Coulomb Excitation of Ru^{99} and Ru^{101} †

O. C. KISTNER AND A. SCHWARZSCHILD
Brookhaven National Laboratory, Upton, New York

(Received 3 August 1966)

The gamma-ray spectra resulting from Coulomb excitation of Ru^{99} and Ru^{101} by 4–7-MeV α particles are reported. Gamma-ray spectra were investigated using both Ge(Li) detectors and NaI(Tl) detectors. More than 14 transitions in Ru^{99} and 21 transitions in Ru^{101} were observed. $B(E2)$ values are presented for 7 states in Ru^{99} and 10 states in Ru^{101}. In addition, transition speeds are presented for several $M1$ and $E2$ transitions between excited states of these nuclei. The level schemes constructed for both nuclei are essentially in agreement with previous studies of radioactive decay. Many of the $E2$ transitions in both nuclei are very much enhanced, indicative of the collective character of the states. The transition speeds are compared with various nuclear-model predictions.

I. INTRODUCTION

RECENT work on the level schemes of Ru^{99} and Ru^{101} obtained from radioactive-decay studies[1–5] have shown a rather complicated level structure for both nuclei for excitations below 1 MeV. These structures cannot be understood within the framework of the simple shell-model description. Several attempts to describe these excited states in terms of coupling with core excitations[6] and also in the language of the Nilson model[3,4] have appeared in the recent literature. The experimental information was not sufficiently detailed to provide a critical test of either of these descriptions.

The $B(E2)$ values for the first excited states of the stable even-even Ru nuclei ($Ru^{96,98,100,102,104}$) have been known[5,7] for some time. These $B(E2)$ values change by almost a factor of three over the range of isotopes measured. The quadrupole deformation parameter β_2 derived[7] from the $B(E2)$ values changes from 0.16 for Ru^{96} to 0.29 for Ru^{104}. The value for Ru^{104} is one of the largest known outside the deformed rare-earth region. One might therefore anticipate that the Ru nuclei are deformed and that the light Ru isotopes may have spectra characteristic of a transition region between spherical and deformed nuclei.

Measurements of the lifetimes of the first excited state of the odd-mass nuclei, Ru^{99} (89 keV)[8] and Ru^{101} (127 keV)[9] performed in this laboratory have shown that the $E2$ transitions involved are very much enhanced. These results point to a predominantly collective nature for the description of these states.

A determination of the $E2$ transition strengths to the other low-lying levels of these nuclei is clearly of value in trying to understand the collective nature of these states. It was clear from the complexity of the level schemes determined from the radioactive decays that the old Coulomb excitation work[10–12] performed with a NaI detector may not have been correctly interpreted. In addition, the older work determined $B(E2)$ values only for the lowest excited states of each nucleus.

The availability of high resolution germanium γ-ray detectors makes possible an extensive determination of the $E2$ strengths to many low-lying states of both nuclei. In particular, we have been able to obtain $E2$ excitation probabilities for seven levels in Ru^{99} and for ten levels in Ru^{101}. The great advantage of the high-resolution detectors is clearly demonstrated. It becomes obvious that the study of Coulomb excitation of odd-mass nuclei will provide much useful information in the future.

II. THE EXPERIMENTAL PROCEDURE

Thick targets of separated metallic Ru isotopes[13] were bombarded with α particles from the Brookhaven Van de Graaff. The targets were prepared by depositing a slurry of fine metallic powder in water on a thick Ta backing and then allowing the water to evaporate. Gamma-ray spectra were observed simultaneously with a Ge(Li) detector and a 3×3 in. NaI detector. Both singles spectra and NaI-Ge two-dimensional coincidence spectra were obtained for a variety of bombarding energies between 4.2- and 7.1-MeV α-particle energy. The beam current used was of the order of 0.15 μA of doubly charged α particles and was limited by the capabilities of the Van de Graaff.

The Ge(Li) detectors used for these experiments were approximately 4-cc planar devices. The earlier experi-

† Work performed under the auspices of the U. S. Atomic Energy Commission.

1 J. S. Evans and R. A. Naumann, Phys. Rev. **140**, B559 (1965).
2 P. Connors, thesis, Pennsylvania State University, 1966 (unpublished).
3 N. K. Aras, G. D. O'Kelley, and G. Chilosi, Phys. Rev. **146**, 869 (1966).
4 N. K. Aras, G. D. O'Kelley, and G. Chilosi (private communication).
5 *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.).
6 O. C. Kistner, Phys. Rev. **144**, 1022 (1966).
7 P. H. Stelson and L. Grodzins, Nuclear Data **1**, Sec. A, 21 (1965).
8 O. C. Kistner, S. Monaro, and A. Schwarzschild, Phys. Rev. **137**, B23 (1965).
9 P. Connors and A. Schwarzschild (to be published).
10 G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).
11 F. K. McGowan, P. H. Stelson (private communication to Nuclear Data Sheets), see Ref. 5.
12 R. C. Ritter, P. H. Stelson, F. K. McGowan, and R. L. Robinson, Phys. Rev. **128**, 2320 (1962).
13 The Ru isotopes were obtained from Oak Ridge National Laboratory. The isotopic abundances of Ru for the two targets were as follows: 101 (97.7%), 99 (0.33%), 100 (0.34%), 102 (1.46%), 104 (0.16%), and 99 (98.3%), 98 (0.09%), 100 (0.71%), 101 (0.36%), 102 (0.40%), 104 (0.12%).

ment on Ru^{99} used a vacuum-tube preamplifier followed by an ORTEC Model 220 amplifier which resulted in pulse-height resolutions of between 4.0 and 4.5 keV full-width at half-maximum (FWHM) over the energy region of 90–700 keV. For the Ru^{101} experiments a dual field-effect transistor (F.E.T.) transistorized preamplifier was used which resulted in considerably improved pulse-height resolutions of between 3.3 and 4.0 keV over the energy region 100–700 keV. This resolution was obtained for runs of about 10-h duration with no pulse-height stabilization. Short runs gave resolutions which were better by about $\frac{1}{2}$ keV. A 4000-channel Nuclear Data pulse-height analyzer was used to analyze the Ge(Li) detector pulses.

Measurement of the relative excitation of the different states as a function of incident energy allows one both to determine the nature of the complicated branching patterns for the γ rays and to confirm that the dominant mode of excitation of the levels is indeed $E2$ Coulomb excitation.

The absolute yield of γ rays was determined from the NaI data. The Ge spectra are used as a guide to the understanding of the NaI spectra. In both cases it was possible to obtain unambiguous absolute $B(E2)$ values for only 2 or 3 levels from the NaI spectra. Relative $B(E2)$ are then obtained from the Ge spectra and normalized to the absolute values obtained from the NaI measurements. This procedure was adopted because of the difficulty in determining the absolute efficiencies of the Ge detector. The low efficiency of the Ge detector requires that it be placed as close as possible to the target (2–3 cm); the geometric efficiency is difficult to ascertain in such an arrangement. Meaningful data can be obtained with the Ge counter only after several hours of counting, in contrast to the large number of counts obtained in the NaI spectra in several minutes. The NaI counter was placed approximately 5 cm from the target at an angle of approximately 125° to the beam direction [near the zero of $P_2(\cos\theta)$]. Because of the poor geometry of the counters, the value of the ground-state spins of these nuclei ($\frac{5}{2}$), and the proximity of the counter angle to the zero of $P_2(\cos\theta)$ it is expected that the effects of anisotropic γ-ray emission following Coulomb excitation will be small. We have analyzed all of our data without taking account of anisotropies in the γ-ray distributions.

The construction of the decay schemes in both cases rests heavily on the known data from radioactive decay studies. In all cases, the energy measurements of γ rays compare favorably (within several tenths keV) with the radioactivity data. Also, all γray branching ratios from Coulomb excitation agree with the radioactivity data. In cases as complicated as these, it is helpful for some level positions to be known from other work.

The γ-γ coincidence data (NaI-Ge) were recorded in the 32×512 channel matrix of a Technical Measurements Corporation 2-parameter pulse-height analyzer. These data are too awkward to present and are therefore not shown here. Because of the limited number of channels available, the resolution on the NaI axis was necessarily poor and accurate intensity determinations could not be made. All the strong coincidences expected from the level scheme were observed, however. In several cases, which will be specifically mentioned, the positions of γ rays in the level schemes were definitely established by the coincidence work.

III. THEORETICAL COULOMB-EXCITATION YIELDS

The theoretical excitation functions were all calculated from the graphs, tables, and formulas given in the review article of Alder, Bohr, Huus, Mottelson, and Winther.[14] For all bombarding energies considered, the value of the parameter η_i of Ref. 14 was greater than 10, so that the function f_{E2} could be read directly from the graph of this reference. For the thick-target yields it is necessary to know dE/dx for the α particles. These were obtained from the measured values of dE/dx for protons given by Stelson and McGowan[15] for Ag. It was assumed that the dE/dx for α particles of energy E is 4 times that of protons at energy $E/2$ and that dE/dx is proportional to the inverse square root of the target atomic number. Thick-target yields were calculated from the formulas and graphs of Ref. 14, Sec. IIIB. Actual numerical integration of the differential yield was carried out for several bombarding energies and state energies. The numerical integration resulted in thick-target yields differing by less than 4% from the values calculated using the graphical procedure of Alder *et al.*

IV. Ru^{101}

A. Ge(Li) Spectra and Decay Scheme

Spectra were taken with the Ge counter at bombarding energies of 7.03, 6.86, 6.25, and 5.66 MeV for counting times of the order of 8 h each. Figure 1 shows the spectrum observed at 6.86 MeV. A list of the γ rays observed is given in Table I. The energies for all of the lines were determined by comparison of the pulse heights to those of a precision pulser. The energy scale was calibrated from the observed positions of several lines in the spectrum whose energies are known accurately from decay-scheme studies of Evans and Naumann[1] and of Connors.[2] Errors assigned to the energies are based on the internal consistency of the line energy determinations in the four separate runs. The relative intensities were determined from a calibration curve for the Ge detector. This was obtained from measurements, in a similar geometry, with radioactive sources of Na^{22} and Hf^{180m} which have several lines of known relative intensities.[5] It is believed that the

[14] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. **28**, 432 (1956).

[15] P. H. Stelson and F. K. McGowan, Phys. Rev. **110**, 489 (1958).

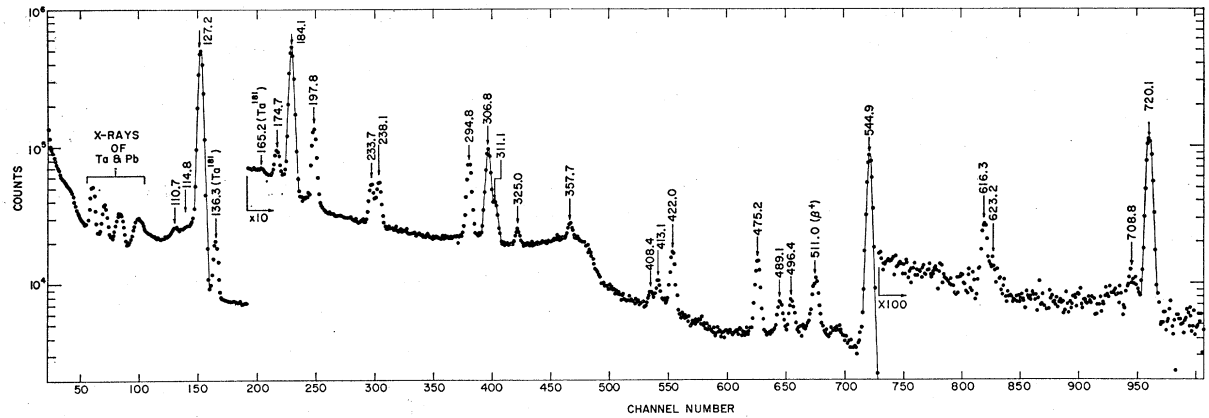

FIG. 1. Li(Ge) counter pulse-height spectrum of γ rays from 6.86-MeV α-particle bombardment of Ru^{101}. The actual spectrum was measured up to channel number 2048. The spectrum (not shown) above channel 1000 is free of structure except for the very weak line at 928.9 keV discussed in the text.

relative intensities given in the table are accurate to better than 10% for the stronger lines and ~20% for the weaker ones. Table I presents absolute intensities in terms of γ rays emitted per incident α particle. It is clear from the table that the relative intensities vary with bombarding energy, the yield of excitation of high-lying states being a much more rapidly varying function of α-particle energy than for the low-lying states. Only relative intensities were determined from the Ge spectra.

Figure 2 presents the level scheme deduced from the Coulomb-excitation data. (Shown also are the schemes from the radioactive-decay studies of Refs. 1, 2, 3, and 4.) The spin and parity assignments shown for the various levels were derived mostly from the radioactivity studies.[16–18] All of the coincidences expected on the basis of these schemes were observed in the NaI-Ge coincidence spectra. Two levels were observed in Coulomb excitation which had not been observed in the radioactive-decay studies. They are at 616.3 and 623.5 keV. For both levels, both the ground-state transition and the stopover to the 127-keV level were observed. The energies of the cascade γ ray and crossover γ ray agree to within 0.2 keV in both cases. In addition, the coincidence of both stopover γ rays with the 127-keV γ ray were observed. Several other new transitions from known levels were observed in the Coulomb-excitation studies. The lack of observation of these weaker transitions in the radioactive-decay studies is quite understandable since the levels are weakly populated in the β decays. The 928.9-keV transition was observed as a very weak line in the Ge spectra at the highest bombarding energies. The transition of 617.7 keV expected from the decay of this state to the state at 311.2 keV was not observed in the Ge spectra because of the presence of the stronger line at 616.3 keV. Coincidences, however,

TABLE I. Gamma-ray intensities and energies. Ru^{101}.

E_γ (keV)	Intensity (γ rays per 10^{10} incident α) E_α (MeV): 7.03	6.86	6.25	5.66	Identification
110.7±0.3	6	3	4	2	422.0 → 311.2
114.8±1.0	···	2	2	···	422.0 → 306.8
127.2±0.2	1230	1100	840	550	127.2 → 0
136.3±0.2	···	···	···	···	Ta^{181}
165.2±0.5	···	···	···	···	Ta^{181}
174.7±0.2	15	11	6	2	719.9 → 544.9
184.1±0.1	260	220	140	80	311.1 → 127.2
197.8±0.1	57	50	33	19	325.0 → 127.2
233.7±0.1	24	20	12	5	544.9 → 311.2
238.1±0.1	28	24	13	6	544.9 → 306.8
294.8±0.2	85	73	45	23	422.0 → 127.2
306.8±0.2	140	100	75	39	306.8 → 0
311.1±0.2	39	30	22	12	311.2 → 0
325.0±0.3	10	11	7	4	325.0 → 0
357.7±0.2	15	11	9	5	Ru^{104}
408.4±0.3	6	3	3	0.7	719.9 → 311.2
413.1±0.2	12	10	4	1.4	719.9 → 306.8
422.0±0.1	44	34	23	21	422.0 → 0
475.2±0.2	53	45	27	11	Ru^{102}
489.1±0.2	24	13	7.4	3.5	616.3 → 127.2
496.4±0.2	21	14	7	2.6	623.5 → 127.2
511.0±0.2	···	···	···	···	Annihilation radiation
544.9±0.1	610	510	270	120	544.9 → 0
616.3±0.3	21	17	8	3	616.3 → 0
623.2±0.6	9	6	2	1	623.5 → 0
708.8±0.3	5	3	3	1.6	?
720.1±0.2	153	122	57	20	719.9 → 0
928.9±1.5	4	1.3	···	···	928.9 → 0

[16] The spin and parity assignments shown in Fig. 2 were derived from the following data: ground state—measured directly (Ref. 17); 127.2 keV—angular distribution of γ rays from Coulomb excitation with heavy ions (Ref. 12), γ-γ directional correlation data on the decay of Rh^{101}, and the $M1$-$E2$ multipole order of the 127-keV transition determined from conversion coefficient measurements; 306.8 keV—gamma-ray branching to the 127-keV level and population by allowed β decay from the $\frac{9}{2}+$ Rh^{101} isomer; 311.2 keV—probable assignment, gamma-ray branching to the 127-keV level and the absence of direct population by beta decay; 325.0 keV—γ-γ directional and polarization correlation data (Ref. 18) on the decay of the $\frac{1}{2}-$ Rh^{101} isomer; 422.0 keV—logft in β decay of $\frac{1}{2}-$ Rh^{101} isomer and γ branching; 544.9 keV—logft in β decay of Tc^{101} and γ branching; 719.9 keV—logft in β decay of Tc^{101} and γ branching; 928.9 keV—observation of $E2$ excitation and logft in β decay of Tc^{101}.

[17] J. H. E. Griffiths and J. Owen, Proc. Phys. Soc. (London) **A65**, 951 (1952).

[18] G. T. Wood, S. Koički, and A. Koički, Phys. Rev. **150**, 956 (1966).

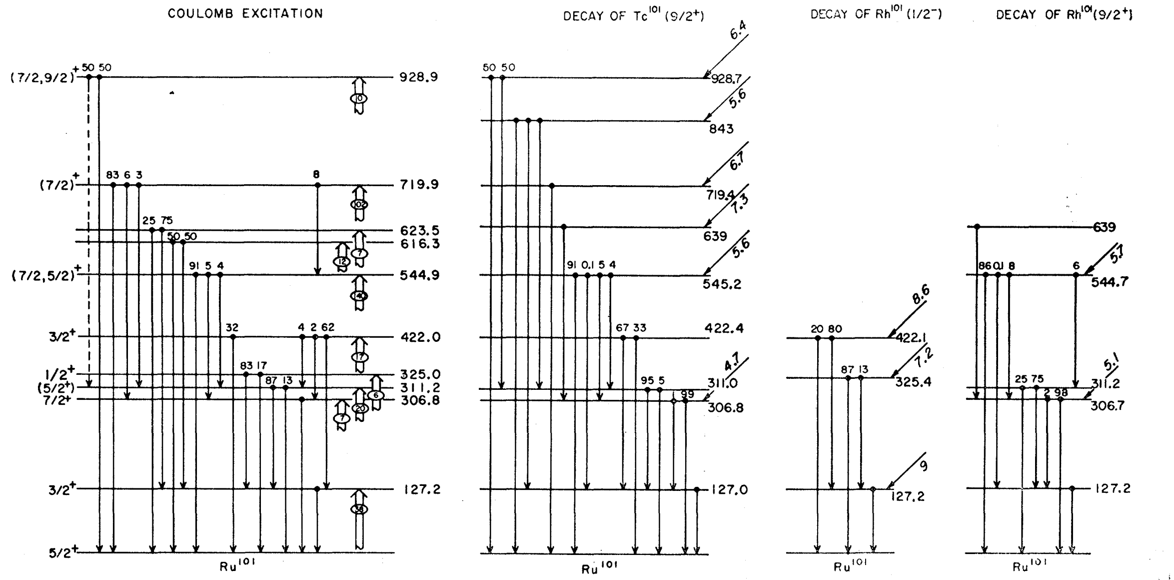

FIG. 2. Level schemes of Ru^{101}. The data for the radioactive decay schemes are from Refs. 1–4. (For the decays of Rh^{99} and Rh^{99m} we have given our estimates of the best values of energies and intensities combining the work of Refs. 1–3.) Logft values for the β-decay feeding of the levels are given in italics. The Coulomb-excitation $B(E2)$ values are shown in the ovals of the upward arrows and are given in the units $e^2\times10^{-51}$ cm^4. Gamma-ray branching ratios are given as percentages of the total γ decay from a given level.

were observed between the 184-keV transition in the Ge counter and a line at about 600 keV in the NaI detector. (The reverse coincidence, 617 in Ge and 184 in NaI, is not seen because of the much lower efficiency.) The relative intensities of the branches from each level shown in the scheme are consistent with the observed branching ratios of the radioactive-decay work, which generally have quite large errors.

B. Determination of B(E2↑) Values

Spectra were measured with the NaI detector at α-particle energies of between 4.5 and 7.1 MeV. A typical spectrum, obtained at 6.66-MeV α-particle energy is shown in Fig. 3. The positions of the significant known lines observed in the Ge spectra are indicated by arrows in the figure. It should be noted that the absolute intensities of the lines at 720, 545, and 127 keV can be determined from these spectra with only a very small correction for neighboring lines (see relative intensities of neighboring lines in Table I). The intensities of these three lines were then determined at the various bombarding energies using known absolute efficiency and geometric corrections for the 3×3 in. NaI detector.

These three γ transitions form the dominant modes of de-excitation of the levels at 719.9, 544.9, and 127.2 keV, respectively. In order to determine the absolute $B(E2\uparrow)$ for these levels from these intensities it is necessary to know the branching ratios of other γ rays depopulating these levels and also of possible feeding from levels above. The feeding of the levels varies with bomdarding energy. To determine these branches and feeding, the relative intensities determined from the Ge(Li) spectra were plotted as a function of α energy and appropriate values used in interpretation of the NaI data. [In calculating the various transition intensities, the conversion coefficients of the various transitions were taken from the work of Connors[2] or from theoretical tables.[19] The only large correction is for $\alpha_T(127.2)=0.160$ (Ref. 2).] After correction for feeding and branching,

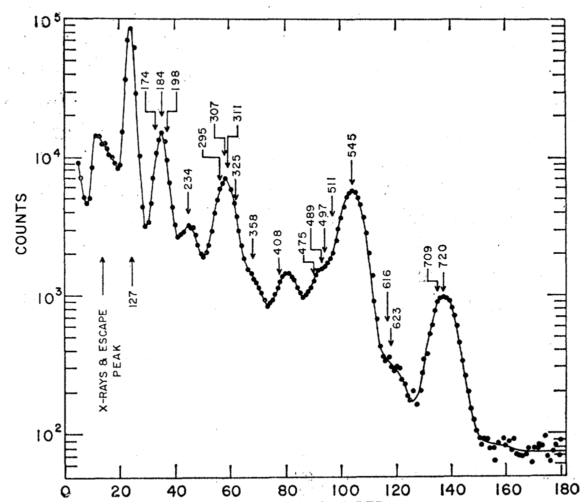

FIG. 3. NaI(Tl) counter pulse-height spectrum of γ rays from 6.66-MeV α-particle bombardment of Ru^{101}. The positions of lines observed in the Ge(Li) spectrum are shown.

[19] L. Sliv and I. Band, Lenningrad Physico-Technical Institute Report, 1956 [English transl.: Report 57ICCK1, issued by Physics Department, University of Illinois, Urbana (unpublished)]; *Internal Conversion Coefficients*, edited by M. E. Rose (North-Holland Publishing Company, Amsterdam, 1958).

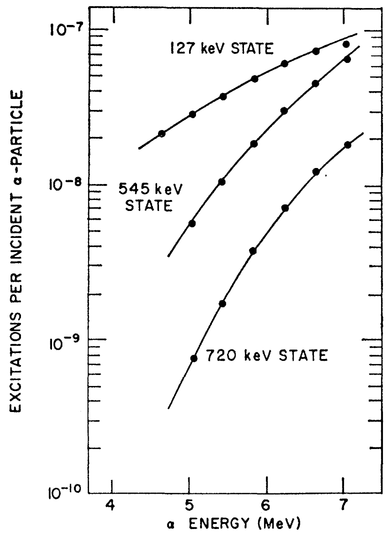

FIG. 4. Coulomb-excitation functions for three states in Ru^{101}. The points are the experimental values and the solid curves are theoretical, normalized excitation functions. The statistical errors in the data are small. The major cause for deviation from the lines is probably the uncertainties in background subtraction at the lower bombarding energies. For the 545- and 720-keV states, the total direct-excitation yield of the level is given; for the 127-keV level, only the yield resulting in γ rays (not including conversion electrons) is presented.

the absolute direct-excitation yields are obtained for the three levels. These yields are plotted in Fig. 4. [Note, that for the 127.2-keV level, only the yield of excitations resulting in γ rays is given. Correction for the conversion coefficient of the 127.2-keV transition was only used in computing the effect of feeding of the level. The determination of a more precise value for α_T for this transition and the total excitation probability is discussed below.] Values of $B(E2\uparrow)$ were calculated at each bombarding energy. Weighted averages (more weight was given to the runs at higher bombarding energy because of smaller background corrections) of the $B(E2)$ values were calculated and are presented in Table II. In all of these calculations, the statistical errors are negligible. The external errors of the $B(E2)$ values as calculated at the different bombarding energies are of the order of 2%. Estimates of the

TABLE II. $B(E2)$ values for states in Ru^{101}.

State E (keV)	$B(E2\uparrow)$ ($e^2\times10^{-48}$ cm^4)	J	$B(E2\downarrow)$
127.2	$(0.032\pm0.003)(1+\alpha)$ $=0.038\pm0.004$	$\frac{3}{2}$	0.057
306.8	0.007 ± 0.002	$\frac{7}{2}$	0.005
311.2	0.020 ± 0.003	$(\frac{5}{2})$	(0.020)
325.0	0.006 ± 0.001	$\frac{1}{2}$	0.018
422.0	0.017 ± 0.002	$\frac{3}{2}$	0.025
544.9	0.140 ± 0.010	$(\frac{7}{2},\frac{5}{2})$	(0.105, 0.140)
616.3	0.012 ± 0.002	?	...
623.5	0.007 ± 0.002	?	...
719.9	0.102 ± 0.008	$(\frac{7}{2})$	(0.077)
928.9	$0.010_{-0.005}^{+0.010}$	$(\frac{7}{2},\frac{9}{2})$	(0.007, 0.006)

systematic errors arising from uncertainties in efficiency calculations, beam-current integration, theoretical thick-target-yield calculations, and background corrections result in the errors quoted in the table.

Since only the relative intensities of γ rays were determined from the Ge spectra it is only possible to obtain relative $B(E2\uparrow)$ values for the other states from these data. These values were calculated for each level shown in the scheme, using the relative intensities given in Table I. It was assumed in all cases that the unbalance in feeding into and out of a given level was due to direct Coulomb excitation. These calculations were performed for the four bombarding energies at which the Ge(Li) spectra were measured. For each bombarding energy the relative $B(E2)$ for the 127.2-, 544.9-, and 719.9-keV states were compared with the absolute $B(E2)$ values determined from the NaI data described above, and a normalization constant was obtained. The $B(E2)$ values for the other states were then determined therefrom. (In addition, the ***absolute*** γ intensities for all the γ rays, which are given in Table I, were also determined.) For each of the states, the $B(E2)$ values obtained at each of the four bombarding energies agree within about 10%. In other words, one may conclude that the excitation, so calculated, is properly following the theoretical $E2$ excitation functions. The average of the $B(E2)$ values with estimated errors (considerably larger than suggested by the internal consistency of the data) are presented in Table II. The value for the 127.2-keV state is in very good agreement with the measured $B(E2)$ of Ritter *et al.*[12] obtained by Coulomb excitation with Ne^{20} ions.

C. Multipole Mixing Ratio for the 127.2-keV Transition

The lifetime of the 127-keV state has been measured by Connors and Schwarzschild[2,9] as $\tau_{1/2}=(6.3\pm0.3)\times10^{-10}$ sec. Given this value, $B(E2\uparrow)$ may be written as a function of δ^2 and the theoretical conversion coefficients. $B(E2\uparrow)$ deduced from the Coulomb-excitation data again depends on the value taken for δ^2 because of the corrections for internal conversion discussed above. These two simultaneous relations were solved graphically with the result that $\delta^2=0.026\pm0.004$. (The theoretical value of the total conversion coefficient[19] corresponding to this mixing ratio is $\alpha_T=0.170\pm0.002$.) The value of $B(E2\uparrow)$ corresponding to this solution is the one given in the table for the 127.2-keV level.

There have been several other measurements from which the mixing ratio of the 127-keV transition can be determined. The conversion coefficient α_K of the transition has been measured.[2] The angular distribution of γ rays following Coulomb excitation by Ne^{20} ions was measur d by Ritter *et al.*[12] Angular and polarization-correlation measurements have been performed[18] on a cascade in the decay of Rh^{101g}. The value for δ^2 resulting from each of these measurements is presented in Fig. 5.

The agreement between the various values of δ^2 is good. Since the value of δ^2 is so small, the agreement is not a sensitive test of the accuracy of our Coulomb-excitation result.

D. Other Transition Probabilities and Level Lifetimes

If the spin of the excited level differs from the ground state by 2 units, then the downward transition has pure quadrupole character. The knowledge of the $B(E2\uparrow)$ (and the intensity, but not necessarily the mixing ratio of the other modes of de-excitation of the level), allow calculation of the lifetime of the level. In Ru^{101} the only excitation in which it is clearly known[18] that $\Delta J=2$ is the excitation of the state at 325.0 keV. From the $B(E2\uparrow)$ for this state and the known branching, we calculate that τ_m(325.0-keV state)$=(2.2\pm0.5)\times10^{-10}$ sec. The mixing ratio $\delta^2=0.014\pm0.007$ for the 197.8-keV transition from the state at 325.0 keV is also known from the angular-correlation studies of Wood *et al.*[18] Using this value, the above lifetime for the level and the measured branching ratio we calculate that the partial γ-ray lifetimes for the 197.8-keV transition are as follows: $\tau_\gamma(E2)=1.9\times10^{-8}$ sec and $\tau_\gamma(M1)=2.8\times10^{-10}$ sec.

If the multipole mixture ($E2$-$M1$) for the ground-state transition is not known, one can still obtain an *upper limit* to the state lifetime by assuming that the transition is pure $E2$. This can be done, of course, for all the levels excited. In most cases this gives little interesting information. The only case in which this limit yields particularly interesting results is for the 719.9-keV state. In that case it can be concluded that τ_m(719.9-keV state)$<5.4\times10^{-12}$ sec and that the partial lifetime for the 174.7-keV transition which branches from this state is τ_γ(174.7 keV)$<6.8\times10^{-11}$ sec. This lifetime is quite short and will be discussed below.

V. Ru^{99}

A. Ge(Li) Spectra and Decay Scheme

The gamma-ray spectrum from the excitation of Ru^{99} was observed with the Ge(Li) counter at only one bombarding energy. This spectrum, taken with 6.95-MeV α particles, is shown in Fig. 6. The energies of the observed lines, their intensities, and identification are given in Table III. Figure 7 gives a level and decay scheme for both the Coulomb excitation and the radioactive decays. The energies of the lines observed in the decay studies are accurate to $\sim$1 keV. The Coulomb-excitation spectrum was energy-calibrated with a precision pulser using Cs^{137} for calibration of the pulser output.

All the coincidences expected from the level scheme were observed in the γ-γ coincidence spectra. Two γ rays are placed in the Coulomb-excitation scheme that were not observed in the decay-scheme studies. The

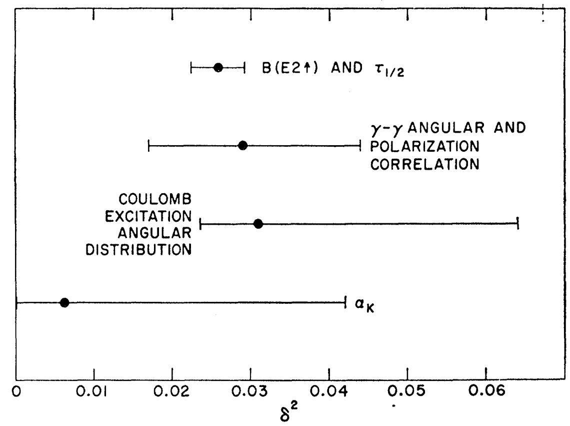

FIG. 5. Values of $\delta^2=E2/M1$ for the 127.1-keV transition as derived from various experiments.

101.4-keV γ ray from the 719.2- to 617.3-keV levels fits on the basis of energy sums as placed, (but could also lie between the 442.0- and 340.4-keV levels). This γ ray was clearly seen with proper intensity in coincidence with the 617-keV transition which is the basis for our assignment. The 378.8-keV γ ray was found in coincidence with the 340.5-keV transition. Its energy agrees with the level spacing to better than 0.2 keV. The 233-keV γ ray between the 322.1- and 89.4-keV levels observed in the decay of Rh^{99} ($\frac{1}{2}-$) was not observed, but its intensity should have been extremely weak in Coulomb excitation.

It is curious that apparently two levels exist in Ru^{99} at 618±1 keV, one of low spin and one of high spin. It is clear from the radioactive-decay schemes that two levels exist, since the branching ratios of γ rays depopulating these states are completely different in the decays of Rh^{99} and Rh^{99m}. From the observed branching

TABLE III. Gamma-ray intensities and energies; Ru^{99}.

E_γ (keV)	Intensity (γ rays per 10^{10} incident 6.95-MeV α particles)	Identification
89.4±0.1	1150	89.4 → 0
101.4±0.8	4	719.2 → 617.3
127.1±0.5	6	Ru^{101}
135.8±0.3	10	Ta^{181}
151.7±0.8	2.5	?
276.8±0.2	21	617.3 → 340.4
322.1±0.4	18	322.1 → 0
340.5±0.2	33	340.4 → 0
352.6±0.2	85	442.0 → 89.4
378.8±0.8	6	719.2 → 340.4
416.2±1.5	11	?
474.8±0.5	17	Ru^{102}
486.0±0.2	55	575.5 → 89.4
510.9±0.3		annihilation $\beta+$
527.9±0.4	36	617.3 → 89.4
539.6±1.0	16	Ru^{100}
575.6±0.3	33	575.5 → 0
617.4±0.2	195	617.3 → 0
719.2±0.2	210	719.2 → 0
871.0±0.8	...	O^{17}

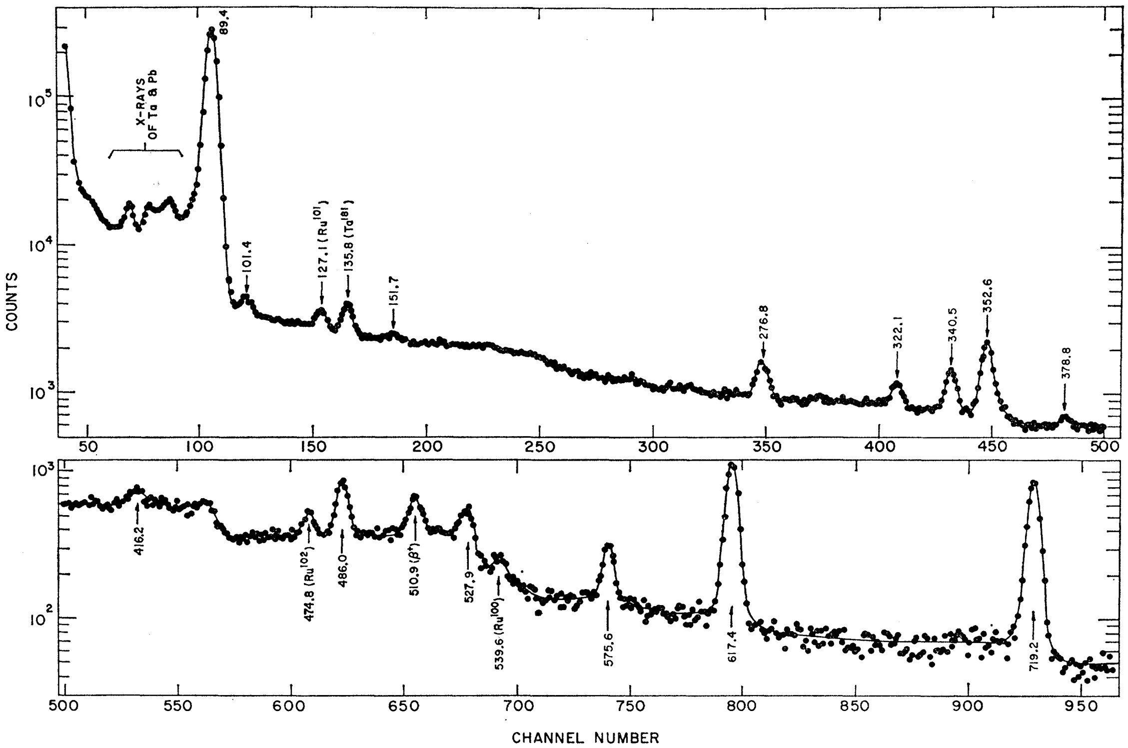

FIG. 6. Li(Ge) counter pulse-height spectrum of γ rays from 6.95-MeV α-particle bombardment of Ru^{99}. The actual spectrum was measured up to channel number 2048. The only line structure above the region shown was the 871.8-keV line due to O^{17}.

in Coulomb excitation it is clear that the dominant excitation is to the high-spin level. A weak excitation of the low-spin level cannot be excluded. We have analyzed our data on the assumption that only one level is populated at this energy. The spin assignments for the various levels shown in Fig. 7 were again derived mostly from the radioactivity data.[20]

B. Determination of $B(E2\uparrow)$ Values

Figure 8 shows the spectrum obtained with the NaI counter at 7.1-MeV bombarding energy. Similar spectra were obtained over a range of bombarding energies from 4.5 to 7.1 MeV. The positions of the known lines observed in the Ge detector spectrum are indicated. It is clear that the NaI spectra can be analyzed unambiguously for the absolute yields of the 719.2-, 617.4-, and 89.4-keV lines. The total number of excitations of the 617.4- and 719-keV levels were determined using the branching ratios from the scheme of Fig. 7. The resulting yields are shown in Fig. 9. The solid curves are theoretical $E2$ excitation functions. The values of $B(E2\uparrow)$ given in Table IV have been obtained from the normalization of the curves to the data.

The 89.4-keV level is fed appreciably from levels above. We assume that all the intensity imbalance of γ rays to and from levels found in the Ge spectrum is due to direct Coulomb excitation of the various levels. From the theoretical excitation functions for the different levels we compute the feeding of the 89.4-keV level at different bombarding energy. This feeding is then approximately corrected for the conversion of the 89.4-keV transition to give the fraction of observed 89.4-keV γ rays which are a result of feeding from higher levels. These calculations indicate that at respective bombarding energies of 4.6 and 7.1 MeV, 2% and 13% of the 89.4-keV γ rays are the result of feeding from excitation of higher levels. After correction for this feeding, the

TABLE IV. $B(E2)$ values for states in Ru^{99}.

State E (keV)	$B(E2\uparrow)$ ($e^2\times10^{-48}$ cm^4)	J	$B(E2\downarrow)$
89.4	$(0.034\pm0.004)(1+\alpha)$ $=0.087\pm0.010$	$\frac{3}{2}$	0.150
322.1	≤0.002	$(\frac{5}{2},\frac{7}{2})$	≤0.003
340.4	≤0.001	$(\frac{7}{2},\frac{9}{2})$	≤0.002
442.0	0.012 ± 0.002	$\frac{3}{2}$	0.018
575.5	0.024 ± 0.003	?	...
617.3	0.083 ± 0.008	$(\frac{7}{2})$	(0.062)
719.2	0.128 ± 0.015	$(\frac{7}{2},\frac{9}{2})$	(0.096, 0.077)

[20] The spin assignments for the various levels shown in Fig. 7 were derived from the following data: ground state—measured directly (Ref. 17); 89.4 keV—Mössbauer effect studies (Ref. 6); 322.1 keV—derived from conversion and γ-γ correlation in decay of Rh^{99}; 340.4 keV—from β decay of Rh^{99m} logft; 442.0 keV—known from γ-γ correlation and ft in Rh^{99} decay (Ref. 2); 575.5 keV—unknown; 617.3 keV—ft in Rh^{99m} decay and strong γ branch to 89.4-keV level; 719.2 keV—ft value in decay of Rh^{99m}.

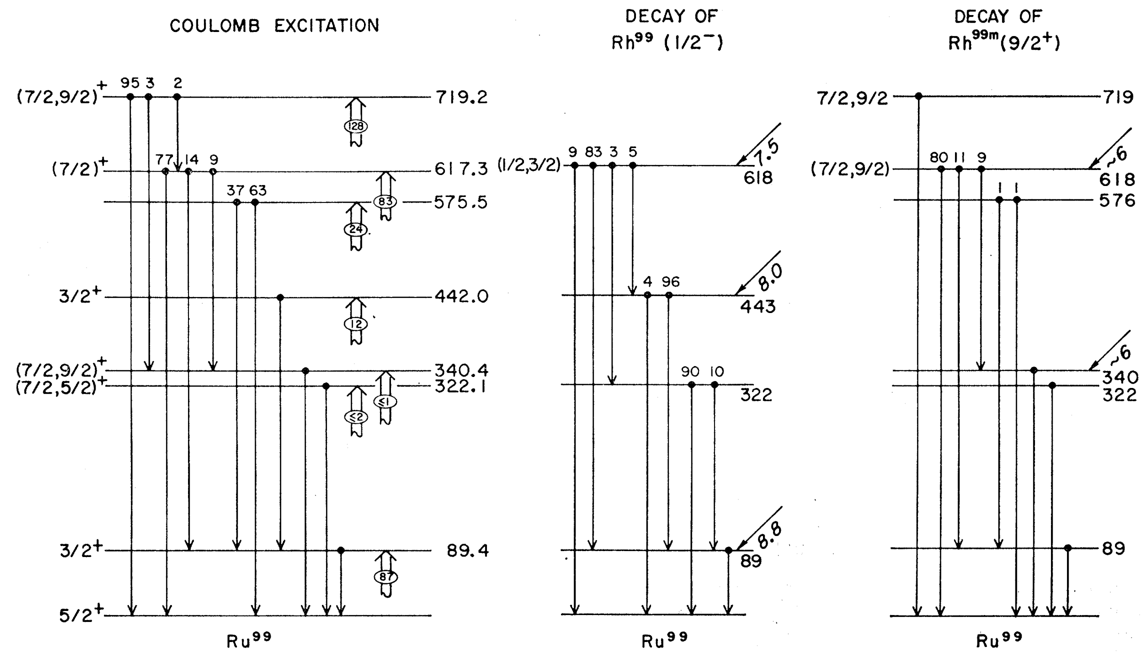

FIG. 7. Level schemes of Ru^{99}. The radioactive-decay schemes are from Ref. 2. For notation, see caption of Fig. 2.

absolute yield of direct excitation is obtained. These data are also shown in Fig. 9. Note that for this transition only the γ-ray yield is given and correction must be made for the internal conversion to obtain the total state excitation probability.

The decay scheme and relative intensities of transitions derived from the Ge spectrum can be used to obtain *relative* Coulomb-excitation yields for the other levels. As before, the assumption is made that all intensity imbalances in the γ-ray intensities are due to direct excitation of the level involved. In this analysis it is assumed that the internal-conversion coefficients of the 101.4- and 89.4-keV transitions are 1.2 and 1.55,[2] respectively, and that all other internal conversion is insignificant. The relative excitation probabilities are normalized to the absolute $B(E2)$ values derived from the NaI data for the 89.4-, 617.3-, and 719.2-keV levels. (The agreement for these levels is better than 15%.) The *absolute* γ-ray yields obtained are given in Table III. $B(E2)$ values are then directly obtained for the different levels and presented in Table IV. The derived $B(E2)$ values for the 340.4- and 322.1-keV levels have large uncertainties since the yields are small. Possible weak unobserved γ-ray feeding by several γ rays to each level cannot be excluded. Thus the $B(E2)$ values for these levels are given only as upper limits.

C. Other Transition Probabilities

The lifetime of the 89.4-keV state has been measured electronically by Kistner *et al.*[8] and more recently and more accurately by Matthias, Rosenblum, and Shirley.[21] The results of these authors are that $\tau_{1/2}=(20\pm1)$ nsec and $\tau_{1/2}=(20.7\pm0.3)$ nsec, respectively. In addition,

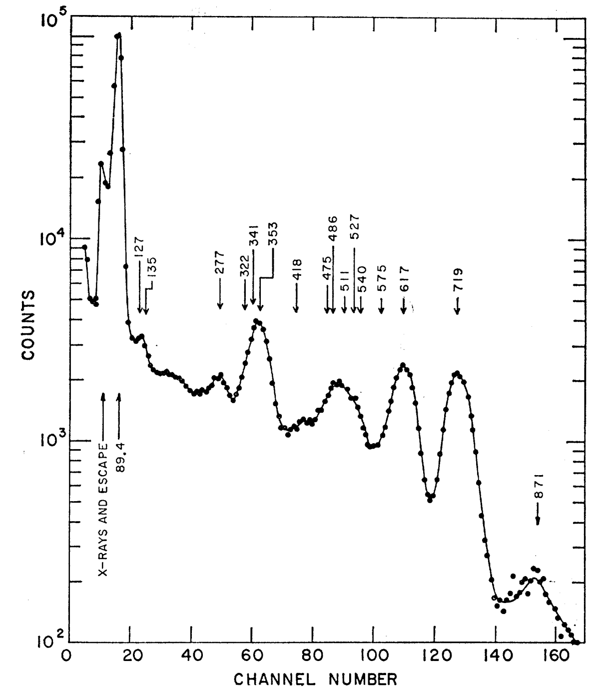

FIG. 8. NaI(Tl) detector pulse-height spectrum of γ rays from 7.1-MeV α-particle bombardment of Ru^{99}. The positions of lines observed in Ge(Li) spectrum are indicated.

[21] E. Matthias, S. S. Rosenblum, and D. A. Shirley, Phys. Rev. **139**, B532 (1965).

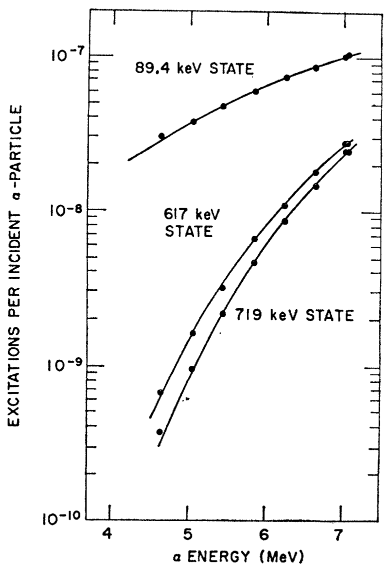

FIG. 9. Coulomb-excitation functions for three states in Ru^{99}. The points are the experimental values and the solid curves are theoretical, normalized excitation functions. The statistical errors in the data are small. The major cause for deviations from the lines is probably the uncertainties in background subtraction. For the 617- and 719-keV states, the total direct-excitation yield is given; for the 89.4-keV state, only the yield resulting in γ rays (not including conversion electrons) is presented.

the $E2$-$M1$ mixing ratio has been determined from Mössbauer studies[6] and further confirmed by measurements of the L conversion electron subshell ratios.[2] These measurements yield $\delta^2=2.7\pm0.6$. Combination of this value with theoretical total conversion coefficients[19] and the measured state lifetime yields a value of the partial $E2$ γ-ray mean-life of $\tau_\gamma(E2)=(106\pm4)$ nsec. This can be compared with the value $\tau_\gamma(E2)=(109\pm13)$ nsec obtained directly from the measured $\epsilon B(E2\uparrow)$ using the above mixing ratio to determine $\epsilon=(1+\alpha_T)^{-1}$. Since δ^2 is large for this transition, the agreement is a significant confirmation of the measured $B(E2)$ value, but a more accurate value of δ^2 cannot be determined from combination of the $B(E2)$ value and the measured lifetime. The value of the partial $M1$ γ-ray lifetime is $\tau_\gamma(M1)=2.9\times10^{-7}$ sec.

As described in Sec. IV, it is possible to calculate upper limits for partial lifetimes for branching γ rays from levels which are directly Coulomb excited. The most significant one in Ru^{99} is the 101.4-keV transition between the 719.2- and 617.3-keV states. The result for this transition is $\tau_\gamma(101.4\text{ keV})<1.4\times10^{-10}$ sec. This limit indicates a very fast $M1$ transition, which will be discussed below.

TABLE V. Enhancements of $E2$ transitions to the ground states of Ru^{101} and Ru^{99}.

State (keV)	J	F_M[a]	F_{Ph}[b]
Ru^{101}			
127.2	$\frac{3}{2}$	46	0.5
306.8	$\frac{7}{2}$	13	0.05
311.2	$(\frac{5}{2})$	6	0.2
325.0	$\frac{1}{2}$	2	0.16
422.0	$\frac{3}{2}$	20	0.2
544.9	$(\frac{7}{2},\frac{5}{2})$	(250,40)	(0.9,1.2)
616.3	?	4[c]	0.1–0.3
623.5	?	2[c]	0.05–0.2
719.9	$\frac{7}{2}$	190	0.7
928.9	$(\frac{7}{2},\frac{9}{2})$	(15,1.5)	(0.1,0.3)
Ru^{99}			
89.4	$\frac{3}{2}$	110	1.4
322.1	$(\frac{5}{2},\frac{7}{2})$	<4	<0.02
340.4	$(\frac{7}{2},\frac{9}{2})$	<2	<0.01
442.0	$\frac{3}{2}$	4	0.2
575.5	?	9[c]	0.2–0.8
617.3	$(\frac{7}{2})$	(150)	(0.65)
719.2	$(\frac{7}{2},\frac{9}{2})$	(240,20)	(0.8,1.0)

[a] F_M is the ratio $B(E2\uparrow)/B_{SP}(E2\uparrow)$, where the value for B_{SP} is the Moszkowski estimate discussed in the text.
[b] F_{Ph} is the ratio $B(E2\downarrow)/B_{2\to0}(E2)$. $B_{2\to0}(E2)$ is taken for the next lowest even-mass nuclei, i.e., Ru^{100} and Ru^{98}. $B_{2\to0}(E2)=0.114e^2\times10^{-48}$ cm² for Ru^{100} and $0.095e^2\times10^{-48}$ cm² for Ru^{98} as taken from the recent compilation of Stelson and Grodzins (Ref. 7).
[c] The spin of the level is not known. The quantity $(2J_e+1)C$ has been taken equal to 1 in the single-particle estimates for these cases.

VI. DISCUSSION

A. Transition Probabilities

Tables II and IV present $B(E2\uparrow)$ values[22] for transitions from the ground states to many levels in Ru^{99} and Ru^{101}. For levels where the spin is reasonably well known, the $B(E2\downarrow)$ are also given. From estimates of the intensity of possible unobserved transitions, it can be concluded that there are no unobserved levels in either nucleus below 1.1-MeV excitation energy which have $B(E2\uparrow)$ from the ground state greater than $0.04e^2\times10^{-48}$ cm⁴.

In Table V the $E2$ transition speeds between the ground and the various excited states are compared to two rather simplified estimates. Column 3 presents the ratio of the measured $B(E2\uparrow)$ to the Moszkowski single-particle estimate.[23] The Moszkowski estimate can

[22] These results are to be compared with the following previous measurements. Coulomb excitation of Ru nuclei has been investigated by Temmer and Heydenburg (Ref. 10) and McGowan and Stelson (Ref. 11) using α particles and by Ritter *et al.* (Ref. 12) using Ne^{20} ion bombardment. For the 89-keV state of Ru^{99}, Temmer and Heydenburg obtained the value $\epsilon B(E2\uparrow)=0.054$ [all $B(E2)$ in this paragraph are given in units of $e^2\times10^{-48}$ cm⁴] to be compared with our value of 0.034. For the 127-, 307-, and 522-keV states of Ru^{101}, they obtained the values 0.061, 0.036, and 0.041. If we assume that their 522-keV state is actually our 545-keV state, then our corresponding values are 0.032, 0.007, 0.140. It is clear that there is essentially no agreement with our results. This is perhaps not surprising in view of the complexity of the level schemes. The work of McGowan and Stelson is not published. Only a table of γ-γ coincidences observed with NaI counters are given in the *Nuclear Data Sheets* (Ref. 5), and those results are somewhat at variance with our decay sheme, probably because of the relatively poor energy resolution of the detectors. In the work of Ritter *et al.*, a value of $\epsilon B(E2)$ for the 127-keV state of Ru^{101} is given equal, to 0.028. Our value is in very good agreement with this number.

[23] S. A. Moszkowski, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), Vol. II, p. 863.

be written in the form

$$B_{SP}(E2\uparrow)=0.0028(A/100)^{4/3}(2J_e+1)\times[C(J_e,J_g,2;\tfrac{1}{2},-\tfrac{1}{2},0)]^2e^2\times10^{-48}\text{ cm}^4,$$

where A is the nuclear mass, J_e is the excited-state spin, J_g is the ground-state spin (a radius constant of 1.2 F has been used). The "statistical factors" for $J_g=\frac{5}{2}$ vary for different states over almost a factor of 10. The quantity $(2J_e+1)[C(J_e,\frac{5}{2},2;\frac{1}{2},-\frac{1}{2},0)]^2$ has the values 1.0, 0.3, 1.14, 0.19, 2.38 for J_e of $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, $\frac{7}{2}$, $\frac{9}{2}$, respectively. In several cases, where the level spin is uncertain, two or more values are given for F_M.

Column 4 presents the ratio of the measured $B(E2)$ values to the $0\rightarrow2$ transitions of the neighboring even-even Ru isotope. Note, that as defined in footnote b to the table, the ratio is with respect to the *de-excitation* $B(E2)$ values.

In Secs. IV C, IV D, and V C several other transition probabilities are derived. These transitions are identified and their rates compared with the Moszkowski estimates in Table VI. Again the statistical factors are included. For the 174.7- and 101.4-keV transitions in Ru^{101} and Ru^{99}, the multipole order has not been determined experimentally. In both cases, these transitions compete with much higher energy, very enhanced, $E2$ transitions. We therefore infer that the dominant parts of the low-energy transitions must be $M1$ in character.

B. Comparison with Nuclear Models

The level structure of the odd-mass Ru nuclei is quite complicated. The level structure in the lowest 1 MeV of excitation has only recently been investigated experimentally from β-decay studies. Almost no nuclear-reaction work has been published on nuclei in this region. Similarly, there appears to be almost no theoretical discussion in the literature of the nuclei of this region.

The approximate positions of the single-particle levels in this region indicate that the low-lying level structure cannot be described by the simple shell model. Almost certainly the dominant character of the ground state of the odd-mass ruthenium isotopes is $d_{5/2}$. The single-particle energies for the $g_{7/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$ orbitals which lie within the same major shell are all more than 1.5 MeV above the $d_{5/2}$ level. However, there are of the order of 10 levels in these nuclei below 1 MeV. As evidenced by the very strong $E2$ transitions to several of these levels, there must be appreciable collective excitation associated with them.

There seems little point at present to try to explain all the $B(E2)$ values which we have determined. However, in both nuclei there are apparently at least three transitions which have very large $B(E2)$ values which should probably be associated with the collective 2+ excitations of the even-even core. Kisslinger and Sorensen[24] have attempted to calculate in detail the properties of many nuclei using a pairing and long-range quadrupole force. A complete set of wave functions calculated on this model using the latest numerical parameters was obtained.[25] As pointed out in their review article, the model does not properly account for the level ordering in this region. However, the wave functions were searched for levels with large $B(E2)$ values to the ground state. Within the set of wave functions there are states with large components of $d_{5/2}$ coupled to one-phonon excitations. However, such states appear to exist below 2 MeV (theoretical excitation energy) for all possible resulting spins. There is no apparent selection of the particular spin states with large $B(E2)$ as observed. In addition, the calculations result in a considerable admixture of $d_{3/2}$ particle in the wave function which is not consistent with the large retardation of the $\frac{3}{2}\rightarrow\frac{5}{2}M1$ transition (89.4 keV) observed in Ru^{99}. The corresponding transition (127.1 keV) in Ru^{101} is not nearly so retarded, which suggests the considerable complexity of the wave functions of the states. It is also clear that the forces used do not properly account for the splitting of the phonon states.

It is interesting to compare our data with the core-excitation model. According to this model, a set of states should exist which correspond to the various possible couplings of the single odd nucleon to the collective 2+ excitation of the core. In addition to the center-of-gravity theorem for the energy of such states given by Lawson and Uretsky,[26] prescriptions for $E2$ and $M1$ transition probabilities and various other moments have been given by deShalit.[27] As applied in its simplest form to the odd Ru isotopes, this model predicts the existence of a multiplet of excited states of spins $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$, each of which has a $B(E2\downarrow)$ to the ground state equal to that of the $2\rightarrow0$ transition in the neighboring nucleus, i.e., F_{Ph} defined above should equal 1. In addition, the ground-state $M1$ transi-

TABLE VI. Enhancements of other transitions in Ru^{101} and Ru^{99}.

Energy (keV)	Identification	Multipole order	F_M
Ru^{101}			
127.2	$(127.2\rightarrow0)$	$M1$ part	1/12
197.8	$(325.0\rightarrow127.2)$	$M1$ part	1/120
197.8	$(325.0\rightarrow127.2)$	$E2$ part	2.5
174.7	$(719.9\rightarrow544.9)$	$(M1)$	>1/15
Ru^{99}			
89.4	$(89.4\rightarrow0)$	$M1$ part	1/10 000
101.4	$719.2\rightarrow617.3$	$(M1)$	>1/6

[24] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35**, 853 (1963).
[25] L. S. Kisslinger (private communication).
[26] R. D. Lawson and J. L. Uretsky, Phys. Rev. **108**, 1300 (1957).
[27] A. deShalit, Phys. Rev. **122**, 1530 (1961).

tion should be forbidden, whereas, if ΔJ permits, an $M1$ transition between members of the multiplet should be allowed.

It is clear from Table V that the condition $F_{\mathrm{Ph}}=1$ does not hold exactly and is approximately true for only 3 levels in each nucleus (127.2, 544.9, and 719.9 in Ru^{101} and 89.4, 617.3, and 719.2 in Ru^{99}). If the center-of-gravity theorem were to hold, the other members of the multiplet should lie below 1.1 MeV. (The 2+ state is at 654 keV and 540 keV in Ru^{98} and Ru^{100}, respectively.) The $M1$ of 89.4 keV in Ru^{99} is extremely highly retarded; however, the 127.2-keV transition in Ru^{101} is retarded only by a factor of 12. The transitions between some of the higher "members of the multiplet" appear to be rather fast $M1$ transitions (174.7 keV in Ru^{101} and 101.4 keV in Ru^{99}; see Table VI) in accordance with the model prediction. In addition, branching ratio arguments suggest that the ground-state $M1$ transitions from the higher levels of the multiplet are retarded, again in agreement with the model prediction.

It should be noted that the magnetic moments of the 89.4-keV state[6] in Ru^{99} and the 127.2-keV state[2] in Ru^{101} are known. They have been compared with the prediction of de-Shalit[27]; the agreement is reasonably good for Ru^{99} but poor[27a] for Ru^{101}.

In order to obtain quantitative agreement of the experiment with the core-excitation model, considerable mixing of states of other single-particle configurations must be invoked. Also, no obvious explanation of the "missing states" is available.

In connection with the decay-scheme work on Ru^{101}, Aras *et al.*[3] proposed a Nilsson-model description of the states of this nucleus. Their assignments apparently fit the γ-branching ratios and β-decay data rather well. However, in light of the present $B(E2)$ data it is clear that their assignments cannot be correct.

C. Sum of $E2$ Strengths

In addition to a discussion of the individual $E2$ transition strengths, it is of interest[28] to compare the sum of observed $E2$ strengths to that for the 2+ state of the neighboring even-even nucleus. The $\Sigma\, B(E2\uparrow)$ is equal to 0.38 and $0.34e^2\times10^{-48}$ cm^4 for Ru^{101} and Ru^{99}, respectively. This sum is equal to approximately 0.65 of the $B(E2;0\rightarrow2)$ for the neighboring even-even nuclei in both cases. Estimates of the sensitivity of our experiment to the excitation of higher energy excited states suggest that no more appreciable $E2$ strength exists for unobserved states below 1.1 MeV for either nucleus. The $\Sigma\, B(E2\uparrow)$ quoted above is therefore for excitation of all states up to 1.1 MeV.

In Ref. 28 it is pointed out that, in comparison of the $\Sigma\, B(E2\uparrow)$ in the odd nuclei to the value for the phonon, a term should be added to the sum to account for the quadrupole moment of the ground state. The fraction of the phonon speed missing from the sum of the measured transitions would be accounted for if the ground-state quadrupole moment were approximately 0.9 b. In the immediate region of the Ru nuclei, no quadrupole moments have been measured. However, for the nuclei $_{48}Cd_{59}{}^{107}$, $_{48}Cd_{61}{}^{109}$, and $_{48}Cd_{63}{}^{111*}$ which also have spin $\frac{5}{2}$, the quadrupole moment is equal to $\sim$0.8 b, indicating a considerable collective contribution.[29–31] If such a large quadrupole moment in the Ru isotopes is the result of admixtures of 1-phonon amplitude to the ground state of the Ru nuclei, then it remains to explain the extremely slow $M1$ transition from the 89.4-keV state in Ru^{99}. In addition, the results of Mössbauer measurements[6] indicate that $Q_{89.4\ \mathrm{keV}}>3Q_0$ in Ru^{99}. Thus if Q_0 is of the order of 1 b, the quadrupole moment of the excited state would be very large.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Chellis Chasman and Dr. Robert Ristinen for lending us the excellent Ge(Li) detectors which they constructed. Also, their constant advice regarding the electronics and pulse-height calibration techniques were indispensable to this work. We also wish to thank Dr. Keith Jones and Dr. David Alburger and Robert Lindgren for providing a useful doubly charged α-particle beam from the Van de Graaff.

[27a] *Note added in proof.* K. Auerbach, K. Siepe, J. Wittkemper, and H. J. Körner [Phys. Letters **23**, 367 (1966)] have recently reported a new measurement of the magnetic g factor of the 127.2-keV state in Ru^{101}, which brings this case also into good agreement with the prediction of de-Shalit.

[28] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. **28**, 432 (1956), see paragraph VC.5; O. Nathan and S. G. Nilsson, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), Vol. 1, p. 644.

[29] F. W. Byron, Jr., M. N. McDermott, and R. Novick, Phys. Rev. **132**, 1181 (1963).

[30] M. N. McDermott and R. Novick, Phys. Rev. **131**, 707 (1963).

[31] H. J. Behrend and D. Budnick, Z. Physik **168**, 155 (1962).