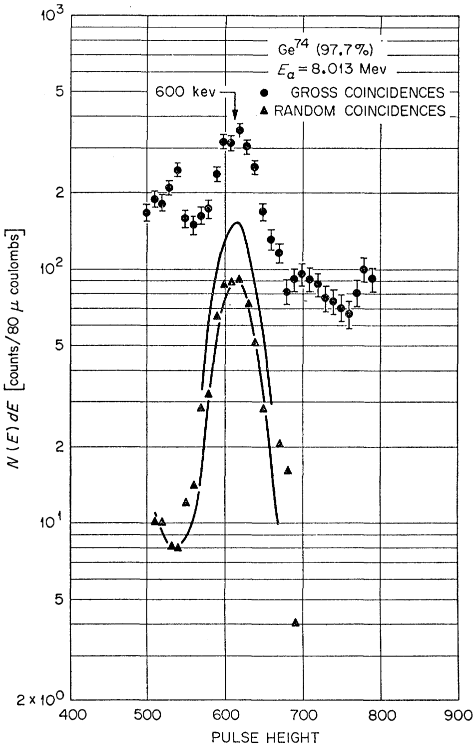


FIG. 1. Coincident spectrum for Ge$^{74}$. See Sec. II C of text for discussion of the spectrum.

other work. It was then possible to extract the $B(E2)$ for the upper cascade transition. Those upper cascade $B(E2)$'s exhibited enhancements comparable to those for the lower cascade transitions. In general, those measurements supported a collective model interpretation.

In this paper we wish to report the results from

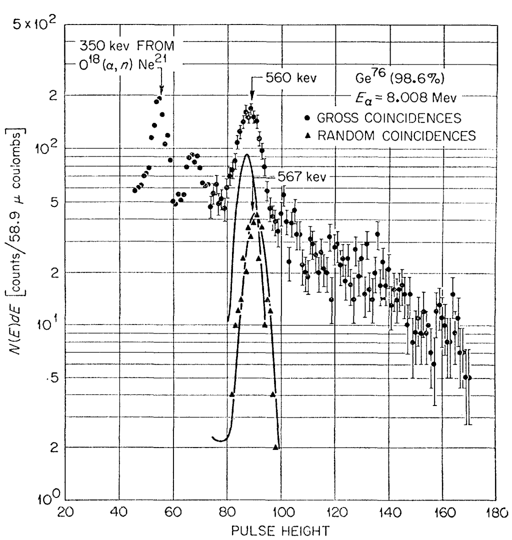


FIG. 2. Coincident spectrum for Ge$^{76}$. See Sec. II C of text for discussion of the spectrum.

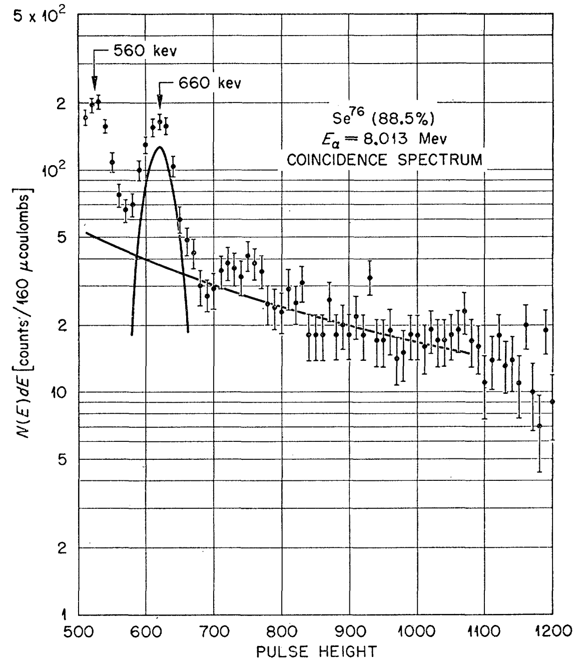


FIG. 3. Coincident spectrum for Se$^{76}$. See Sec. II C of text for discussion of the spectrum.

Coulomb excitation of the second 2+ states in Ge$^{74}$, Ge$^{76}$, Se$^{76}$, Se$^{78}$, and Se$^{80}$.[2]

## II. EXPERIMENTAL METHOD

The detection of the excitation of the second 2+ state was accomplished by coincident measurements on the cascade gamma rays. In general, the direct observation of the gamma rays in the singles spectrum was limited by the chemical purity of the targets because there are gamma rays from nuclear reactions produced by bombardment of minute amounts of the light-element

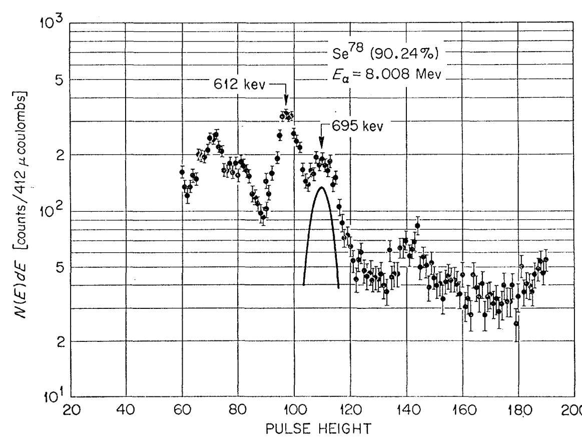


FIG. 4. Coincident spectrum for Se$^{78}$. See Sec. II C of text for discussion of the spectrum.

[2] A preliminary report of this work is given by the authors in Bull. Am. Phys. Soc. 4, 232 (1959).

TABLE I. Summary of the observed gamma-ray energies. Column 1 lists the nucleus. Column 2 gives the energy of the gamma ray from the decay of the first 2+ state. Column 3 gives the energy of the upper cascade gamma ray. The last column lists the energy of the second 2+ state.

| (1) Nucleus | (2) $E_1$ (kev) | (3) $E_2$ (kev) | (4) $(E_1+E_2)$ (kev) |
|---|---|---|---|
| $Ge^{74}$ | 600±6 | 600±8 | 1200±10 |
| $Ge^{76}$ | 567±6 | 560±8 | 1127±10 |
| $Se^{76}$ | 560±5 | 660±8 | 1220±10 |
| $Se^{78}$ | 612±6 | 695±9 | 1307±11 |
| $Se^{80}$ | 665±7 | 790±10 | 1455±12 |

target impurities. In the case of $Ge^{74}$ and $Ge^{76}$ the upper cascade transition $2' \rightarrow 2$ coincided in energy with the transition from the first 2+ state.

The experimental arrangement of the detectors and the method of measuring the gamma-ray yields have already been described.[1] The two gamma-ray detectors were 3- ×3-in. NaI(Tl) cylindrical crystals. A bevelled crystal located at 0° with respect to the incident ion beam was used to obtain higher efficiencies by increasing the solid angle. The distance from the target to the front face of the crystal was 4 cm. The coincident spectrum from the detector located at 90° with respect to the ion beam was displayed on a multichannel analyzer. This detector, which was not bevelled, was 5 cm from the target. Aside from these changes, the equipment was identical to that in the previous report.[1]

In all cases, the targets were prepared from enriched isotopes[3] by sintering metallic powders into thin foils about 100 mg/cm². These targets have also been used to measure the Coulomb excitation of the first 2+ state.

### A. Gamma-Ray Spectra

Typical coincident spectra are shown for each of the 5 nuclei studied in Figs. 1 through 5. In each case there is, in addition to the random coincident peak located at the energy of the first 2+ state, a true coincident peak which results from the weak excitation of the second

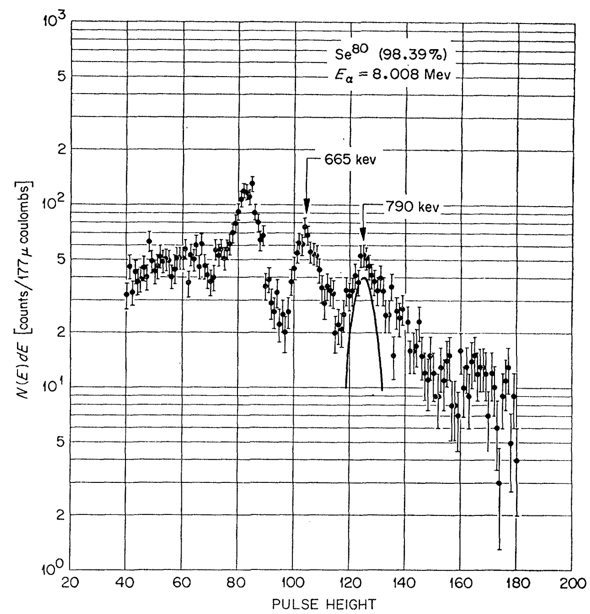


FIG. 5. Coincident spectrum for $Se^{80}$. See Sec. II C of text for discussion of the spectrum.

2+ state. In the case of $Ge^{74}$ and $Ge^{76}$, it was necessary to reduce the beam current below that normally used because the random peak coincided in energy with the true coincident peak. The energies of the observed gamma rays are listed in Table I. The number of Coulomb excitations of the second 2+ state, which were observed to decay by cascade emission, is given in column 4 of Table II for the corresponding $\alpha$-particle energy listed in column 3. An isotropic gamma-ray correlation is assumed in obtaining the numbers listed.

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

For $Ge^{76}$ the gamma-ray yield was measured at several $\alpha$-particle energies to determine whether the yield varied correctly for the Coulomb excitation pro-

TABLE II. Summary of the information on the observed number of Coulomb excitations and the corresponding $\epsilon B(E2)_{ex}$. Columns 1 and 2 list the nucleus and the energy of the second 2+ state. Column 4 lists the number of excitations of the second 2+ state which were observed to decay by cascade emission per $6.24\times10^{12}$ incident $\alpha$ particles with corresponding energies listed in column 3. Column 5 lists the theoretical thick target Coulomb excitation integral in (kev mg/cm²). Column 6 lists the quantity $\epsilon B(E2)_{ex}$ in ($cm^4e^2$).

| (1) Nucleus | (2) $E$ (Mev) | (3) $E_\alpha$ (Mev) | (4) $I$ | (5) $Y$ | (6) $B(E2)_{ex}$ |
|---|---|---|---|---|---|
| $Ge^{74}$ | 1.200 | 8.013 | $(1.15\pm0.15)\times10^4$ | $3.41\times10^3$ | $(4.39\pm0.57)\times10^{-51}$ |
| $Ge^{76}$ | 1.127 | 8.013 | $(1.43\pm0.16)\times10^4$ | $4.46\times10^3$ | $(4.18\pm0.46)\times10^{-51}$ |
| | | 7.012 | $(4.77\pm0.67)\times10^3$ | $1.37\times10^3$ | $(4.54\pm0.64)\times10^{-51}$ |
| | | 8.008 | $(1.45\pm0.17)\times10^4$ | $4.43\times10^3$ | $(4.26\pm0.51)\times10^{-51}$ |
| | | 7.055 | $(5.40\pm0.65)\times10^3$ | $1.45\times10^3$ | $(4.85\pm0.58)\times10^{-51}$ |
| | | 6.034 | $(9.3\ \pm2.0)\ \times10^2$ | $2.69\times10^2$ | $(4.50\pm0.95)\times10^{-51}$ |
| $Se^{76}$ | 1.220 | 8.013 | $(1.25\pm0.19)\times10^4$ | $2.62\times10^3$ | $(7.63\pm1.14)\times10^{-51}$ |
| $Se^{78}$ | 1.307 | 8.013 | $(6.55\pm1.24)\times10^3$ | $1.88\times10^3$ | $(5.57\pm1.06)\times10^{-51}$ |
| | | 8.008 | $(8.71\pm1.32)\times10^3$ | $1.87\times10^3$ | $(7.45\pm1.12)\times10^{-51}$ |
| $Se^{80}$ | 1.455 | 8.013 | $(6.35\pm1.33)\times10^3$ | $1.04\times10^3$ | $(9.77\pm2.05)\times10^{-51}$ |
| | | 8.008 | $(7.49\pm1.56)\times10^3$ | $1.03\times10^3$ | $(11.6\ \pm2.4)\ \times10^{-51}$ |

[3] Isotopically enriched samples were obtained from the Stable Isotopes Department of Oak Ridge National Laboratory.

TABLE III. Best values for $\epsilon B(E2)_{ex}$. Columns 3 and 4 list the values for $\epsilon B(E2)_{ex}$ and the absolute percentage error under the restrictive assumptions mentioned in the text.

| Nucleus | $E$ (kev) | $\epsilon B(E2)_{ex}\times 10^{51}$ ($cm^4e^2$) | Percentage error |
|---|---|---|---|
| $Ge^{74}$ | 1200 | 4.39 | 14 |
| $Ge^{76}$ | 1127 | 4.43 | 10 |
| $Se^{76}$ | 1220 | 7.63 | 17 |
| $Se^{78}$ | 1307 | 6.50 | 13 |
| $Se^{80}$ | 1455 | 10.7 | 16 |

cess. The excitation functions for the other nuclei investigated were not obtained because the energies of the second 2+ state and the mass numbers are nearly the same. We shall initially assume, as in reference 1, that the excitation of the second 2+ state is by direct $E2$ excitation via the crossover transition. The quantity $\epsilon B(E2)_{ex}$, 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 defined in a previous paper.[4] The quantity $\epsilon$ is defined as the ratio [cascade/(cascade+crossover)]. The errors listed for $\epsilon B(E2)_{ex}$ in Table II include only the errors entering into the determination of the gamma-ray yields at different $\alpha$-particle energies. For $Ge^{76}$ the observed constancy of the $\epsilon B(E2)_{ex}$ with changing $\alpha$-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 $\epsilon B(E2)_{ex}$ for each nucleus. The errors given in Table III include all sources of error which enter under the assumption that the gamma-ray yields result from direct $E2$ excitation. For instance, the errors reflect the uncertainty in the evaluation of the thick target Coulomb excitation integral. This uncertainty results from errors in: (a) the excitation energy of the state, (b) the incident energy of the $\alpha$ particles, and (c) the rate of energy loss of the $\alpha$ particles in the target. Three possible sources of systematic errors, which are not included in Table III, are: (1) contribution to gamma-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 gamma rays.

### 1. Compound Nucleus Contribution

A theoretical estimate of the compound nucleus cross section was taken from the work of Igo.[5] Recent experimental information[6] in the mass region $A=58$ to 70 confirms the calculations by Igo. At 6 Mev the compound nucleus cross section is larger than the Coulomb excitation cross section of the second 2+ state in $Ge^{76}$ by a factor of 3, and at 8 Mev the compound nucleus cross section is larger by a factor of 60. It is clear that the variation with $\alpha$-particle energy is quite different for the two processes. However, the quantity of interest here is the partial compound nucleus cross section for the reaction $(\alpha,\alpha'\gamma)$. One expects the $(\alpha,\alpha'\gamma)$ reaction to vary even more rapidly with $\alpha$-particle energy than does the compound nucleus reaction because the $(\alpha,\alpha'\gamma)$ reaction essentially depends on the product of two $\alpha$-particle penetrabilities rather than directly on the $\alpha$-particle penetrability. If, however, one takes the cross section for the $(\alpha,\alpha'\gamma)$ reaction to have the same shape as the compound nucleus cross section, then the number of excitations of the second 2+ state in $Ge^{76}$ (thick target) would have increased by 500 times in changing the $\alpha$-particle energy from 6 to 8 Mev. Actually, the yield increased a factor of $16.3\pm3.9$ which is in good agreement with the theoretical factor of 16.6 for Coulomb excitation. This is strong evidence that the contribution via compound nucleus reactions is not a significant part of the observed gamma-ray yields.

### 2. "Double E2" Coulomb Excitation

We follow a procedure given in a previous report[1] to estimate the expected number of excitations of the second 2+ state by "double $E2$" excitation. An approximate theoretical expression for the cross section[7] is

$$\sigma_{E2,E2}=0.027a^{-2}\sigma_{E2}(0\rightarrow 2)\sigma_{E2}(2\rightarrow 2'), \qquad (1)$$

where $2a$ is the distance of closest approach in a head-on collision. To use formula (1) a knowledge is required of the $B(E2,\, 2\rightarrow 2')$ which is one of the quantities to be extracted from the measurements. In order to proceed with an estimate of the expected number of excitations of the second 2+ state by "double $E2$" excitation, we have taken

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

This means $B(E2,\, 2\rightarrow 2')=\frac{1}{5}B(E2,\, 0\rightarrow 2)$ and the values for $B(E2,\, 0\rightarrow 2)$ are taken to be those previously published.[8] This choice for the value of $R$ is in general agreement with the results[1] from the region $A=100$ to 122. We list in Table IV the calculated values for the number of excitations of the second 2+ state by "double $E2$" for $\alpha$ particles incident on a thick target. An estimate of the importance of "double $E2$" excitation can now be made by comparing the total number of excitations listed in Table IV to the observed number of excitations (cascade decay only) listed in Table II. This comparison indicates that "double $E2$" excitation of the second 2+ state is a few percent of the observed excitation.

[4] P. H. Stelson and F. K. McGowan, Phys. Rev. **110**, 489 (1958).
[5] G. Igo, Phys. Rev. **115**, 1665 (1959).
[6] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. 4, 266 (1960).
[7] K. Alder, A. Bohr, T. Huus, B. R. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).
[8] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. 4, 232 (1959); and P. H. Stelson and F. K. McGowan (to be published).

TABLE IV. The calculated number of "double $E2$" excitations are listed in column 3 for $\alpha$ particles incident on a thick target. We have taken $R=1$ (see text for $R$).

| Nucleus | $E_\alpha$ (Mev) | Excitations per $6.24\times10^{12}$ $\alpha$ particles |
|---|---|---|
| $Ge^{74}$ | 8.013 | $9.9\times10^2$ |
| $Ge^{76}$ | 8.013 | $8.1\times10^2$ |
| | 7.012 | $2.2\times10^2$ |
| $Se^{76}$ | 8.013 | $9.7\times10^2$ |
| $Se^{78}$ | 8.013 | $6.4\times10^2$ |
| $Se^{80}$ | 8.013 | $2.4\times10^2$ |

In addition to the "double $E2$" contribution one expects that the two modes of excitations, direct $E2$ and "double $E2$," would be coherent.[7] As a result the cross section will contain an interference term. Since the phase of the interference term in the cross section is not known, the coherence of the two modes of excitation makes the small admixture of "double $E2$" excitation a more serious source of uncertainty. For those cases where the cascade/crossover ratio is known, we have subtracted the "double $E2$" contribution from the observed yield and have included an error $\frac{2}{3}$ of the maximum value of the interference term to be assigned to the $B(E2)$ from this source of uncertainty (our errors are considered to be standard deviations).

### *3. Angular Correlation*

Neglect of the angular correlation of the coincident cascade gamma rays could introduce significant errors in the values for $B(E2)$. The spin and multipole sequence of interest for direct $E2$ excitation is

$$\begin{array}{c} A \qquad\quad B \qquad\quad C \\ 0(E2)2'(E2+M1)2(E2)0. \end{array}$$

Transition $A$ is the direct $E2$ excitation, transition $B$ is the upper cascade gamma ray observed at 90° with respect to the $\alpha$-particle direction, and transition $C$ is the lower cascade gamma ray observed at 0° with respect to the $\alpha$-particle direction. The coefficients $A_2$ and $A_4$ of the triple correlation function $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$, where $\theta$ is the angle between the detector fixed at 0° and the second detector, can be relatively large.[1] In Fig. 15 of reference 1 the coefficients $A_2$ and $A_4$ for the cascade

$$j_0(L_0)j_1(L_1L_1')j_2(L_2)j_3$$

are given as a function of $\delta=(E2/M1)^{\frac{1}{2}}$ for the case of 10-Mev $\alpha$ particles on $Cd^{114}$. The mixing ratio $\delta$ is defined in terms of the reduced matrix elements as[9]

$$\delta=\delta_1=(j_2\|L_1'\|j_1)/(j_2\|L_1\|j_1).$$

In our measurements the angular correlation is considerably attenuated by the finite angular resolution of the detectors. For the case of the Coulomb excitation of the 1220-kev state in $Se^{76}$ with 8-Mev $\alpha$ particles incident on a thick target, the particle parameters are $(a_2)_t=0.925$ and $(a_4)_t=-0.085$. Substitution of $\theta=90°$ together with the finite angular resolution of the detectors gives the result $W(90°)=1.041$ for the case of pure $E2$ radiation for the upper cascade.

Angular correlation measurements[10–12] from radioactive decay have established the mixing ratio $\delta_1=6.5$ for $Se^{76}$ and $\delta_1=3.5$ for $Ge^{74}$. Introduction of these values for the mixing ratio $\delta_1$ gives the result $W(90°)=1.07$ for $Se^{76}$ and $W(90°)=1.08$ for $Ge^{74}$. For the purpose of applying a correction for the angular correlation effect, we have, after subtracting the "double $E2$" contribution from the observed yields, applied corrections of $-8\%$ to $Ge^{74}$, $-7\%$ to $Se^{76}$, and $-4\%$ to $Se^{78}$. We have taken the error associated with the angular correlation effect as $\pm3\%$. This treatment of the correlation ignores the "double $E2$" complication of the Coulomb excitation.

## C. Individual Cases

### *$Ge^{74}$*

A coincident spectrum for $Ge^{74}$ is shown in Fig. 1. The true coincident peak for this nucleus coincides with the random coincident peak. The coincident gamma ray has an energy of $(600\pm8)$ kev and this places the second 2+ state at $(1200\pm10)$ kev.

The decay of $Ga^{74}$ and $As^{74}$ excites several states[13] in $Ge^{74}$. The energies of the first and second 2+ states agree with the Coulomb excitation results. Furthermore, two groups of workers[11,12,14] have established values for cascade/crossover$=2.0\pm0.4$ and $E2/M1=12_{-7}^{+17}$ for the upper cascade gamma ray. With this information we can extract the values for $B(E2,\,2'\rightarrow0)$, $B(E2,\,2'\rightarrow2)$, and $B(M1,\,2'\rightarrow2)$. These are listed in Table V.

### *$Ge^{76}$*

Figure 2 shows a Coulomb excitation coincident spectrum for $Ge^{76}$. The true coincident peak for this nucleus almost coincides in energy with the random coincident peak. The coincident gamma ray has an energy of $(560\pm8)$ kev and this places the second 2+ state at $(1127\pm10)$ kev. Unfortunately, the crossover gamma ray was not observed and therefore a value for cascade/crossover is not available. There is no information from radioactive decay measurements on the states in $Ge^{76}$.

[9] M. E. Rose, Oak Ridge National Laboratory Report ORNL-2516, 1958 (unpublished).

[10] Z. Grabowski, S. Gustafsson, and I. Marklund, Arkiv Fysik **17**, 411 (1960).

[11] T. Yamazaki, H. Ikegami, and N. Sakai, J. Phys. Soc. Japan **15**, 957 (1960).

[12] R. L. Robinson and E. Eichler, Oak Ridge National Laboratory Report ORNL-2910, 1960 (unpublished).

[13] See, for instance, *Nuclear Data Sheets*, prepared by Nuclear Data Group (National Academy of Sciences, National Research Council, Washington, D. C.).

[14] E. Eichler, J. A. Marinsky, G. D. O'Kelley, and N. R. Johnson, Bull. Am. Phys. Soc. **5**, 10 (1960); E. Eichler (private communication).

TABLE V. Summary of information on gamma-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 cascade/crossover and $E2/M1$ taken from radioactive decay studies. Columns 5, 6, and 7 list the reduced electromagnetic transition rates for decay of 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 previous listed information.

| (1) Nucleus | (2) $E$ (kev) | (3) Cascade/ crossover | (4) $E2/M1$ | (5) $B(E2, 2'\rightarrow 0)$ ($cm^4e^2$) | (6) $B(E2, 2'\rightarrow 2)$ ($cm^4e^2$) | (7) $B(M1, 2'\rightarrow 2)$ | (8) $\frac{B(E2, 2'\rightarrow 2)}{B(E2, 2\rightarrow 0)}=R$ | (9) Mean life $\tau$ (sec) |
|---|---|---|---|---|---|---|---|---|
| $Ge^{74}$ | 1200 | $2.0\pm0.4$[a,b] | $12_{-7}^{+17}$ [b,c] | $(1.1\pm0.4)\times10^{-51}$ | $(6.8\pm2.7)\times10^{-50}$ | $(1.4_{-0.8}^{+2.0})\times10^{-3}$ | $1.08\pm0.44$ | $(9.5\pm3.3)\times10^{-12}$ |
| $Se^{76}$ | 1220 | $1.8\pm0.2$[d,e,f] | $42\pm7$[g] | $(2.1\pm0.8)\times10^{-51}$ | $(8.1\pm2.9)\times10^{-50}$ | $(5.9\pm2.4)\times10^{-4}$ | $0.83\pm0.31$ | $(5.1\pm1.7)\times10^{-12}$ |
| $Se^{78}$ | 1307 | $1.3\pm0.2$[h] | | $(2.1\pm0.7)\times10^{-51}$ | $(6.4\pm2.4)\times10^{-50}$ | | $0.83\pm0.31$ | $(4.4\pm1.5)\times10^{-12}$ |

[a] See reference 14.
[b] See reference 11.
[c] See reference 12.
[d] See reference 15.
[e] See reference 16.
[f] See reference 17.
[g] See reference 10.
[h] See reference 18.

### $Se^{76}$

Some information[13,15–17] on the levels in $Se^{76}$ is available from radioactive decay measurements on $As^{76}$ and $Br^{76}$. The first and second 2+ states at 559 kev and 1216 kev are excited in the decay of $As^{76}$ and $Br^{76}$.

Figure 3 shows a Coulomb excitation coincident spectrum for $Se^{76}$. The random coincident peak is at 560 kev. The peak at 660 kev represents the upper cascade gamma ray in coincidence with the 560-kev gamma ray. The position of the second 2+ state at $(1220\pm10)$ kev agrees with the radioactive decay measurements. Recently, several groups of workers[15–17] have established the value for cascade/crossover$=1.8\pm0.2$. There have been many measurements[13] of the angular correlation of the gamma rays from the decay of $As^{76}$. We have taken the value of $E2/M1=42\pm7$ for the $2'\rightarrow 2$ transition from the work of Grabowski *et al.*[10] With this information we can extract values for $B(E2, 2'\rightarrow 0)$, $B(E2, 2'\rightarrow 2)$, and $B(M1, 2'\rightarrow 2)$. These are listed in Table V.

### $Se^{78}$

A Coulomb excitation coincident spectrum for $Se^{78}$ is given in Fig. 4. A true coincident peak is observed at $(695\pm9)$ kev. This places the second 2+ state at $(1307\pm11)$ kev.

The decay of $As^{78}$ excites several states in $Se^{78}$. A value of cascade/crossover$=1.3\pm0.2$ is taken from the radioactive decay measurements of Van Lieshout.[18] The $B(E2)$ values extracted for the cascade and crossover transitions from the second 2+ state are given in Table V. It is assumed in obtaining the cascade $B(E2)$ that this gamma ray is pure $E2$.

### $Se^{80}$

A coincident spectrum for $Se^{80}$ is shown in Fig. 5. A true coincident peak is observed which corresponds to a gamma-ray energy of $(790\pm10)$ kev. This places the second 2+ state at $(1455\pm12)$ kev.

Nothing is known from radioactive decay measurements about the branching ratio cascade/crossover for the decay of the second 2+ state. Several excited states have been observed in $Se^{80}$ by the $(p,p')$ reaction.[19] Below 2-Mev excitation in $Se^{80}$, states were observed at 661, 1444, 1470, 1689, and 1954 kev.

## III. CONCLUSIONS

For the even-even nuclei ($A=74$ to 80) which have rather strongly enhanced $2+\rightarrow 0+$ $E2$ transition rates, it is found that a second 2+ state systematically occurs with an energy somewhere between 2.0 and 2.2 times that of the first 2+ state. The collective model of Scharff-Goldhaber and Weneser[20] predicts a triplet of states 0+, 2+, and 4+ in this energy region. The systematic occurrence of 0+ and 4+ states with excitation energies near to that of the second 2+ state has not been observed in the radioactive decay measurements.[13] On the other hand, the displaced harmonic oscillator ($\gamma$ unstable) model of Wilets and Jean,[21] the Raz model,[22] and the asymmetric rotor model of Davydov and Filippov[23] predict no 0+ state in this energy range.

In $Ge^{74}$ a third excited state is observed at 1470 kev with spin 3 or 4. The energy of this state is 2.45 times that of the first 2+ state.[14] The Davydov-Filippov model would predict a 4+ and a 3+ state at 2.67 and 3.0 times that of the first 2+ state, respectively.

The $\beta$ decay of $Br^{76}$ should be a favorable case to excite a possible collective 0+ state near the second 2+ state in $Se^{76}$. The spin of $Br^{76}$ is 1 and the $Q$ value for $\beta$ decay is 4.63 Mev. Beta-decay groups[13] have been observed to the 0+ ground state, to the first and second

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TABLE VI. Comparison with Davydov-Filippov model. Column 2 lists the quantity $\gamma$ (in degrees) for the nucleus listed in column 1. Gamma 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 $B(E2, 2' \to 0)/B(E2, 2 \to 0)$.

| (1) Nucleus | (2) $\gamma$ (deg) | (3) $B(E2, 2' \to 2)/B(E2, 2 \to 0)$ Theory | (4) Exp. | (5) $B(E2, 2' \to 0)/B(E2, 2 \to 0)$ Theory | (6) Exp. |
|---|---|---|---|---|---|
| $Ge^{74}$ | 30 | 1.43 | $1.08 \pm 0.44$ | 0 | $0.018 \pm 0.006$ |
| $Ge^{76}$ | 30 | 1.43 | | 0 | $\geq 0.017$ |
| $Se^{76}$ | 26.7 | 1.13 | $0.83 \pm 0.31$ | 0.023 | $0.022 \pm 0.007$ |
| $Se^{78}$ | 27.1 | 1.18 | $0.83 \pm 0.31$ | 0.018 | $0.027 \pm 0.009$ |
| $Se^{80}$ | 26.6 | 1.12 | | 0.024 | $\geq 0.037$ |

2+ states, and to excited states at 1.86 Mev and above in $Se^{76}$. From the radioactive decay measurements by Girgis *et al.*,[16] there is no evidence for a 0+ state in the region near the second 2+ state in $Se^{76}$.

The $B(E2, 2' \to 0)$ values for the crossover transition from the second 2+ state to the ground state exhibit some uniformity, being about single-particle value or a little less. The upper cascade $B(E2, 2' \to 2)$ values are strongly enhanced, being comparable to the enhancement for the $2+ \to 0+$ $E2$ transition. This information is summarized in Table V. The observed values for the ratio $R$ fluctuate about unity. For $Ge^{74}$ and $Se^{76}$ information is obtained on the $B(M1, 2' \to 2)$ for the upper cascade transition. The $B(M1)$ values are about $10^{-3}$ of the single-particle estimate. This information on transition rates is in qualitative agreement with the different collective models.

The predictions of the asymmetric rotor model of Davydov and Filippov[23] are particularly interesting since this model offers possible quantitative predictions for both $R$ and the ratio $B(E2, 2' \to 0)/B(E2, 2 \to 0)$. In Table VI we have compared our results with the predictions of this model. The model predicts quite well the observed trends in the ratios of the $B(E2)$ values.

Figure 6 is an up-to-date plot of the ratio $B(E2, 2' \to 2)/B(E2, 2 \to 0)$ vs the parameter $\gamma$ in the asymmetric rotor model of Davydov and Filippov. The curve labelled rotations is the prediction by this model. The phonon model (line labelled vibrations) predicts this ratio to be 2.

More recently, Davydov and Chaban[24] have relaxed the "adiabatic" approximation (fixed $\beta$ and $\gamma$) for the

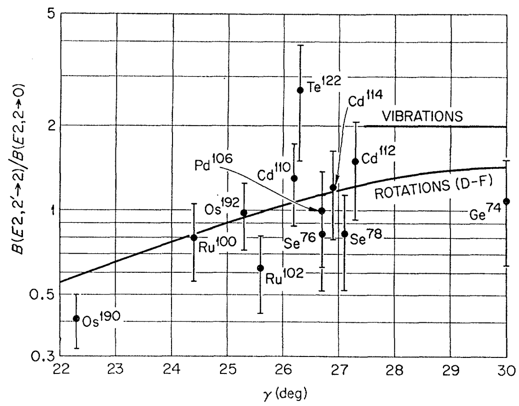


FIG. 6. Plot of the ratio $B(E2, 2' \to 2)/B(E2, 2 \to 0)$ vs the parameter $\gamma$. The Davydov-Filippov model predicts the curved labelled rotations. The phonon model (line labelled vibrations) predicts this ratio to be 2.

asymmetric rotor model by taking into account the coupling between rotational and $\beta$-vibrational motions. The nucleus is rigid with respect to a change of the equilibrium value of the parameter $\gamma$ which measures the deviation of the nuclear shape from axial symmetry. The nonadiabaticity parameter $\mu$ is proportional to the ratio of the root-mean-square of the zero-point vibration amplitude in the ground state to the deformation $\beta_0$. The inclusion of the rotation-vibration interaction changes appreciably the level spectrum of the Davydov-Filippov model. The introduction of the rotation-vibration interaction necessitates a change in the value of $\gamma$ for a given nucleus. The major change in the reduced transition probabilities due to interaction between the $\beta$-vibrational and rotational motions is determined by the change in the value of $\gamma$. To determine the parameters $\gamma$ and $\mu$ in this model one needs to know the energies of 3 excited states, for example, the first and second 2+ states and the 0+ state. Although 0+ states have been identified[13,25] in $Ru^{102}$, $Pd^{106}$, $Cd^{112}$, and $Cd^{114}$, the evidence is not yet clear if these 0+ states are primarily collective states. For $Ru^{102}$ the values of the parameters in the Davydov-Chaban model are $\gamma = 23.5°$ and $\mu = 0.42$. Shifting the point for $B(E2, 2' \to 2)/B(E2, 2 \to 0)$ for $Ru^{102}$ from 25.6° to 23.5° would improve the agreement with the prediction of the asymmetric rotor model. On the other hand, the points for $Pd^{106}$, $Cd^{112}$, and $Cd^{114}$ are shifted to $\gamma \approx 23°$ where the agreement with the predictions of the asymmetric rotor model is not as good.

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