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TRIAXIALITY AND ITS DYNAMICS IN ^{104}Ru INVESTIGATED BY
MULTIPLE COULOMB EXCITATION

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*Triaxiality and its dynamics in ^{104}Ru
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ABSTRACT

The electromagnetic properties of ^{104}Ru have been investigated by multiple Coulomb excitation. Thin and thick targets of ^{104}Ru have been bombarded with 4.6 MeV/u ^{208}Pb . From the measurement of particle-particle- γ coincidences and the γ -multiplicity (thin target) and $\gamma\gamma$ coincidences (thick target) the level scheme of ^{104}Ru could be extended appreciably. Numerous $B(E2)$ -values for the ground state band and excited bands as well as static quadrupole moments for the ground state band up to $I^\pi = 8^+$ could be determined by comparing experimental Coulomb excitation yields (thin target) to semiclassical calculations. The results are discussed in the framework of different collective models as the generalized collective model, the interacting boson model and the asymmetric rotor model considering especially the aspects of triaxial deformation and γ -softness. The electromagnetic moments show the first excited 0^+ -state not to be the predicted collective excitation but to belong to an intruder configuration.

$$E \left[\begin{array}{l} \text{NUCLEAR REACTION } ^{104}\text{Ru}(^{208}\text{Pb}, ^{208}\text{Pb}'), E = 4.6 \text{ MeV/u; measured} \\ \sigma(E_\gamma, \theta_\gamma, \theta_p) \text{ and } \gamma\gamma \text{ coin. } ^{104}\text{Ru} \text{ deduced levels, J, B(E2), Q. Enriched} \\ \text{targets.} \end{array} \right]$$

1. INTRODUCTION

The interest in the neutron-rich nuclei in the $A=100$ region has been stimulated by the prediction of a region of deformation in the middle of the $N=50-82$ shell. Deformed nuclei are known to exist for proton and neutron numbers in between the shell closures; the lanthanides and actinides with $Z=60-78$, $N=90-116$ and $Z>90$, $N>140$, respectively, are well known to be axially symmetric, strongly deformed prolate nuclei. However, different microscopic calculations^{1, 5)} for the middle of the $N=50-82$ shell ($Z=44-46$) revealed that the situation there is not as clear as for the "classical" deformed nuclei: around $A=100$ different types of deformation, prolate, oblate or triaxial seem to be possible; as none is energetically strongly favoured even a coexistence between different types of deformation may occur in one nucleus.

An answer to the question, whether these predictions have an experimental correspondence can be obtained only from systematic investigations of sequences of isotopes over adjacent mass numbers. In the series of Ru isotopes the nucleus ^{104}Ru , which will be the main object of this publication, plays a crucial role in this context. As the most neutron-rich stable isotope it represents the link between the nuclei around the shell closure at $N=50$ and the region far from stability, where detailed

spectroscopic information is difficult to achieve and hence rather scarce.

First evidence for an increase in collectivity with increasing neutron number is based on the properties of the lowest excited states in the neutron-rich ($N \geq 54$) Ru isotopes: the continuous decrease in the excitation energy $E(2_1^+)$ of the first excited 2^+ -state from ≈ 650 keV for ^{98}Ru to ≈ 240 keV for ^{110}Ru and the simultaneous increase of the ratio $E(4_1^+)/E(2_1^+)$ from 2.14 to 2.76 and of the $B(E2, 2_1^+ \rightarrow 0_1^+)$ -values from ≈ 20 to 65 single particle units^{8, 11)} point in this direction.

Previous information concerning the level scheme of ^{104}Ru was obtained by Sümmerer et al.¹²⁾ from $\gamma\gamma$ -angular correlation studies of the γ -radiation following the β^- -decay of $18.4 \text{ min-}^{104}\text{Tc}$. In allowed β -decay only levels up to a certain spin value are populated and in general no information about $B(E2)$ -values is obtained; in this case levels up to $\pi = 4^+$ could be identified. In Coulomb excitation experiments using light heavy ions ($\alpha, ^{16}\text{O}$) the lowest excited states $2_1^+, 4_1^+, 2_2^+$ and 0_2^+ were populated and the corresponding $B(E2)$ -values have been determined by McGowan et al.⁸⁾ and Landsberger et al.⁹⁾. Concerning the expected onset of deformation the experiments performed so far are encourage but more detailed information is needed: For the identification and interpretation

of possible band structures it is important to know the level energies of higher spin members ($I > 4$) as well as the electric matrix elements (ME) i.e. quadrupole moments and intra- and inter-band $B(E2)$ -values. Another interesting question is connected with the possible coexistence of different excitation modes; low lying excited 0^+ -states in the neutron-rich Mo, Ru and Pd isotopes are populated in two neutron transfer reactions with quite remarkable strength^{13, 15}); a fact which makes an interpretation of these states as "simple" collective excitations rather questionable. Again the knowledge of electric matrix elements should confirm or rule out the need for extra degrees of freedom in the interpretation of these low lying 0^+ -states and the bands built on them.

To obtain all these informations, multiple Coulomb excitation (MCE) seemed to be the most promising tool and therefore this technique has been used for the present investigation. In the following section we will present the experimental set-up we used to study the multiple Coulomb excitation of ^{104}Ru with ^{208}Pb projectiles. The resulting level scheme of ^{104}Ru is presented in section 3. In section 4 it is outlined, how the calculations for the Coulomb excitation process and the subsequent γ -decay are performed. From the comparison of the calculated γ -yields to the experimental ones $E2$ matrix elements - i.e. $B(E2)$ -values and quadrupole moments - could be determined; the corresponding analysis will be

described in section 5. The results of the present experiment stress the importance of the γ -degree of freedom for describing the onset of deformation in the $A \approx 100$ region; the discussion hence will be concentrated on the question of triaxiality and γ -softness.

2. EXPERIMENTAL PROCEDURE

The present multiple Coulomb excitation experiments on ^{104}Ru were performed using the ^{208}Pb -beam supplied by the Darmstadt UNILAC. All measurements were carried out at a projectile energy of 4.6 MeV/u, which corresponds to distances of closest approach of ≥ 16.5 fm, while the sum of the nuclear radii $r_0(A_1^{1/3} + A_2^{1/3})$ amounts to only 12.5 fm if a radius parameter¹⁶ of $r_0 = 1.18$ fm is assumed. Thus for all scattering angles the surfaces of the two colliding nuclei are more than 4.6 fm apart; at these surface distances the excitation probabilities are known¹⁷) not to be affected by nuclear interactions but to be solely due to the electromagnetic interaction between the projectile and the target nucleus. Inelastic scattering calculations with a realistic nuclear potential support this assumption; they will be described in more detail in section 4.1.

By using an experimental set-up shown schematically in fig.1 two measurements could be performed simultaneously:

(i) In the first experiment the ^{208}Pb beam of 4.6 MeV/u passed through a thin target of $520\mu\text{g}/\text{cm}^2$ ^{104}Ru (enriched to 99.15%), which was produced by sputtering the material onto a $34\mu\text{g}/\text{cm}^2$ carbon foil. Both, the recoiling target nuclei and the corresponding scattered projectiles were detected in two parallel plate avalanche detectors, which were position sensitive in ϑ -direction, ϑ being the polar angle with respect to the beam axis. The kinematic of the scattering system ^{208}Pb on ^{104}Ru allowed to use a symmetric set-up of the two detectors R and L, which covered a range of $17^\circ \leq \vartheta \leq 58^\circ$ each: For Ru recoil nuclei detected in either one of the two particle detectors the equivalent c.m. scattering angles of the Pb projectiles are $64^\circ \leq \vartheta \leq 146^\circ$, which correspond to laboratory scattering angles of $20.2^\circ \leq \vartheta \leq 30^\circ$ well within the range subtended by the other particle detector. In the azimuthal direction the two detectors covered a range of $\Delta\phi = \pm 28^\circ$ each.

As the distance between the target and the particle detectors was 145 mm, the time between the prompt anode signals of the two particle detectors allows for a unique identification of the particles, i.e. whether the Ru recoil nucleus has been detected in particle detector R or L. The angle calibration of the particle detectors was performed optically

and by measuring the maximum scattering angles for ^{208}Pb projectiles scattered from medium mass targets (^{90}Zr , ^{104}Ru , ^{120}Sn , ^{154}Sm). The accuracy of the absolute angle calibration is $\Delta\vartheta = \pm 0.5^\circ$ - it is of the same order as the angular resolution of the total system, which is mainly determined by the size of the beam spot. A more detailed description of the particle detectors and the continuous delayline read-out used to determine the ϑ -coordinate will be given in a forthcoming publication¹⁸).

The coincident γ -radiation was recorded by means of 3 Ge detectors and 2 NaI detectors. The positions of the γ -detectors are indicated in fig.1; the distances of the Ge detectors from the target were 90 mm (Ge2, Ge3) and 200 mm (Ge1). The data have been stored event by event on magnetic tape, each event consisting of the position, time and energy loss information of both particle detectors and time and energy signals of the five γ -detectors.

Fig.2(a) shows a γ -spectrum recorded with Ge2 in coincidence with two particles. Due to the large recoil velocities of up to 12% of the velocity of light and the large acceptance angles of the particle detectors the γ -lines are strongly Doppler broadened. The double bump structure of the peaks is due to the detection of the Ru recoil nuclei in either detector L (low energy bump) or R (high energy bump). Taking advantage of the fact

that the scattering process can be very well described by the elastic scattering relations and that the scattering angle is known, the kinematic of each scattering event can be reconstructed and the observed γ -energy can thus be corrected for the Doppler shift on an event by event basis. Fig.2(b) shows the spectrum of fig.2(a) after applying the Doppler correction and selecting only those events, where the recoil nuclei have been detected in particle detector L. The corresponding γ -spectrum with multiplicity 22, that is where at least one additional γ -detector has contributed, is displayed in fig.2(c). Note the relative enhancement of γ -rays depopulating higher excited states in this two-fold spectrum (fig.2(c)) as compared to the one-fold spectrum shown in fig.2(b).

To obtain the γ -yields as a function of the scattering angle θ , ten software windows were placed on the recoil angles and the corresponding γ -spectra were generated for each of the six possible Ge-particle detector combinations. Figs.2(d) and 2(e) show γ -spectra for two extreme scattering angles, i.e. two extreme impact parameters. At large impact parameters ($64^\circ \leq \theta \leq 70^\circ$, fig.2(d)) mainly low spin states are excited, whereas at small impact parameters ($126^\circ \leq \theta \leq 146^\circ$, fig.2(e)) the excitation of the higher states is strongly favoured. From these spectra the γ -yields were determined for all transitions with intensities $\geq 1\%$ as compared to the $2_1^+ \rightarrow 0_1^+$ transition. The γ -yields were corrected for the efficiency of the

γ -detector taking into account that the energies of the observed γ -rays are Doppler shifted.

(ii) In the second experiment the 208Pb beam, after passing through the thin target of the first experiment, was used to bombard a thick 10^4Ru target ($\approx 2\text{mg/cm}^2$ 10^4Ru on 50mg/cm^2 208Pb) mounted in a small scattering chamber about 1.50 m downstream from the first experiment (see fig.1). In this experiment γ -singles and $\gamma\gamma$ -coincidence spectra were measured with two Ge detectors in close geometry (target to detector distance 45 mm). Although in particular the high spin states decay predominantly in flight because their lifetimes are of the order of or even smaller than the stopping time of the recoiling Ru nuclei in the Ru/Pb target ($\approx 3\text{ps}$), stopped components could be observed for all transitions seen in the thin target experiment. By using the γ -ray energies determined in the β^- -decay study¹²⁾ for calibration, precise energies (typically $\delta E_\gamma \approx \pm 0.2\text{keV}$) for the newly observed transitions could be obtained. Moreover, the $\gamma\gamma$ -coincidence spectra helped to place several of these transitions in the level scheme of 10^4Ru .

3. THE LEVEL SCHEME OF ^{104}Ru

The level scheme of ^{104}Ru , which could be extended appreciably by the present experiment, is shown in fig.3. The results deduced from the γ -coincidences performed with the thick target are supported and complemented by the impact parameter dependence of the γ -lines as well as by the multiplicity information obtained by a comparison of the line intensities resulting from the two-fold and one-fold gamma-particle coincidence spectra discussed above.

Fig.4 shows the two-fold/one-fold intensity ratio $Y_{I \rightarrow I'}(2)/Y_{I \rightarrow I'}(1)$ for the ground state band (gsb) and γ -band transitions $I \rightarrow I'$ as a function of the multiplicity $M_{I \rightarrow I'}$, which is defined as the total number of γ -transitions in the decay cascade containing the transition $I \rightarrow I'$. The multiplicity $M_{I \rightarrow I'}$ can be considered to be composed of two parts: the first one describes the contribution from the feeding of the level I from higher excited states, the other corresponds to the decay of the level I to the ground state. This latter component follows from the level scheme (fig.3 and ref.12) and is shown in fig.4 as the left hand limitation of the solid bars (in the case of unresolved multiplets in addition we had to use the relative excitation probabilities of the corresponding levels, as observed in the present experiment, to compute this part of the multipli-

city); for higher excited levels I it should converge to the total value of $M_{I \rightarrow I'}$. The right hand limitation of the bars corresponds to the total multiplicity $M_{I \rightarrow I'}$, as it results from the excitation probabilities calculated with the Coulomb excitation program (see section 4.1) using the final set of electromagnetic matrix elements as input parameters. The two-fold/one-fold yield ratio $Y_{I \rightarrow I'}(2)/Y_{I \rightarrow I'}(1)$ is expected to be proportional to the multiplicity $M_{I \rightarrow I'}$, under the assumption that the absolute total efficiency of the gamma detectors is energy independent over the energy region of interest. The approximate proportionality is indicated in fig.4 by the straight line. The close proximity of the measured yield ratios to this line confirms the placement of the corresponding transitions in the level scheme of ^{104}Ru . For the discussion of the two transitions at 651 keV and 964 keV and their multiplicities see below. Additional information was obtained from a reanalysis¹³⁾ of the β^- -decay data¹²⁾ allowing the placement of several so far unassigned γ -lines also observed after MCE. In the following some details of the level scheme will be outlined.

The ground state band

The gsb could be identified up to the 8^+ -state unambiguously. Extrapolating from these identified members of the gsb one would expect an

energy of 840 ± 20 keV for the $10_1^{+}8_1^{+}$ transition. The only observed transition in this energy region, the 852.3 keV γ -line, is ruled out as a possible candidate for this $10_1^{+}8_1^{+}$ transition; it is observed also in the β^- -decay experiment and could be assigned¹⁹ to a level at 2094.7 keV, which is also depopulated by two further γ -rays at 1201.6 keV and 1206.5 keV; all three transitions and their relative intensities agree to the coincidence pattern obtained from the β^- -decay experiment^{12,19}. On the other hand we can give an estimate for the E2 strength connecting the 8_1^{+} -state with the next higher excited state (for details see section 5.1 and 5.2). It appears not to be drastically smaller than one would expect extrapolating the B(E2)-values of the gsb transitions and the corresponding transition should be observable in the present experiment. According to the multiplicity data shown in fig.4 there are two possible candidates for a $10_1^{+}8_1^{+}$ transition; both the γ -lines at 964.3 keV and 651.5 keV show a multiplicity of 5 or larger resulting from the shown proportionality between the yield ratio $Y_{I+1}(2)/Y_{I+1}(1)$ and M_{I+1} . In both cases the particle gamma angular correlation is consistent with such an assignment. The 964.3 keV transition carries the expected intensity, but its energy is about 100 keV above the estimated value for the $10_1^{+}8_1^{+}$ transition; the intensity of the other candidate, the 651.5 keV transition, corresponds to about 40% of the estimated strength only.

When discussing the expected intensity of the 10^{+} -member of the gsb one should be aware that the collective strength between the 8_1^{+} -state and the 10^{+} -state of the gsb can be distributed among several 10^{+} -states, as it is the case in the neutron-rich Pd isotopes, which are in many aspects rather similar to ^{104}Ru . In these nuclei up to three 10^{+} -states are known^{20,22}, two of them are assumed to correspond mainly to 2p-2h configurations. From odd-mass Ru isotopes the $h_{11/2}$ -level is known to come very low in energy. It is thus conceivable that in ^{104}Ru a band built on an aligned $\psi h_{11/2}^2$ quasi particle state is crossing the gsb at spin $I=10$. Depending on the interaction strength between both bands, some or even all E2 strength may then be contained in the transition from the 8_1^{+} -state to the 10^{+} -state of the 2qp band. The experimental information gathered so far is not sufficient to allow an conclusive answer to this question; it should be noted, however, that the observed intensity of both the 964.3 keV and the 651.5 keV γ -ray is too strong to identify either one of these transitions with the $10_1^{+}8_1^{+}$ transition of the γ -band.

The gamma-band

The γ -band as well could be identified unambiguously up to the 8⁺-member. The level at 1502.6 keV, for which a spin value of $I=3$ has been proposed in ref.12 based on a slightly small χ^2 for this spin hypothesis

as compared to the hypothesis $I=4$, is clearly identified as the 4^+ -member of the γ -band in our experiment. The energy of the $8^+_{2^+8^+}1$ transition is calculated to be 668.2 keV from the level difference and hence cannot be resolved from the 667.8 keV $6^+_{1^+4^+}1$ transition. From the branching ratios observed for the lower members of the γ -band the intensity of the $8^+_{2^+8^+}1$ transition can be estimated to be vanishingly small as compared to the $6^+_{1^+4^+}1$ gsb transition. The odd-spin members of the γ -band are only weakly populated in MCE. The $3^+_{1^+}$ -state was already known from the β^- -decay investigation. The spin-assignment for the $5^+_{1^+}$ -state follows from band systematics (energies and decay properties); the same is true for the location of the $7^+_{1^+}$ -state, but here the assignment is only a very tentative one.

Other excited levels

The $0^+_{2^+}$ -state at 988.3 keV and the $2^+_{3^+}$ -state at 1515.4 keV already known from the β^- -decay are populated also in the present experiment. Among the transitions depopulating the $2^+_{3^+}$ -state we could observe only the stronger ones in this experiment; for the unobserved rather weak transitions (shown as dashed lines in the level scheme) the energies are taken from the β^- -decay investigation¹²). Two possible candidates for the 4^+ -member of this sequence are the levels at 2007.8 keV and 2232.4 keV.

Among those two we favour the latter one, since its energy agrees rather well with the value extrapolated (based on the arguments given in section 6) from the $0^+_{2^+}$ and $2^+_{3^+}$ energies. Both levels, whose existence could be verified also from the reanalysis of the β^- -decay data¹³), show only a decay to the $4^+_{1^+}$ -state; from systematics one would expect this decay pattern for the 4^+ -member of the above mentioned sequence. There is an explanation for the second candidate (2007.8 keV) as well: most collective nuclear models predict a band starting with $I^\pi=4^+$ also in this energy region, showing the same decay properties.

The two 3^- -states (1970.4 keV and 2481.9 keV) already known from a (d,d') reaction²³) and observed also in β^- -decay, are weakly populated also in the present MCE experiment. At 2285.1 keV we observe a state, decaying to the $3^-_{1^+}$ and the $4^+_{1^+}$ -state. In analogy to the neighbouring isotopes^{20,21}) $^{102}108\text{Pd}$ one would expect in this energy region a 5^- -state showing just these decay properties. In the β -decay experiment¹²) a spin of 2^+ was assigned to this level from the $\gamma\gamma$ -angular correlation of the $I \rightarrow 4^+_{1^+} 2^+_{1^+}$ cascade. For the $I \rightarrow (4^+_{1^+}) 2^+_{1^+} 0^+_{1^+}$ cascade on the other hand the spin hypothesis of 5 is found to be the best solution¹⁹). Concluding we propose $I^\pi=5^-$ for the level at 2285.1 keV.

The two transitions at 977.2 keV and 980.8 keV had been identified already in the β^- -decay investigation¹²⁾ to belong to the decay of ^{104}Tc to ^{104}Ru but could not be placed in the level scheme of ^{104}Ru ; the $\gamma\gamma$ -coincidence pattern observed in the β^- -decay experiment together with the fact, that the transitions are also seen in the present MCE experiment - this excludes the possible existence of an intermediate unobserved high energy transition - leads to the conclusion, that the two transitions depopulate levels at 1335.2 keV and 1873.9 keV as shown in fig.3. Since these 1335.2 keV and 1873.9 keV states show an exclusive decay to the 2_1^+ and 2_2^+ -states, respectively, they are good candidates for excited 0^+ -states.

The level scheme shown in fig.3 represents $\approx 99\%$ of the intensity observed in our experiment. Some additional weak γ -lines, which must originate from the deexcitation of levels in ^{104}Ru as they are observed in the particle particle gamma coincidence spectra could not be placed in the level scheme. These transitions, which are listed in table 1, cannot be due to other Ru isotopes, because even the $2_1^+ \rightarrow 0_1^+$ transition of ^{102}Ru (with $\approx 0.3\%$ the strongest impurity in the target) is not observed in the particle gamma coincidence experiment. During the completion of the present work we became aware of a similar Coulomb excitation study of ^{104}Ru ;

the results²⁴⁾ concerning the level scheme agree with the corresponding part of our findings.

4. GAMMA RAY YIELDS AFTER COULOMB EXCITATION

4.1 Coulomb excitation calculations

In general the dominant steps in Coulomb excitation are E2 transitions and it is a well established technique to determine E2 ME's for low lying states by measuring Coulomb excitation cross sections using light heavy ions (α , ^{16}O). The method we use for the determination of E2 ME's by MCE is based on the comparison of experimental to calculated γ -yields for a large range of scattering angles. The calculations of the γ -yields are performed in a two step procedure, which has been described already shortly in refs.25,26. In a first step the cross sections $\sigma_I(\theta)$ for the population of the different excited states and the corresponding statistical tensors²⁷⁾ $\alpha_{\kappa}^I(\theta)$ are calculated using a modified de Boer-Winther code²⁸⁾. The use of the semiclassical approximation underlying this code is justified in this case, since the condition²⁹⁾ $n \gg 1$ is fulfilled; the Sommerfeld parameter η is about 270 for the present experiment, whereas only levels up to $I = 10^+$ have been excited. In a second step the statistical tensors are used to perform a γ -decay calculation for the excited

levels providing the δ -yields. The Coulomb excitation calculations are performed under the assumption of a certain set of electromagnetic moments; these starting values for the ME's are then changed iteratively until optimal agreement between calculated and experimental δ -yields is obtained for all detected scattering angles. The correlation between the δ -yields and the various ME's will be discussed in section 5.1.

Relative phases of the matrix elements

Performing the Coulomb excitation calculations one has to be aware of the fact, that not only the absolute values of the ME's, but also their relative phases are of importance due to the constructive or destructive interference of different excitation paths. As long as only a few levels are involved, the measured cross sections can in general be connected unambiguously to a set of E2 ME's; then the δ -yield for every transition is mainly determined by only one E2 ME. This was the case for instance in Coulomb excitation experiments^{8,9)} of ^{104}Ru with α and ^{16}O , where only the $2_1^+ - 4_1^+, 2_2^+$ and 0_2^+ -state have been excited; there the corresponding E2 ME's and the relevant relative phases could be determined unambiguously. When going to heavier projectiles like ^{208}Pb the number of ME's one has to take into account increases rapidly. In the same proportion rise also the number of possible interference terms and the

importance of the correct choice of the relative phases for all involved ME's.

In contrast to typical rotational nuclei, where the band structure is well pronounced and consequently the interband ME's are small and their relative phases are thus only of minor importance, interband ME's become comparable to the inband ME's in the case of transitional nuclei: thus for the determination of $B(E2)$ -values the choice of at least some relative phases is crucial. Fig.5 shows the E2 ME's we had to take into account for the analysis of the present experiment; for the definition of these reduced ME's see ref.27 (RPT phase convention). One is free to choose the phase for the wave function of each state arbitrarily. Without any loss of generality we therefore can adjust these phases such that the transition ME's framed in fig.5 have the signs shown. After having chosen these phases the remaining phases are fixed and in principle they are physical observables. In section 5.2 we will discuss in detail, which of these phases we could determine experimentally and what systematic errors are induced by the remaining undetermined signs. The signs of the ME's shown in fig.5 represent the set we used for the final fit. The importance of other transition modes as E1, E3, E4 and M1 will be discussed in section 5.1.

Accuracy of the semiclassical approach

For calculating the Coulomb excitation cross sections and hence the yields of the observed γ -rays from the subsequent decay we used, as already mentioned above, the semiclassical approach, as it is realized by the de Boer-Winther code²⁸). There the projectile nucleus is assumed to move along a classical trajectory, whereas the excitation of the nucleus is treated quantum mechanically. To test the accuracy of this treatment we have compared γ -ray yields calculated with the semiclassical code and the subsequent decay program²⁵) with yields resulting from a fully quantum mechanical coupled-channel calculation using the computer code PTOLMW²⁹). Due to the large Sommerfeld parameter for the considered scattering process ($\eta=270$) partial waves up to $L=700$ had to be included in the coupled channel calculation. In order not to increase the computing time too much, in these calculations only the gsb up to the 12^+ -level had been included. It turned out that the agreement between the two different calculations is rather good; the differences between the normalized γ -yield ratios $I_{\gamma I'}/I_{\gamma I''}(\theta)$ (see equation (6) in section 5) up to $I''=10^+$ are only in the order of a few percent (see table 2).

To test a possible influence of the onset of nuclear interaction at close projectile-to-target distances a second coupled channel calculation

was performed including besides pure Coulomb also nuclear interaction. The corresponding optical model parameters were taken from the reaction³¹) ^{86}Kr on ^{209}Bi at $\approx 700\text{MeV}$. The resulting differences in the yield ratios compared to the semiclassical calculation are also shown in table 2. Note that also in this case the deviations are very small. It becomes obvious, that our estimate for the safe beam energy (see section 2) is justified. We can thus conclude, that for the yield ratios considered in the present experiment (up to $I''=8^+$) the accuracy of the semiclassical Coulomb excitation calculations is rather good, i.e. in every case the deviations are smaller than 3%. The resulting errors for the deduced electromagnetic moments are well within the error limits given for the final results.

4.2 Deorientation effects

Due to the rather long lifetimes of the states of interest

- the $2^+_{I=1}$ -state in ^{100}Ru has a lifetime of 82.5 ps - Coulomb excitation experiments are complicated by a notable deorientation of the aligned states. It will be explained in the following how we could treat this effect in the present experiment, where the emitters of the observed γ -radiation are highly ionized atoms recoiling into vacuum with $v=0.1c$. It is well known that the interaction between the nuclear magnetic moment and

the hyperfine field originating from partly unfilled inner electron shells changes the occupation probability amongst the $2I+1$ magnetic sub-states of a level with spin I , so that the alignment of the corresponding level will be destroyed at least partly. In extreme cases deorientation effects may lead to an isotropic directional gamma angular correlation. Since a complete theoretical treatment of the complicated process causing the deorientation effect is not available, we have employed a experimental method to determine the magnitude of the effect at least for some strongly excited states. For the other levels we have used the Abragam and Pound³²⁾ model to interpolate (and extrapolate) according to the excited level's lifetime; as shown in a more detailed investigation³¹⁾ of the deorientation effects after MCE of ^{240}Cm with ^{209}Pb projectiles, the effective deorientation observed in time integrated measurements at high recoil velocities can be described rather well by such a rather simple ansatz. With the assumption of an isotropic randomly fluctuating field H caused by deexcitation processes in the highly excited atomic shell, we can include the deorientation effects by writing for the directional particle gamma angular correlation in the rest-coordinate system of the emitting nucleus:

$$W_{I+I'}(\theta, \theta_g) = \sum_{J, k} \sum_{k'} A_{kk'}^J(\theta) \left[\prod_{N=3}^I G_k(N) \right] A_k(I+I') \mathcal{Y}_{kk}(\theta_g) \quad (1)$$

N labels the excited nuclear states, J denotes the state directly populated by the Coulomb excitation process, $k=0, 2, 4$ and $k'=k-1, \dots, -k$. The

tensors $A_{kk}^J(\theta)$ contain the statistical tensors²¹⁾ $a_{kk}^J(\theta)$, describing the alignment of the state J caused by the excitation process, as well as the U_k -coefficients for all unobserved cascade transitions ($J \rightarrow \dots N \rightarrow I$). $A_k(I+I')$ is the gamma angular correlation coefficient for the observed transition $I \rightarrow I'$ and the $\mathcal{Y}_{kk}(\theta_g)$ are the spherical harmonics. Equation (1) can be easily generalized for the case of several competing decay paths between the states J and I . In the Abragam and Pound model the deorientation coefficients $G_k(N)$ are given by

$$G_k(N) = 1 / (1 + \lambda_k(N) \tau(N)) \quad (2)$$

and for purely magnetic interaction one has

$$\lambda_2(N) / \lambda_4(N) = 6/20. \quad (3)$$

In (2) $\tau(N)$ denotes the lifetime of the state N . In addition this model yields

$$\lambda_2(N) \cdot H^2 g(N)^2 \tau_c \quad (4)$$

where $g(N)$ is the nuclear g -factor of the state N and τ_c is the correlation time between the fluctuations of the hyperfine field H and the nuclear spin precession. Since in most cases g -factors for higher excited states are not known, one usually uses the g -factor of the 2_1^+ state for all other states as well and consequently $\lambda_k(N)$ can be replaced by λ_k .

Fig. 6 shows the directional gamma angular correlation of the $2_1^+ \rightarrow 0_1^+$ transition calculated in the lab-system for three different recoil

angles. In this case the recoiling target nuclei are detected in particle detector I, the arrows mark the positions, where gamma detectors had been placed in our experiment (see fig.1). The left part of fig.6 represents a calculation, where no deorientation is taken into account, i.e. $G_2 \approx 1.0$, whereas the right part of fig.6 shows the same angular distribution assuming $G_2 \approx 0.26$. Note the filling of the deep minima in the angular distribution in the direction perpendicular to the recoil axis. Consequently at $\vartheta_\gamma = +30^\circ$ and $\vartheta_\gamma = -150^\circ$ the γ -yields show a dramatically different dependence on the scattering angle. At $\vartheta_\gamma = -30^\circ$ and $+150^\circ$ on the other hand this dependence is affected only slightly. This effect is even better visualized by forming the γ -yield ratio $Y_{2_1^+ + 0_1^+}(30^\circ)/Y_{2_1^+ + 0_1^+}(150^\circ)$. Fig.7 shows the experimental values for this ratio together with the calculated ones for different amounts of deorientation. The solid line corresponds to no and the dashed line to complete deorientation. The dashed dotted line represents the best fit to these experimental yield ratios, it is the result of a χ^2 -minimisation yielding $G_2(2_1^+) = 0.26 \pm 0.07$. G_4 was calculated according to (2) and (3) and the lifetimes of the excited states and the feeding were taken from the final set of E2 ME's (5.2). The fit was performed under the simplifying assumption, that the γ -yield ratios for different scattering angles and hence different recoil velocities can be described by deorientation coefficients corresponding to a recoil velocity of $v=0.09c$ (obtained by averaging over the detected velocity range of

$v=(0.07-0.12)c$); this point will be reexamined below. In the same way values for G_2 could be determined from the corresponding yield ratios for the 6_1^{+4} transition and the doublet $4_1^{+2} 2_1^{+2}$. Since the 4_1^{+2} and 2_2^{+2} states have nearly the same lifetime the assumption of the same deorientation coefficients for these two states is reasonable. Moreover the g -factors for the 4_1^{+2} and 2_2^{+2} states are not expected to be very different. The corresponding experimental yield ratios for the doublet $4_1^{+2} 2_1^{+2}$ and the result of the fit are shown in the right part of fig.7.

In fig.8 we have plotted the experimentally determined deorientation coefficient G_2 versus the mean lifetime τ of the corresponding nuclear level. The solid line and the errorband were calculated using equation (2); they correspond to an average value of $\lambda_2 = 0.13 \cdot 10^{-11} \text{ s}$. This value gives the best reproduction of our experimental points for the 6_1^{+4} state and the $4_1^{+2} 2_1^{+2}$ doublet, the error resulting mainly from the latter value. From fig.8 it can be noted that for shorter lifetimes ($\leq 20 \text{ ps}$) our data are consistent with the parametrization of the Abrogam and Pound ansatz; consequently we have used the deorientation coefficients according to this parametrization with the exception of the 2_1^{+2} state, where the experimental point lies clearly above the curve. This is probably due to a hard core effect characteristic for nonfluctuating

hyperfine fields; these effects are known³⁴⁾ to be important for longer lifetimes and we therefore have used a G_2 of 0.26 for the 2_1^+ -state.

In fig.9 our average deorientation coefficient is compared to values obtained from other experiments for this target mass range. In all cases considered the lifetimes were short enough to make an analysis on the basis of the Abragam and Pound formulae (2) to (4) meaningful; the different g-factors were taken into account by plotting λ_2/g^2 . Since the hyperfinefield is velocity dependent, the quantity λ_2/g^2 is plotted versus the recoil velocity occurring in the different experiments. The drawn line corresponds to a velocity dependence used in the literature^{34,40)}, namely

$$\lambda_2/g^2 \propto v^{1.2}. \quad (5)$$

Obviously our high velocity value ($\langle v/c \rangle = 9\%$) agrees to this velocity dependence.

To check how the averaging over the velocity range ($v/c = 0.07-0.12$) covered by our particle detectors influences our analysis we have repeated the calculation of the yield ratio $Y(30^\circ)/Y(150^\circ)$ for the doublet $4_1^{+2}, 2_1^{+2}, 2_1^{+2}$ including the velocity dependence of λ_k according to (5).

The result of this calculation is shown in fig.7 as the dotted line; since there are only small deviations to the best fit assuming constant λ_k 's

occurring at small scattering angles the use of an average $v/c = 0.09$ is justified.

5. DETERMINATION OF E2 MATRIX ELEMENTS

5.1 The dependence of the gamma-yields on the electromagnetic moments

As in the present experiment we are concerned with MCE of a transitional nucleus, the correlation between the γ -yields for the observed transitions and the whole set of E2 ME's used in the calculations is expected to be much more complicated than in the case of gsb transitions in rotational nuclei, where it was found²⁶⁾ that the γ -ray yield $Y_{I+I-2}(\theta)$ below a certain angle θ is mainly determined by the $B(E2, I+I-2)$ -value. In the case of the transitional nucleus ^{104}Ru , where the band structure is less pronounced, one expects several $B(E2)$ -values to compete in their influences on one transition yield. Since it is our aim to determine model independent $B(E2)$ -values, we have to study these correlations in detail to find out whether there are scattering angles, where the competing influences are small and the γ -yield is mainly determined by one ME.

Another important difference between NCE of rotational and transitional nuclei is connected to the fact, that in general the excitation energies are considerably higher for the latter ones. Since the reorientation effect increases with increasing excitation energy, there is a possibility to determine not only transition ME's but also static quadrupole moments of higher excited states in transitional nuclei; this point will be discussed in detail further down.

For the comparison of experiment and Coulomb excitation calculation we use yield ratios

$$r_{I+I'}^{I'}(\theta) = Y_{I+I'}^{I'}(\theta) / Y_{\text{norm}}^{I'}(\theta) \quad (6)$$

rather than yields. The most suitable normalization depends on the transition considered and is chosen for every transition individually. For transitions in a rotational band we normalize to the next lower inband transition (if there is one), i.e. $Y_{\text{norm}}^{I'}(\theta) = Y_{I-2+I-4}^{I'}(\theta)$, whereas for interband transitions we normalize to the corresponding inband transition depopulating the same level.

Dependence on E2 matrix elements

For each of the E2 ME's connecting the excited states considered we have tested the influence on the γ -yields of each observed transition for

the whole detected range of scattering angles. The resulting correlation is a three dimensional matrix, the so-called sensitivity matrix, which is defined by

$$C_{I+I', J+J'}^{I'}(\theta) = \frac{\Delta r_{I+I'}^{I'}(\theta) \Delta \langle J' \| E2 \| J \rangle^2}{r_{I+I'}^{I'}(\theta) \langle J' \| E2 \| J \rangle^2} \quad (7)$$

where $\Delta r_{I+I'}^{I'}(\theta)$ is the difference between the two yield ratios for the transition $I+I'$ corresponding to two different reduced E2 ME's $\langle J' \| E2 \| J \rangle$. To avoid problems arising from the linearized sensitivity ansatz it was made sure that the sensitivity matrix was calculated for differences within 20% from the final set of E2 ME's. The relative phases have been chosen as indicated in fig. 5.

The ground state band. At first we will consider that part of the sensitivity matrix, which is concerned with the gsb. As a typical example we show in fig. 10 the various correlations connected to the γ -yield ratio $r_{6_4^+ \rightarrow 4_1^+}^{4_1^+}(\theta)$. For the sake of clarity only the largest elements of the sensitivity matrix are shown. Fig. 11 shows the experimental γ -yields for the $6_1^{+4} 1_1^+$ transition (normalized to $2_1^{+0} 1_1^+$) in dependence on the scattering angle θ . From a comparison of figs. 10 and 11 it can be seen that at small scattering angles, where the γ -yield is rather small, $r_{6_4^+ \rightarrow 4_1^+}^{4_1^+}(\theta)$ is strongly correlated to the corresponding transition ME $\langle 4_1^+ \| E2 \| 0_1^+ \rangle$ and the influence from other ME's is small. In the region of large θ , on the

other hand, where the experimental yield reaches a maximum, there is no longer a specific correlation to the corresponding transition ME due to the increasing influence of other ME's. Consequently the $B(E2)$ -values for the gsb have to be determined from the γ -yields at small scattering angles. At these small scattering angles the largest off diagonal correlation is to the preceding and the subsequent inband transitions (to the $\langle 2_1 \| E2 \| 4_1 \rangle$ and the $\langle 6_1 \| E2 \| 8_1 \rangle$ ME's for the case considered in fig.10). But since these transitions are observed, their ME's can be fixed independently by fitting the corresponding γ -yield ratios. The same is true for the even smaller sideband contributions, where at least estimates can be obtained for the most important ME's.

At intermediate scattering angles, where the correlation to the $6_1^{+4} B(E2)$ -value is small, the diagonal $E2$ ME $\langle 6_1 \| E2 \| 6_1 \rangle$ has a considerable influence (cf. fig.10). If it is possible to determine the other ME's showing a comparable correlation at these scattering angles with reasonable accuracy, one can aim to determine also static quadrupole moments for the gsb from the γ -yields at this intermediate region. In particular at large scattering angles the γ -yields are sensitive to the ME for the next higher transition. We exploited this feature to estimate the $E2$ -strength connecting the 8_1^{+} -state to the next higher excited state(s): from the $8_1^{+6} \gamma$ -ray yield at these large scattering angles we are able

to give an estimate for the $10_1^{+8} E2$ ME without unambiguously identifying a 10_1^{+8} transition. For the other gsb transitions the correlation pattern is similar. The main difference is that - with increasing spin - the whole correlation pattern is shifted towards larger scattering angles.

The gamma band. In the left part of fig.12 the correlation for the $6_2^{+4} 4_2^{+}$ inband transition yield normalized to $Y_{4_2^{+2} 2_2^{+}}^{+4}(\theta)$, i.e. $r_{6_2^{+4} 4_2^{+}}^{+4}(\theta)$ is shown, whereas the right part of fig.12 represents the sensitivity for the out of band transition $6_2^{+6} 6_1^{+}$ normalized to $Y_{6_2^{+4} 4_2^{+}}^{+6}(\theta)$, i.e. $r_{6_2^{+6} 6_1^{+}}^{+6}(\theta)$. This latter sensitivity shows, that the yield ratio $r_{6_2^{+6} 6_1^{+}}^{+6}(\theta)$ is essentially the branching ratio corresponding to the 6_2^{+} -state; deviations from a constant value are due to angular correlation effects, which are small in this case. In case the M1 contribution is known, the ratio $|\langle 6_1^{+} \| E2 \| 6_2^{+} \rangle|^2 / |\langle 4_2^{+} \| E2 \| 6_2^{+} \rangle|^2$ can be determined from this branching ratio with high accuracy. The same is true for the analogue yield ratio $r_{6_2^{+4} 4_1^{+}}^{+4}(\theta)$ and the corresponding branching ratio. For the ratio $r_{6_2^{+4} 4_2^{+}}^{+4}(\theta)$ the main correlation at small scattering angles is to the ME $\langle 4_2^{+} \| E2 \| 6_2^{+} \rangle$. If this ME is increased both the ME's $\langle 6_1^{+} \| E2 \| 6_2^{+} \rangle$ and $\langle 4_1^{+} \| E2 \| 6_2^{+} \rangle$ have to be increased as well to agree with the branching ratios fixed experimentally. Since the correlation between $r_{6_2^{+6} 6_1^{+}}^{+6}(\theta)$ and each of these three $E2$ ME's has the same sign (positive), the sensitivity for the determi-

nation of the inband $B(E2)$ -value is even increased. The next important correlation for $r_{6_2^+4_2^+}(0)$ stems from the two ME's $\langle 4_1^+ \| E2 \| 4_2^+ \rangle$ and $\langle 2_2^+ \| E2 \| 4_2^+ \rangle$. Again these two ME's can be fixed accurately relative to each other via the corresponding branching ratio. Since their correlations to $r_{6_2^+4_2^+}(0)$ have the opposite sign, they mainly compensate each other; additionally the $\langle 2_2^+ \| E2 \| 4_2^+ \rangle$ ME can be determined separately. The $6_1^+4_1^+$ and the $8_2^+6_2^+$ transition ME's influence the $6_2^+4_2^+$ yield as well, but both ME's can be determined from the corresponding yield ratios separately; other correlations are rather small. As the influence of E2 ME's involving odd spin members of the δ -band is only of the order of 0.5-2.0% it is not shown in fig. 12 for the sake of clarity. Thus we can conclude that it is possible to determine $B(E2)$ -values also for the δ -band, although the correlation pattern is more complicated than in the case of the gsb.

Other excited states. For the $0_2^+, 2_3^+, \dots$ sequence we find even a more complex pattern. The part of the sensitivity matrix concerning the two transitions we observed in our experiment, $0_2^+2_1^+$ and $2_3^+2_1^+$, both normalized to $r_{2_2^+0_2^+}$, is shown in fig. 13. The yield of the $0_2^+2_1^+$ transition is strongly correlated to the corresponding $B(E2)$ -value. Only for large scattering angles the influence of the $2_3^+0_2^+$ ME increases rapidly corresponding to the increasing cross section for the $0_2^+2_3^+$ excitation

step at smaller impact parameters. The largest influence of other ME's comes from the transitions $4_1^+2_1^+$ and $2_2^+2_1^+$; the excitation step $2_1^+0_2^+$ has to compete with the transitions to the 4_1^+ and 2_2^+ -state.

Both ME's can be determined from the corresponding yield ratios. The influence of other ME's, not plotted in this figure, is found to be smaller than those shown. Thus we can expect to be able to determine from the $0_2^+2_1^+$ δ -ray yields at small scattering angles the corresponding $B(E2)$ -value; consequently the yields at large scattering angles can be exploited to determine the ME $\langle 0_2^+ \| E2 \| 2_3^+ \rangle$, although the corresponding gamma transition is not observed in this experiment. The $2_3^+2_1^+$ δ -yield shows to be strongly correlated to several ME's, some of which have the same scattering angle dependence. As the two ME's of the transitions $0_2^+2_1^+$ and $2_3^+0_2^+$ can be obtained as outlined before and the other ME's are known, the only stronger correlation left is between the $B(E2)$ -value for $2_1^+2_3^+$ and the static quadrupole moment of the 2_3^+ -state, which consequently can be determined from our data.

Influence of other excited bands

To test the influence of an additional excited band, which might have escaped observation, we constructed an $\Gamma_{4,5,6}^+$ band (which would rise also assuming a hexadecapole deformation as discussed below), starting

with the proposed 4^+_1 -state at 2007.8 keV; the corresponding E2 ME's were taken from the prediction of the asymmetric rotor model⁴⁴) for such a band and scaled in order to reproduce the intensity of the 1119.3 keV γ -ray (2007.8 keV $\rightarrow 4^+_1$). It should be mentioned here that this is the strongest observed transition not included in the set of E2 ME's used in the fit. From a test calculation including this band its influence on the determined E2 transition ME's is found to be less than 1% in all cases; the diagonal ME's are influenced by less than 10%. These uncertainties are within our error bars and all possible other bands not taken into account certainly produce even smaller effects.

Phase dependences. The Coulomb excitation process does not only depend on the absolute value, but also on the relative phases of ME's. So far we have used phases as indicated in fig.5. Only the sign of the interference term⁴²) $P_3(2^+_2)$ and the sign of the quadrupole moment⁹) of 2^+_1 are known from previous experiments. Although the gross structure of the sensitivity plots, i.e. the dependence on the scattering angle, is not changed essentially, the absolute γ -yields and yield ratios do depend on the relative signs of the transition ME's as well as on the signs of the quadrupole moments. In sect. 5.2 we will see to what extent phases of ME's are fixed by our data.

E2/M1 mixing ratios

As discussed, the excitation process is mainly determined by E2 ME's, whereas the decay may also be influenced by M1 transitions. For the decay of members of the γ -band we took into account M1 radiation for the $\Delta I=1$ inband transitions and for the $\Delta I=0,1$ interband transitions to the gsb. The magnitude of these M1 ME's can be estimated from the E2/M1 mixing ratios determined in the β^- -decay study^{12,19}) for the $2^+_2 \rightarrow 2^+_1$, $3^+_2 \rightarrow 2^+_1$ and $4^+_2 \rightarrow 4^+_1$ transitions. For the extrapolation to higher spin members we used the spin dependence proposed by Greiner⁴³). These M1 ME's are small and it turned out, that their influence on the determined E2 ME's is negligible. For the $2^+_3 \rightarrow 2^+_1$ transition we could also use an experimental E2/M1 mixing ratio¹²) - here the M1 contribution is quite considerable.

Dependence on E1 and E3 matrix elements

Up to now we did not consider negative parity states, but at least two of them (3^-_1 at 1970.4 keV and 3^-_2 at 2481.9 keV) are excited in the present MCE experiment. To test their effect on the resulting E2 ME's we have performed a Coulomb excitation calculation, where we used an input data set containing in addition to the usual E2 and M1 also E3 and E1 ME's: We assumed a band with $I^\pi=5^-,7^-,9^-$, ... built on the 3^-_1 -state with a level

spacing equal to that of the gsb and included E3 and E1 ME's between these negative parity states and the gsb. The ME $\langle 3_1^- \| E3 \| 0_1^+ \rangle = 0.23e^2b^3$ has been determined in previous experiments²²), while for the E1 transition to the 2_1^+ state we assumed a reasonable hindrance factor of 10^4 giving $\langle 2_1^+ \| E1 \| 3_1^- \rangle = 0.002e^2b$; these values reproduce the predominant decay of the 3_1^- to the 2_1^+ -state. For the higher spin members E3 ME's corresponding to the Alaga rule and appropriate E1 ME's were adopted. Although this Coulomb excitation calculation yielded an intensity for the $3_1^- \rightarrow 2_1^+$ γ -ray, which was even larger than we observed experimentally, the change of the gsb γ -ray yield ratios was only between 0% and 0.3%; thus we conclude that our results do not depend on negative parity bands. The influence on the other γ -ray yields cannot be calculated as the corresponding ME's are not known. Since no other decay branch of the 3_1^- -state is observed, one can expect however, that these unknown influences affect the quantities deduced from the other γ -ray yields only within their errors.

Dipole polarization. In the Coulomb excitation process the virtual excitation of the giant dipole resonance can be described by a reduction of the effective Coulomb interaction between projectile and target nucleus. To include this effect we have chosen the usual dipole polarization

description²⁷), where the nuclear polarizability P is described by the empirical equation

$$P = 1.7 \cdot 10^{-3} A^{5/3} \text{ fm.} \quad (8)$$

This estimate is known to be in fair agreement with estimates²⁷) based on the dipole sum rule. A complete neglect of the effect for instance is found to increase the γ -ray yield ratio $r_{+}^{+} + (0)$ by about 5% nearly independent of the scattering angle. In view of the fact that the polarization ansatz we use is expected to hold as well for rotational as for vibrational nuclei²⁷) the error introduced by this description into the final result should be rather small.

Dependence on E4 matrix elements

For the Ru isotopes no experimental E4 ME's are known. To test their influence we assumed a hexadecapole parameter $\beta_4 = 0.05$ and rigid rotor E4 ME's between the states of the gsb. A hexadecapole deformation of this order has been measured for the Pt and Os isotopes, for instance, which are similar to the Ru isotopes in several aspects. It turned out that the influence of these E4 ME's on the normalized γ -yields is smaller than 0.7% for all scattering angles; these changes are certainly smaller than the errors of the deduced E2 ME's.

5.2 The fitting procedure and experimental results

For the determination of E2 ME's from the γ -yield ratios we used an iterative fitting routine on the basis of the linearized sensitivity ansatz. To account for the nonlinearity of the problem each iteration step consisted of a linear (differential) fit followed by a full Coulomb excitation plus γ -decay calculation to determine the remaining differences to the experimental yield ratios. The special linear fit routine used for the Coulomb excitation experiments^{25,26}) on rotational nuclei is suited for cases, where one yield ratio is strongly correlated to just one E2 ME. Its essence is the following: the E2 transition $ME \langle J \| E2 \| J' \rangle$ for the observed transition $J' \rightarrow J$ is determined in that region of scattering angles, where the corresponding sensitivity is large and hence the correlation to other ME's is small. We have used this routine to determine B(E2)-values for the transitions depopulating levels of the gsb and the γ -band.

However, as the γ -yields are measured over a large range of scattering angles, we expect to be able - as shown above - to deduce more information than just these B(E2)-values. In order to account also for the dependence of one γ -yield on several ME's we applied a more general fit procedure. Taking advantage of the complete sensitivity matrix we used a

linear least square fit routine based on a n-dimensional χ^2 -minimisation, which allowed the simultaneous variation of a larger number of ME's. In addition with this routine we could study the correlations between all considered ME's and their errors. We applied this routine to determine quadrupole moments for the levels of the gsb by allowing the E2 transition ME's for the gsb as well as the diagonal E2 ME's for the $2_1^+, 4_1^+, 6_1^+$ and 8_1^+ -state to vary. The transition ME's resulting from this fit are identical to those obtained by the first method within the error bars (see below). For the $6_1^+ \rightarrow 4_1^+$ transition the calculated yield curve is compared in fig.11 to the experimental one. The curves *b* represent the final fit; for comparison, the curves *a* represent the best fit obtained under the condition that the quadrupole moments for the levels of the gsb are extrapolated from the known experimental value^{9,42}) of the 2_1^+ -state using the rigid rotor model⁴¹) (i.e. they are not allowed to vary during the fit). From this figure it is obvious that our measurement is sensitive to these quadrupole moments and that an independent determination of B(E2)-values and quadrupole moments is indeed possible. The same method was applied to determine the $\langle 2_1^+ \| E2 \| 0_2^+ \rangle$, $\langle 0_2^+ \| E2 \| 2_3^+ \rangle$, $\langle 2_1^+ \| E2 \| 2_3^+ \rangle$ and $\langle 2_3^+ \| E2 \| 2_3^+ \rangle$ ME's from the γ -yields for the two transitions $0_2^+ \rightarrow 2_1^+$ and $2_3^+ \rightarrow 2_1^+$ respectively.

The resulting ME's and B(E2)-values are shown in tables 3-6 and figs. 14 and 15. The given errors contain both statistic and systematic contributions. The statistical uncertainties range from 0.5 to 5.0% for the E2 transition ME's and from 25 to 50% for the diagonal ME's; the different sources for systematic errors will be outlined in the following. The adopted uncertainty in the deorientation coefficients was already indicated in fig. 8; it contributes with maximum 4% (15%) to the errors of the deduced transition (diagonal) ME's. Of minor importance are the uncertainties in the angle calibration and the beam energy. We assumed the angles to be accurate to $\pm 0.5^\circ$ and the beam energy to 4 MeV ($\approx 0.4\%$). For the energy loss of the ^{208}Pb beam in the target we used values according to the recent compilation of Ziegler⁽⁸⁾. Both uncertainties contribute $\approx 1\%$ to the deduced errors each.

As we are aiming at model independent E2 ME's, the influence of the assumptions (and their uncertainties) made for ME's, which could not be determined experimentally, has to be carefully investigated; their ambiguity and correlation to the deduced quantities give the main contribution to systematic uncertainties. In fig. 16 the values of these undetermined E2 ME's are shown as we adopted them for the final fit. These values are to a wide extent model independent as in most of the cases our assumptions are restricted to an extrapolation of known or estimated ME's to higher spin

members of the corresponding bands. In the following we will give a brief discussion of the different assumptions we have made.

(i) The ground state band has been extrapolated to higher spin values by extending the transition ME's measured up to 10_1^+ according to the rigid rotor formula⁽⁴⁾. The diagonal ME's for $I^\pi > 8^+$ were assumed to be constant. Both assumptions do not show any significant influence on the determined ME's.

(ii) The signs of the quadrupole moments of the γ -band are chosen according to the corresponding Clebsch Gordan coefficients; the absolute values are strongly dependent on the deformation and softness of the assumed potential in γ -direction. Our assumption corresponds to a situation intermediate between a prolate rigid rotor⁽⁴⁾, a triaxial rotor⁽⁴⁾ ($\gamma=25^\circ$) and a completely γ -unstable case⁽⁸⁾. The given uncertainties include all these extreme descriptions.

(iii) Odd-spin members of the γ -band: in our experiment we observe the $3_1^{+ \rightarrow 2} 1_1^+$ transition as the smaller component ($\approx 18\%$) of the doublet at ≈ 890 keV. This is sufficient to give an estimate of 0.240.1 eB for the corresponding E2 ME (the M1 contribution to this transition is known⁽¹²⁾ to be small). From the known⁽¹²⁾ branching of the decay of the 3_1^+ -state we can also give estimates for the ME's $\langle 4_1^+ \| E2 \| 3_1^+ \rangle$ and $\langle 2_2^+ \| E2 \| 3_1^+ \rangle$. For extrapolating the correspond-

ing transition ME to the higher odd-spin members of the γ -band we used the rigid rotor formula and the Alaga rule. Again the given uncertainties include all possible extrapolations (γ -rigid and γ -unstable asymmetric rotor and prolate rigid rotor). The transition ME's between odd-spin states of the γ -band are interpolated between the neighbouring inband transitions connecting even spin levels.

(iv) The I⁺I⁺+2 transitions between γ -band and gsb are not observable due to their small transition energies. Collective models predict these E2 ME's to be small; we have assumed 0.1 eb and included a large uncertainty of $\pm 100\%$.

(v) The assumed ME's for the $\Delta I=0$ and $\Delta I=2$ transitions between γ -band and gsb are extrapolated from the values determined experimentally up to the 6_2^+ -state. For the $\Delta I=0$ transitions the prolate axial and the triaxial rigid rotor give two opposite spin dependences. We have chosen the intermediate case corresponding to a γ -soft potential. Again all extremes are within the given uncertainties.

(vi) We assumed the 0_2^+ and 2_3^+ -states belonging to a band, which we continued with a 4^+ - and 6^+ -member and appropriate inband and inter-band ME's corresponding to our experimentally determined E2 ME's and the known branching^{12,19)} of the 2_3^+ -state. The inband

transition ME's are extrapolated according to the rigid rotor formula, the transition ME's to the gsb are assumed to be constant for these higher spin members. The transition ME's to the γ -band result from an IBA-2 fit⁴⁹⁾ of the Ru and Pd isotopes. They are in agreement with the known branching¹⁹⁾ of the 2_3^+ to the 2_2^+ -state. Assuming them all to be equal zero, on the other hand, yields no notable differences in those calculated yields, which have to be compared to experimental quantities. Values corresponding to other model assumptions are in between these two possibilities. Hence our results are not sensitive to these assumptions and consequently these ME's can not be deduced from our experiment.

The uncertainties of the assumed ME's like included in the error estimates of the determined ME's are listed in fig.16 in brackets. The contribution to the deduced errors amounts to 0.5-10% of the determined transition E2 ME's and to 40-100% of the determined diagonal E2 ME's.

The second main contribution to systematic errors has its origin in undetermined relative phases of ME's. Our final choice is shown in fig.5 (see also section 4.1). Since we could determine the signs of the quadrupole moments for the 2_1^+ to 8_1^+ -state, there is no more ambiguity

for the gsb. Concerning the $\Delta I=0$ and $\Delta I=2$ transitions between γ -band and gsb the interference term

$$P_3(2_2^+) = \langle 0_1^+ \| E2 \| 2_1^+ \rangle \langle 2_1^+ \| E2 \| 2_2^+ \rangle \langle 2_2^+ \| E2 \| 0_1^+ \rangle$$

has been determined in previous reorientation precession measurements⁽²⁾ after Coulomb excitation with α and ^{16}O to be positive corresponding to constructive interference. From the present experiment we draw the same conclusion and extrapolate it to the three next higher corresponding P_3 -terms, where the 4_2^+ , 6_2^+ and 8_2^+ -state are involved. This extrapolation is based on the argument, that assuming opposite signs for these interference terms the resulting excitation probabilities in the γ -band are reduced by about a factor of 3; in order to obtain agreement with the experimental γ -yields the corresponding intra- and inter-band $B(E2)$ -values would result to be larger by about the same factor, which is certainly unreasonable.

For all ME's underlined in fig.16, both possible relative phases are considered in the error estimates. Since we are not able to verify the phases of the $I+1+2$ ME's between γ -band and gsb experimentally, they have been assumed to be positive in agreement with predictions of the generalized collective model⁽⁸⁾ and the interacting boson model⁽⁹⁾; choosing reverse signs results in changes of 1-6% in the transitional ME's and in an increase of 40-85% in the diagonal ME's. This is included in the error

estimates. Uncertainties in phases, where odd-spin members of the γ -band are involved, do not contribute significantly to systematic errors.

The resulting E2 ME's ($B(E2)$ -values) for the gsb are shown in table 3 and fig.14. For comparison we also show the results of previous experiments with light heavy ions. Our results for the $B(E2, 4_1^+ \rightarrow 2_1^+)$ -value and the static quadrupole moment of the 2_1^+ -state are found to be in excellent agreement with these values. Note that the given errors for the quadrupole moments are large due to systematic uncertainties, but they are not fully correlated, i.e. systematic errors do not cause a simultaneous shift of all quadrupole moments in the one or the other direction. Due to the rather large lower error bar for the $B(E2, 10_1^+ \rightarrow 8_1^+)$ -value the error of the quadrupole moment of the 8_1^+ -state is including the zero.

For the γ -band the resulting E2 ME's ($B(E2)$ -values) from our fit are shown in table 4 and fig.15. Again our results for the 2_2^+ -state are in good agreement with previously determined values. The γ -line corresponding to the $6_2^+ \rightarrow 6_1^+$ transition contains an unassigned contamination, the intensity of which can be estimated only roughly. This leads to the larger error for the $B(E2, 6_2^+ \rightarrow 6_1^+)$ -value and consequently also to a larger error in the $B(E2, 8_2^+ \rightarrow 6_2^+)$ -value. In table 5 some of the resulting E2 branching

ratios are compared to the corresponding values resulting from other experiments^{8,9,12,19}); the overall agreement is satisfactory.

The E2(M1) ME's involving the 0_2^+ and 2_3^+ -state are shown in table 6. In this case we obtain two different sets of solutions depending on the phase of the interference term

$$P(2_3^+) = \langle 2_1^+ \| E2 \| 0_2^+ \rangle \langle 0_2^+ \| E2 \| 2_3^+ \rangle \langle 2_3^+ \| E2 \| 2_1^+ \rangle.$$

We favour the first set corresponding to a positive interference term, since for this case the E2 ME for the $2_1^+ \rightarrow 0_2^+$ transition is in good agreement with the result of Coulomb excitation experiments^{8,9}) with light heavy ions, which should not be influenced notably by this interference term. Assuming a negative interference term, the agreement is significantly worse. The large errors for the two ME's $\langle 2_1^+ \| E2 \| 2_3^+ \rangle$ and $\langle 2_3^+ \| E2 \| 2_3^+ \rangle$ are due to the very strong mutual correlation of these two quantities for all scattering angles (see fig.13). The errors deduced for these states contain the contributions mentioned above and also the uncertainty of the E2/M1 mixing ratio $\Delta = 0.54 \pm 0.21$ of the $2_3^+ \rightarrow 2_1^+$ transition¹²). The known branching^{12,19}) of the 2_3^+ -state to the 0_1^+ , 2_2^+ and 4_1^+ -levels allows to deduce the corresponding absolute E2 ME's, as well. The value for the $2_3^+ \rightarrow 2_2^+$ transition has to be regarded as an upper limit only, since no M1 contribution was taken into account.

6. DISCUSSION

The predominantly collective character of the excited states of ^{104}Ru considered here (with excitation energies up to about 3 MeV) is reflected by large $B(E2)$ -values, which were determined in the present experiment, to amount up to 50-100 single particle units. Consequently the following discussion of the observed level energies and electromagnetic moments will be concentrated on collective degrees of freedom, especially the quadrupole deformation and the γ -asymmetry, and on the interpretation of our results in the framework of different collective models.

The observed excitation energies and $B(E2)$ -values suggest the arrangement of most of the observed levels in sequences as shown in figs.3 and 17. The level spacings resemble more a rotational pattern than that of an anharmonic vibrator. Although the rather low lying first excited 0^+ -state seems to favour its interpretation as a member of a 2-phonon triplet, a vibrational interpretation of ^{104}Ru is also ruled out by the large observed $B(E2)$ -values and the large quadrupole moment of the 2_1^+ -state. On the other hand the level spacing of the gsb also clearly deviates from the simple axial rigid rotor description as well as some characteristic $B(E2)$ -ratios do. In a recent schematic investigation^{5,1)} it has been demonstrated that the neutron-rich Ru and Pd isotopes have to be

placed in the region of the phase transition between the two limiting symmetries $SU(5)$ and $O(6)$ of the interacting boson model ⁴⁹) (IBA-1); in terms of geometric collective models the $SU(5) \rightarrow O(6)$ transition corresponds to a transition between anharmonic vibrational and γ -unstable rotational nuclei. This result is consistent with the description of the neutron-rich Ru isotopes in the framework of the generalized collective model ^{74,89}). As shown in the IBA-1 investigation the nucleus ¹⁰⁴Ru is located clearly on the $O(6)$ - or γ -unstable - side of the $SU(5) \rightarrow O(6)$ transition. Furthermore it has been shown, that a transition $SU(5) \rightarrow SU(3)$, which corresponds to a transition towards the axial rigid rotor description, can be excluded for the neutron-rich Ru and Pd isotopes. Hence we will concentrate in the following on collective models, which include the γ -degree of freedom; in particular, we will discuss the softness of the γ -deformed potential in γ -direction, i.e. whether our data allow to distinguish between a γ -rigid, a γ -soft or a γ -unstable deformation. The corresponding model calculations have been performed in the framework of the asymmetric rotor model ⁴⁴) of Davydov and Filippov (AR), the generalized collective model ⁴⁸) of Gneuss and Greiner (GCM) and the interacting boson model ⁴⁹) if Arima and Iachello (IBA-2).

The observed energy levels are shown in fig.17 in comparison to these different model calculations. The parameters β and γ of the AR model are

chosen to reproduce the $B(E2)$ -values connecting the $0_1^{+}, 2_1^{+}$ - and 2_2^{+} -states; the best agreement is obtained for $\beta=0.275$ and $\gamma=25^\circ$. The GCM parameters are said to be adapted to the level energies and $E2$ properties in ¹⁰⁴Ru as far as known at the time when the fit ⁴⁸) was performed. The resulting potential energy surface exhibits a β -deformed minimum around $\beta \approx 0.22$ together with an extreme softness in γ -direction. For the IBA-2 fit ⁴⁹) all known experimental data for the neutron-rich Ru and Pd isotopes were included to adjust the model parameters. The description of the gsb energies (fig.17) and $B(E2)$ -values (fig.14) is of about the same quality for these three model calculations and reproduces the gross trends of the experimental data, although there are some distinct deviations:

- (i) There is a sudden increase in the $B(E2)$ -values between the $4_1^{+}, 2_1^{+}$ and the $6_1^{+}, 4_1^{+}$ transition. This behaviour cannot be reproduced by any of the three models.
- (ii) The level spacings and the $B(E2)$ -values of the gsb resulting from the GCM fit are systematically too low, indicating that the deformation of $\beta \approx 0.22$ is somewhat too small.
- (iii) There is no evidence for a reduction in $B(E2)$ -values as predicted by the IBA due to the finite boson number and hence for the corresponding cut-off at $I=16$.
- (iv) All models predict a smooth continuation of the gsb to spins $I > 8$. The fact that we do not observe this regular continuation of the

gsb - see the discussion in section 3 - indicates that additional degrees of freedom may become important in this spin region.

In contrast to the items discussed before, the model predictions concerning the static quadrupole moments of the gsb are quite different. The experimental quadrupole moments of the gsb (fig.14,right) show a spin dependence, which is rather well reproduced assuming a rigid triaxial deformation with $\gamma=25^\circ$ (AR) for ^{10}Ru , whereas the other collective models predict either the opposite spin dependence, (i.e. a strong increase with increasing spin) or all quadrupole moments to be zero, as is the case for the $O(6)$ limit of the IBA-1 or the AR with $\gamma=30^\circ$. While the magnitude and the spin dependence of the gsb quadrupole moments indicate a γ -deformation of $20^\circ \leq \gamma < 30^\circ$, the observed decrease in the quadrupole moments does not contain an information about the softness of the potential in γ -direction; it can also be reproduced by a γ -soft calculation (see for instance ref.22, where such a model calculation for ^{11}Pd is shown). Thus, we come to the conclusion, that in order to describe the observed static quadrupole moments within the collective degrees of freedom considered in these models, the ground state deformation of ^{10}Ru has to be either statically or dynamically triaxial with a mean asymmetry around 25° .

Another interesting aspect^{5,2)} appears in the framework of the interacting boson model with the inclusion of a $L=4$ boson (g-boson) in addition to the usual s,d-space ($L=0,2$). The occurrence of this $L=4$ boson can be thought of as the alignment of a pair of nucleons at a certain excitation energy giving rise to triaxial deformation. This is one possible way to include triaxiality in the interacting boson model, which in its usual form (IBA-1, IBA-2) contains only either rigid axial symmetric or γ -unstable deformation. Schematic IBA-1 calculations, which include this effect, have been performed recently^{5,3)}; the g-boson configuration was located about 2 MeV above the normal s,d-configuration and an appropriate mixing of these two configurations was introduced. The resulting gsb properties are in significantly better agreement with our data than is the IBA-2 fit^{4,9)}: The increase of the gsb $B(E2)$ -values with increasing spin is steeper, in addition the effects of the cut-off are shifted to higher spin values. The gsb quadrupole moments are affected only for states with $L \geq 4$, where the contribution of the g-boson may be either positive or negative depending on the quadrupole moment of this g-boson, hence on its underlying microscopic structure. If we assume the g-boson to be built of a pair of $g_{9/2}$ -protons, its quadrupole moment is expected to be positive and to diminish the absolute values of the static quadrupole moments for states with $L \geq 4$. The resulting gsb quadrupole moments are nearly constant independent of the spin, in much better agreement to our findings. From this

and the information on the $B(E2)$ -values we come to the conclusion that including a $L=4$ boson in the interacting boson model gives indeed a better description of this nucleus. To obtain complete agreement to all the experimental data, however, the triaxiality produced by just one g -pair is not sufficient; one probably has to take into account the alignment of additional nucleon(proton)-pairs ($L=6,8$). This will be the subject of further investigations.

In addition to the gsb , fig.17 also shows a comparison of the experimental level energies for excited bands to the results of the different model calculations. In general a rather low lying (quasi)- γ -band as observed here contradicts the axial rigid rotor description of a nucleus and again indicates the importance of including the γ -degree of freedom in the ground state deformation. Information concerning the γ -softness is contained in the odd-even staggering of this γ -band, for instance. A γ -soft potential manifests itself in a $(3^+, 4^+)$, $(5^+, 6^+)$,... clustering, as it is the case for the IBA-2 and GCM calculations shown in fig.17, whereas a γ -rigid potential (AR) causes a pronounced $(2^+, 3^+)$, $(4^+, 5^+)$,... clustering, which may even result in a crossing of the even and odd spin members of such a cluster. The experimental data show an indication of the clustering as predicted for the γ -soft case, but the amount of the observed odd-even staggering is significantly smaller than calculated.

The same is observed in other nuclei (Pd,Os,Pt), where the γ -degree of freedom appears to be important.

The experimental $B(E2)$ -values for transitions in the γ -band and between the γ -band and the gsb are compared to the different model calculations in fig.15. Obviously there is no qualitative but only a quantitative difference between the predictions of the γ -soft and the γ -rigid models; however, a γ -soft description seems to be favoured: (i) The inband $B(E2)$ -values are clearly larger than it is predicted for an asymmetric rigid rotor (AR); the axial rigid rotor values (RR), assuming the same intrinsic quadrupole moment Q_0 as for the gsb , are even lower. Again there is no evidence for the cut-off predicted by the interacting boson model. However, the agreement between IBA calculations and experiment is again improved appreciably by including the g -boson³⁾ in the model calculations. (ii) In the region of interest the decrease of the $\Delta I=0$ $B(E2)$ -values to the gsb is much steeper with increasing spin for a γ -rigid deformation ($\propto 1/I^2$) than for a γ -soft potential ($\propto 1/I$). Our experimental data are in between these two cases and the relatively large systematic uncertainties do not allow a clear distinction. (iii) The $\Delta I=2$ transitions to the gsb are predicted to be much stronger for the γ -rigid case than observed in the experiment, which is in rather good agreement to the γ -soft calculations (especially the GCM).

To demonstrate the difference between a χ -rigid and a χ -soft description even clearer, we compare the experimental to the theoretical B(E2)-ratios for the states of the χ -band in table 7. Evidently the experimental data for ^{104}Ru are in better agreement with the χ -soft models.

Finally it should be mentioned that the observed interband B(E2)-values to the gsb are clearly different from those expected for axial rigid rotational nuclei: In a rigid rotor nucleus the inband E2 ME's of the χ -band are typically larger by a factor of 5-10 as compared to the interband E2 ME's to the gsb and both the $\Delta I=0$ and $\Delta I=2$ ME's are of the same order of magnitude. In the case of ^{104}Ru , however, the difference is less than a factor of 2 for the $\Delta I=0$ transitions, but a factor of 10 and more for the $\Delta I=2$ transitions. Furthermore the Alaga rule gives the opposite spin dependence for these interband transition ME's.

As already mentioned in the introduction, the attempt to interpret the first excited 0^+ -state (0_2^+) in the framework of the usual collective degrees of freedom leads to contradictory arguments. The low excitation energy alludes to a two-phonon triplet, but based on the arguments given above ^{104}Ru is not a vibrational nucleus at all. A further argument is the experimental ratio $B(E2, 0_2^+ \rightarrow 2_1^+)/B(E2, 2_1^+ \rightarrow 0_1^+) = 0.43$, which corresponds

to only about 20% of the vibrational⁽⁴¹⁾ value. Even more, the above mentioned investigation of the transition $SU(5) \rightarrow O(6)$ in the interacting boson model⁽⁵¹⁾ shows ^{104}Ru to be on the $O(6)$ side of this transitional region, thereby also fixing energies and B(E2)-values for excited 0^+ -states and bands built on them. According to this schematic calculation the first excited 0^+ -state in ^{104}Ru is expected at 1300-1400 keV. This is a notably higher excitation energy than observed experimentally for the 0_2^+ -state (988.3 keV), but in surprisingly good agreement to the level at 1335.2 keV, for which we propose spin $I^\pi=0^+$. This level is predicted⁽⁵¹⁾ to decay mainly by E2 to the 2_2^+ -level and the data are not in disagreement to this prediction; due to the low energy the expected intensity of the transition to the 2_2^+ -state is too weak to be resolved from the background both in the present MCE experiment and in the $\chi\chi$ -coincidences of the β^- -decay investigation^(12,19). In this context one should remember, that difficulties with the interpretation of excited 0^+ -states are a well-known problem in this mass region. In the neighbouring nuclei $^{100,102}\text{Ru}$ and $^{104,110}\text{Pd}$, for instance, the 0_2^+ -states are observed at rather low excitation energy too and do not fit in the schematic $SU(5) \rightarrow O(6)$ description, whereas in ^{102}Ru and $^{106,110}\text{Pd}$, where they are known^(54, 58), the 0_3^+ -states show again both the predicted⁽⁵¹⁾ excitation energies and the E2 decay properties of the collective 0^+ excitation. The apparent agreement of both the IBA-2 and the GCM calculations shown in

fig.17 with the observed excitation energies and the $B(E2)$ -values for the 0_2^+ and 2_3^+ -states should thus be considered somewhat artificial since the adjustment of the free model parameters was performed just to reproduce these states. In the case of the GCM fit this is probably the reason for the resulting deformation to be too small. The pure AR model contains no excited 0^+ -state at all, but it can be generated by including 0 and 2 quasiparticle couplings⁽³⁾ or β -vibrations⁽⁶⁾.

As we propose to identify - at least for $^{102,104}\text{Ru}$ and $^{106,110}\text{Pd}$ - the 0_3^+ -state with the expected collective excited 0^+ -state, the question arises about the nature of the low lying 0_2^+ -state. Its quite strong population in two nucleon transfer reactions^(1,15) indicates rather a different underlying configuration than a "classical" collective excitation mode. It especially suggests the excitation of two nucleons across the Fermi surface. In a microscopic picture deformation is related to the isoscalar part of the nucleon-nucleon interaction, i.e. the proton-neutron interaction^(1,16,2): Shell model and HFB calculations for the $^{A}_{40}\text{Zr}$ and $^{A}_{42}\text{Mo}$ isotopes⁽³⁾ have shown that in the $A=100$ region the onset of deformation is due to the $\pi 1g_{9/2}$ - $\nu 1g_{7/2}$ interaction. Furthermore the excitation of a pair of protons over the $Z=40$ subshell gap in the $g_{9/2}$ -level leads to the coexistence of two intrinsic configurations with very different deformation. In this picture both the sudden onset of

deformation for $N \geq 58$ in Zr and Mo isotopes and the coexistence of a deformed excited 0^+ -state and a more spherical ground state for $N < 56$ - and vice versa for $N \geq 58$ - can be understood: due to the filling of the $\nu 1g_{7/2}$ level after the $N=56$ subshell gap the $\pi 1g_{9/2}$ - $\nu 1g_{7/2}$ interaction increases and leads to a lowering of the deformed configuration which crosses the spherical configuration between $N=56$ and 58. This is also the essence of a recent IBA-2 calculation⁽⁶⁾, where two different proton boson numbers and a mixing between the two different configurations have been used to reproduce both excitation energies and transition probabilities in the neutron-rich Zr and Mo isotopes.

In the same picture we can understand the very smooth onset of deformation in the $^{A}_{44}\text{Ru}$ and $^{A}_{46}\text{Pd}$ isotopes: the $1g_{9/2}$ -level is filled with at least 4(6) protons independent from the neutron number and both the excitation energies and the two neutron separation energies⁽¹⁵⁾ reveal that there is no $N=56$ subshell gap in these isotopes. If one again assumes the excited 0^+ -states to be based on a different proton configuration than the ground state, one would not expect the two configurations to have a very different deformation for these nuclei. That is indeed what is observed experimentally: the $2_3^+ - 0_2^+$ spacing of 527 keV compared to the $2_1^+ - 0_1^+$ spacing of 358 keV indicates the excited configuration to be somewhat less deformed. This is supported by the corresponding $E2$ ME of

0.74 eb (see table 6) and 0.91 eb, respectively, yielding $\beta=0.245$ for the excited configuration and $\beta=0.275$ for the ground state configuration. Furthermore, the small quadrupole moment of the 2_3^+ -state ($\langle 2_3^+ || E2 || 2_3^+ \rangle = -0.06 \pm 0.19$ eb) points to a γ -deformation for the excited configuration, which is closer to $\gamma=30^\circ$ as compared to the ground state configuration ($\langle \gamma \rangle = 25^\circ$) again. First IBA-calculations⁶⁾ including an additional s', d'-configuration besides the normal s, d-configuration and a small configuration mixing show excitation energies and B(E2)-values in reasonable agreement with experimental data; a more detailed investigation is in progress. As a different proton configuration and deformation for the ground state and the first excited 0_1^+ -state could give rise to enhanced E0 transitions between these states, a measurement of the corresponding E0 strength should provide a good test for our interpretation.

From the excitation energies, the B(E2)-values and the quadrupole moments determined in the present MCE experiment we conclude that ^{100}Ru is a deformed nucleus; the best description is obtained for a triaxial ground state deformation $\sim 20^\circ \leq \gamma < 30^\circ$ - and a potential, which is soft in γ -direction. The 0_2^+ -state is not the collective first excited 0^+ -state predicted by the nuclear models considered; it is very likely based on an intruder configuration, which is slightly less deformed in β -direction but closer to $\gamma=30^\circ$.

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REFERENCES

- 1) D.A. Arseniev, A. Sobiczewski and V.G. Soloviev, Nucl.Phys.
A139(1969)269
- 2) I. Ragnarsson, Proc.Int.Conf.on properties of nuclei far from
the region of beta-stability, Leysin, 1970, Cern 70-30, p.847
- 3) W. Fabian, G.E.W. Horlacher and K. Albrecht, Nucl.Phys.
A190(1972)533
- 4) A. Faessler, J.E. Galonska, U. Götz and H.C. Pauli,
Nucl.Phys.*A230*(1974)302
- 5) D. Bucurescu, G. Constantinescu and M. Ivascu, Rev.Rom.Phys.
Tome 24, No. 10 (Bucarest 1979), p.941
- 6) C.M. Lederer and V.S. Shirley, Table of isotopes (Wiley, New York,
1978)
- 7) K. Sümmerner, N. Kaffrell, N. Trautmann, K. Broden, G. Skarnemark,
T. Björnstad, I. Haldorsen and J.A. Maruhn, Nucl.Phys.*A339*(1980)74
- 8) F.K. McGowan, R.L. Robinson, P.H. Stelson and W.T. Milner, Nucl.Phys.
A173(1968)529
- 9) S. Landsberger, R. Lecomte, P. Paradis and S. Monaro, Phys.Rev.
C21(1980)588
- 10) R.C. Jared, H. Nifenecker and S.G. Thompson, Proc.3.Symp.on
physics and chemistry of fission, Rochester, 1974, Vol.2, p.211
- 11) E. Cheifetz, H.A. Selic, A. Wolf, R. Chechik and J.B. Wilhelmy,
Proc.Workshop on nuclear spectroscopy of fission products,
Grenoble, 1979, ed.T.v.Egidy (Inst.of Phys., Bristol, 1980), p.193
- 12) K. Sümmerner, N. Kaffrell and N. Trautmann, Nucl.Phys.*A308*(1978)1
- 13) H. Bohn, P. Kienle, D. Proetel and R.L. Hersberger, Z.Physik*A274*
(1975)327
- 14) R.F. Casten, E.R. Flynn, O. Hansen and T.J. Mulligan, Nucl.Phys.
A184(1972)357
- 15) R.E. Anderson, J.J. Kraushaar, I.C. Oelrich, R.M. DeVecchio,
R.A. Naumann, E.R. Flynn and C.E. Moss, Phys.Rev.*C15*(1977)123
- 16) W.D. Myers in Droplet model of atomic nuclei (Plenum, New York, 1978)
- 17) M.W. Guidry, P.A. Butler, R. Donangelo, E. Grosse, Y. El Masi,
I.Y. Lee, F.S. Stephens, R.M. Diamond, L.L. Riedinger, C.R. Bingham,
A.C. Kahler, J.A. Vrbá, E.L. Robinson and N.R. Johnson,
Phys.Rev.Lett.*40*(1978)1016
- 18) P. Fuchs et al, to be published
- 19) J. Stachel, N. Kaffrell and K. Sümmerner, reanalysis of the data
of ref. 12, unpublished
- 20) J.A. Grau, L.E. Samuelson, F.A. Rickey, P.C. Simms and G.J. Smith,
Phys.Rev.*C14*(1976)2297
- 21) W.F. Piel, G. Scharff-Goldhaber, A.H. Lumpkin, Y.K. Lee and
D.C. Stromswold, Phys.Rev.*C23*(1981)708

- 22) L. Hasselgren and D. Cline in Interacting bose fermi systems in nuclei, ed. F. Iachello (Plenum, New York, 1981)
- 23) J. Rekstad and P.O. Tjøm, J.Phys. **G3**(1977)411
- 24) J. Srebrny, private communication
- 25) H. Ower, Th.W. Elze, J. Idzko, K. Stelzer, H. Emling, P. Fuchs, E. Grosse, D. Schwalm, H.J. Wollersheim, N. Kaffrell and N. Trautmann, to be published in Nucl.Phys.
- 26) E. Grosse, A. Bažanda, H. Emling, F. Folkmann, P. Fuchs, R.B. Piercey, D. Schwalm, H.J. Wollersheim, D. Evers and H. Ower, Phys.Scripta **24**(1981)337
- 27) K. Alder and A. Winther, Electromagnetic excitation (North Holland, Amsterdam, 1975)
- 28) A. Winther and J. de Boer, in Coulomb excitation, ed. K. Alder and A. Winther (Academic Press, New York, 1966), p.303
- 29) D. Schwalm, Proc.Int.summer school on nuclear structure, Dronten, 1980 (Plenum, New York, 1981)
- 30) M.J. Rhoades-Brown, M.H. Macfarlane and S.C. Pieper, Phys.Rev. **C21**(1980), 2417 and 2436
- 31) J.R. Birkelund, J.R. Huizenga, H. Freiesleben, K.L. Wolf, J.P. Unik and V.E. Viola, Phys.Rev. **C13**(1976)133
- 32) A. Abragam and R.V. Pound, Phys.Rev. **92**(1953)943
- 33) Ch. Michel et al., to be published
- 34) R. Nordhagen in Hyperfine interactions in excited nuclei, ed. G. Goldring and R. Kalish (Gordon and Breach, New York, 1971), p.893
- 35) R. Beyer, R.P. Scharenberg and J. Thompson, Phys.Rev. **C2**(1970)1469
- 36) W.R. Lutz, J.A. Thomson, R.D. Scharenberg and R.D. Larsen, Phys.Rev. **C6**(1972)1385
- 37) O. Häusser, T.K. Alexander, A.B. McDonald and W.T. Diamond, Nucl.Phys. **A175**(1971)593
- 38) J. de Boer, I.D. Rogers and S. Steadman in Hyperfine interactions in excited nuclei, ed. G. Goldring and R. Kalish (Gordon and Breach, New York, 1971), p.964
- 39) N.K.B. Shu, R. Levy, N. Tsoupas, A. Lopez-Garcia, W. Andrejtscheff and N. Benczer-Koller, to be published
- 40) D. Ward, H.R. Andrews, R.L. Graham, J.S. Geiger and N. Rud, Nucl.Phys. **A234**(1974)94
- 41) A. Bohr and B. Mottelson in Nuclear structure, Vol.II (W.A. Benjamin, Inc., Reading, 1975)
- 42) C. Fahlander, L. Hasselgren, G. Possnert and J.E. Thun, Phys.Scripta **18**(1978)47
- 43) W. Greiner, Nucl.Phys. **80**(1966)48
- 44) A.S. Davydov and G.F. Filippov, Nucl.Phys. **8**(1958)237
- H. Toki and A. Faessler, Z.Physik **A276**(1976)35
- 45) M. Maynard, D.C. Palmer, J.R. Cresswell, P.D. Forsyth, I. Hall and

- D.G.E. Martin, *J.Phys.C3*(1977)1735
- 46) M.F. Nolan, I. Hall, D.J. Thomas and M.J. Throop, *J. Phys.A6*(1973) L57
- 47) P.H. Stelson, *Adv.Nucl.Phys.1*(1968)1
- 48) G. Gneuss and W. Greiner, *Nucl.Phys.A171*(1971)449
- P.O. Hess and J.A. Maruhn in *Future directions in studies of nuclei far from stability*, ed. J.H. Hamilton et al. (North Holland, Amsterdam, 1980)
- 49) F. Iachello in *Interacting bosons in nuclear physics*, ed. F. Iachello (Plenum, New York, 1979)
- P. Van Isacker and G. Puddu, *Nucl.Phys.A348*(1980)125
- 50) J.F. Ziegler, *Handbook of stopping cross sections for energetic ions in all elements* (Pergamon, New York, 1980) Vol.5, p.280
- 51) J. Stachel, P. Van Isacker, and K. Heyde, *Phys.Rev.C25*(1982)650
- 52) F. Iachello, private communication
- 53) J. Stachel, N. Blassi and F. Iachello, to be published
- 54) D. De Frenne, H. Thierens, E. Jacobs, P. De Gelder, P. D'hondt, A. De Clercq, K. Heyde and A.J. Derytter, *Phys.Rev.C18*(1978)486
- 55) B. Singh and H.W. Taylor, *Nucl.Phys.A155*(1970)70
- 56) J. Konijn, E.W.A. Lingeman, F. Diederix, B.J. Meijer, P. Koldewijn and A.A.C. Klaasse, *Nucl.Phys.A138*(1969)514
- 57) S.T. Hsue, H.H. Hsu, F.K. Wahn, W.R. Western and S.A. Williams, *Phys.Rev.C12*(1975)582
- 58) L.I. Govor, A.M. Demidov, I.B. Shukalov, M.R. Ahmed, Kh.I. Shakarchi, S. Al-Najjar, M.A. Al-Amili and N. Al-Assafi, *Nucl.Phys.A245*(1975)13
- 59) H.L. Yadav, H. Toki and A. Faessler, *Phys.Lett.76B*(1978)144
- 60) A.S. Davydov and A.A. Chaban, *Nucl.Phys.20*(1960)499
- 61) A. De-Shalit and M. Goldhaber, *Phys.Rev.92*(1953)1211
- 62) I. Talmi, *Rev.Mod.Phys.34*(1962)704
- I. Uhma, *Phys.Rev.132*(1963)2225
- 63) P. Federman and S. Pittel, *Phys.Rev.C20*(1979)820
- 64) M. Sambataro and G. Molnar, *Nucl.Phys.A376*(1982)201
- 65) A. Wapstra and K. Bos, *Atomic and nuclear data tables* 19(1977)175
- 66) A. van den Berg, M. Sambataro and F. Iachello, private communication

FIGURE CAPTIONS

Fig. 1 Schematic view of the experimental set-up: After multiple

Coulomb excitation using a thin target (target 1: 520 μ g/cm² ¹⁰⁴Ru on 34 μ g/cm² C) the recoil nuclei have were detected in a position sensitive particle detector L at $\zeta=17^\circ-58^\circ$ in coincidence with the scattered projectiles detected in R under $\psi=30^\circ-20^\circ$ and the deexcitation γ -rays detected in the different Ge- and NaI-detectors. Due to the symmetry of the set-up data were also taken with the role of the detectors R and L interchanged. A thick target (target 2: ≈ 2 mg/cm² ¹⁰⁴Ru on 50mg/cm² ²⁰⁸Pb) was placed about 1.50 m downstream to measure $\gamma\gamma$ -coincidences in a close geometry.

Fig. 2 γ -spectra measured with Ge2 in coincidence with scattered projectiles and Ru recoil nuclei

(a) uncorrected spectrum with recoil nuclei detected either in particle detector L or R at c.m. scattering angles of $\theta=64^\circ-146^\circ$.
(b) the same spectrum as (a) after Doppler correction and with the condition, that the recoil nuclei have been detected in particle detector L.

(c) the same spectrum as (b) with the condition that at least one additional γ -ray has been detected in coincidence.

(d,e) the same spectra as (b), but for two different, smaller regions of impact parameters.

Fig. 3 Level scheme of ¹⁰⁴Ru. The dots mark new levels (or new spin assignments) resulting from this experiment. The exact energies for the transitions marked by * result from this experiment, all other energies are taken from ref.12. The dashed lines indicate transitions observed only in the β^- -decay investigation¹²).

Fig. 4 Ratio of the γ -yields observed in twofold and onefold particle gamma coincidence spectra for different transitions $[I \rightarrow I']$ in ¹⁰⁴Ru as a function of the expected multiplicity $M_{I \rightarrow I'}$; the left and right hand limitations of each bar correspond to the minimal and calculated total multiplicity for the respective transition (see also text). The expected appropriate proportionality between the calculated multiplicity and the experimental yield ratio is indicated by the straight line. The arrow indicates the calculated multiplicity for the $10_1^{-8} 8_1$ transition.

Fig. 5 Relative phases of the reduced E2 ME's $\langle I' \| E2 \| I \rangle$ as used for the determination of $B(E2)$ -values and quadrupole moments. For the reduced ME's we use the definition as given by Alder and Winther²⁷⁾.

The thick drawn signs symbolize transitions strong enough, to use the corresponding δ -yields for the determination of E2 ME's. For the meaning of the framed signs see text. Where no signs are marked, the corresponding E2 ME's are zero.

Fig. 6 Calculated δ -angular distribution for the $2_1^{+0} \rightarrow 1_1^{+}$ transition corresponding to the experimental set-up shown in fig.1. The three curves correspond to three different recoil angles; full line: $\zeta=55.2^\circ-58.0^\circ$, dashed-dotted line: $\zeta=43.6^\circ-46.7^\circ$, dotted line: $\zeta=17.3^\circ-27.3^\circ$. The positions of the δ -detectors are marked by the arrows.

left: $G_2=G_4=1.0$ for the 2_1^{+} -state,
right: with realistic deorientation, i.e. $G_2=0.26$, $G_4=0.09$ for the 2_1^{+} -state.

Fig. 7 *left:* Experimental yield ratios for the $2_1^{+0} \rightarrow 1_1^{+}$ δ -rays registered in the Ge detectors at 30° and 150° and recoil nuclei detected in

particle detector L. Full line: $G_2=1.0$, dashed line: $G_2=0.0$, dashed-dotted line: $G_2=0.26$.

right: same as left for the doublet $4_1^{+2} \rightarrow 2_1^{+2}$; dashed-dotted line: $G_2=0.45$, dotted line: see text.

Fig. 8 Experimental deorientation coefficients G_2 in dependence on the lifetime τ of the corresponding nuclear level. The full line and the dashed errorband correspond to the lifetime dependence of the Abragam and Pound ansatz using the given value of λ_2 . For the other excited levels the G_2 values have been taken from this curve as indicated by the arrows.

Fig. 9 The velocity dependence of experimental values λ_2/g^2 . The value for ^{104}Ru is resulting from this experiment, the other points correspond to the mean values taken from the literature^{35,39)}. The drawn line corresponds to $\lambda_2/g^2 \propto v^{-1.2}$.

Fig. 10 Calculated sensitivity $C_{G_4^{+4}, J \rightarrow J'}$ of the δ -yield ratio $r_{G_4^{+4}, J \rightarrow J'}^{+} + (\theta)$ in dependence on the scattering angle. The curves are labeled by the corresponding values $J \rightarrow J'$.

Fig. 11 Experimental γ -yields for the $6_1^{+} \rightarrow 4_1^{+}$ transition normalized to $2_1^{+} \rightarrow 0_1^{+}$ in dependence on the scattering angle θ . The γ -radiation has been detected with Ge2; the open circles (dashed lines) correspond to events, where the recoiling target nuclei have been detected in particle detector L, the filled circles (solid lines) represent events, where the recoil nuclei have been detected in R. For the curves a the quadrupole moments of the gsb have been extrapolated from the experimental value for the 2_1^{+} -state using the rigid rotor formula⁴¹); the curves b represent the result of varying both the gsb B(E2)-values and the quadrupole moments during the fit (see 5.2).

Fig. 12 Calculated sensitivity for the $6_2^{+} \rightarrow 4_2^{+}$ in-band transition and the $6_2^{+} \rightarrow 6_1^{+}$ γ -band to gsb transition in dependence on the scattering angle θ .

Fig. 13 Calculated sensitivity for the $0_2^{+} \rightarrow 2_1^{+}$ and the $2_3^{+} \rightarrow 2_1^{+}$ transitions in dependence on the scattering angle θ .

Fig. 14 Experimental B(E2)-values and diagonal E2 ME's for the gsb of ^{104}Ru . The filled circles are resulting from the present experiment, the open circles correspond to the mean values of refs.8,9

and refs.9,42 respectively. The diagonal E2 ME is related directly⁴¹) to the static quadrupole moment Q(I) by

$$\langle I \| E2 \| I \rangle = \sqrt{5(2I+1)(I+1)(2I+3)/(16\pi I(I-1))} Q(I)$$

Our data are compared with the predictions of different collective models as the generalized collective model⁴⁸) (GCM), the asymmetric rotor model⁴⁴) (AR) for $\gamma=25^\circ$, the axial symmetric rigid rotor model⁴¹) (RR) and the interacting boson model⁴⁹) (IBA-2).

Fig. 15 B(E2)-values for transitions involving the γ -band of ^{104}Ru (filled circles: this experiment; open circles: refs.8,9). In comparison the predictions of the same collective models as in fig.14 are shown.

Fig. 16 Absolute values of the undetermined ME's $\langle I' \| E2 \| I \rangle$ and their uncertainties as assumed for the final fit. For the phases of these ME's see fig.5. For the underlined ME's both possible relative phases are included in the error estimates. The filled circles symbolize ME's, which could be determined in the present experiment (figs.14,15 and tables 3,4,6).

Fig. 17 Comparison of experimental and calculated level energies for ^{104}Ru . The collective model predictions shown are the same as in figs. 14, 15. The asymmetric rotor calculation contains a 2-parameter VMI fit⁽⁴⁾ to the 2_1^+ and 4_1^+ excitation energies.

Fig. 3

Fig. 2

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 14

Fig. 15

150Zr-2441

Fig. 16

Fig. 17

Table 1: γ -ray energies and relative yield ratios (summed over all detected recoil angles) of transitions in ^{104}Ru , which could not be placed in the level scheme.

E_γ/keV	$\frac{Y_{I \rightarrow I'}}{Y_{2_1 \rightarrow 0_1}} / \%$
651.5	.48
912.4	.19
935.0	.15
964.3	.53
994.9	.30
1085.6	.14
1219.1	.25
1250.1	.05
1271.0	.07
1465.4	.65
1473.9	.13

Table 2: Difference between normalized γ -ray yield ratios for the gsb of ^{104}Ru resulting from a semiclassical and a fully quantum mechanical calculation for the Coulomb excitation process (a). In the columns (b) the effect of the nuclear potential is included (see text).

θ	$\Delta r_{L_1 \rightarrow 2_1}^+ / \%$		$\Delta r_{6_1 \rightarrow 4_1}^+ / \%$		$\Delta r_{8_1 \rightarrow 6_1}^+ / \%$		$\Delta r_{10_1 \rightarrow 8_1}^+ / \%$	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
64.0-69.4	+2.0	+2.0	+1.7	+1.9	+1.3	+2.7	+3.3	+4.5
92.8-99.4	+0.4	+0.1	+0.9	+1.4	+1.3	+1.7	+1.1	+0.9
126.0-149.2	-1.1	-1.2	-0.4	+0.4	+1.2	+2.6	+1.1	+3.5

Table 3: Experimental E2 ME's for the gsb of ^{104}Ru as compared to previous experiments.

I $\rightarrow$ I'	<I' E2 I>/eb		
	this experiment	ref. 8	ref. 9
$2_1^{+} \rightarrow 0_1^{+}$	.910 ^a	$\pm .906$ (33)	$\pm .914$ (25)
$4_1^{+} \rightarrow 2_1^{+}$	1.444 (78)	± 1.41 (13)	± 1.467 (80)
$6_1^{+} \rightarrow 4_1^{+}$	2.168 (89)		
$8_1^{+} \rightarrow 6_1^{+}$	2.457 (57)		
$10_1^{+} \rightarrow 8_1^{+}$	2.71 ($^{+15}_{-65}$)		
		ref. 42	ref. 9
$2_1^{+} \rightarrow 2_1^{+}$	-.91 (40)	-1.00 (25) ^b	-.92 (11) ^b
$4_1^{+} \rightarrow 4_1^{+}$	-.26 (41)		
$6_1^{+} \rightarrow 6_1^{+}$	-.36 (32)		
$8_1^{+} \rightarrow 8_1^{+}$	-.47 (39) ^c		

^a The mean value of refs. 8 and 9 has been adopted.

^b Only the two most recent and accurate measurements of this quantity are shown here (see also refs. 45-47).

^c Due to the large lower error bar of the ME $\langle 8_1^{+} || E2 || 10_1^{+} \rangle$ the error of the ME $\langle 8_1^{+} || E2 || 8_1^{+} \rangle$ is including the zero.

Table 4: Experimental E2 ME's for the transitions depopulating the δ -band of ^{104}Ru .

I $\rightarrow$ I'	<I' E2 I>/eb		
	this experiment	ref. 8	ref. 9
$2_2^{+} \rightarrow 2_1^{+}$	-.894 (68)	$\pm .775$ (65)	$\pm .914$ (55)
$2_2^{+} \rightarrow 0_1^{+}$	-.171 (13)	$\pm .167$ (7)	$\pm .163$ (10)
$4_2^{+} \rightarrow 2_2^{+}$	.924 (108)		
$4_2^{+} \rightarrow 2_1^{+}$	-.073 (9)		
$4_2^{+} \rightarrow 4_1^{+}$	-.714 (84)		
$6_2^{+} \rightarrow 4_2^{+}$	-1.597 (113)		
$6_2^{+} \rightarrow 4_1^{+}$	-.024 (4)		
$6_2^{+} \rightarrow 6_1^{+}$	-.874 ($^{+158}_{-195}$)		
$8_2^{+} \rightarrow 6_2^{+}$	2.42 ($^{+26}_{-36}$)		

Table 5: Experimental B(E2) ratios for the γ -band of ^{104}Ru as compared to previous experiments

	this work	ref.12	ref.8	ref.9
$\frac{B(E2, 2^+_2 \rightarrow 0^+_1)}{B(E2, 2^+_2 \rightarrow 2^+_1)}$	.037 (6)	.054 (8)	.047 (9)	.040 (6)
$\frac{B(E2, 4^+_2 \rightarrow 2^+_1)}{B(E2, 4^+_2 \rightarrow 2^+_2)}$	.0063 (4)	.0090 (16)		
$\frac{B(E2, 4^+_2 \rightarrow 4^+_1)}{B(E2, 4^+_2 \rightarrow 2^+_2)}$	.60 (2)	.57 (9)		

Table 6: Experimental ME's for the 0^+_2 - and 2^+_3 -states in ^{104}Ru .

I $\rightarrow$ I'	$\langle I' E2 I \rangle / \text{eb}$		
	this experiment ^a	ref.8	ref.9
$0^+_2 \rightarrow 2^+_1$	- .261 (10)	$\pm$.276 (14)	$\pm$.269 (14)
$2^+_3 \rightarrow 0^+_1$	.737 (74)		
$2^+_3 \rightarrow 2^+_1$	- .112 (51)	.154 (51)	
$2^+_3 \rightarrow 2^+_3$	- .06 (19)	- .69 (19)	
$2^+_3 \rightarrow 0^+_b$	- .073 (45)	- .101 (53)	
$2^+_3 \rightarrow 4^+_1$	- .35 (22)	- .48 (26)	
$2^+_3 \rightarrow 2^+_c$	$\pm$.23 (23)	$\pm$.31 (31)	
$\langle I' M1 I \rangle / \mu_B$			
$2^+_3 \rightarrow 2^+_b$	- .247 (130)	.337 (143)	

^a The two sets of ME's obtained correspond to the two possible signs of the ME $\langle 2^+_1 || E2 || 2^+_3 \rangle$.

^b These ME's are based on the relative intensities of the transitions leaving the 2^+_3 -state and the E2/M1 mixing ratio for the $2^+_3 \rightarrow 2^+_1$ transition as determined in the β^- -decay investigation¹².

^c These values result from the known branching of the 2^+_3 - to the 2^+_2 -state¹³; for the $2^+_3 \rightarrow 2^+_2$ transition no M1 contribution is taken into account.

Table 7: B(E2) ratios for the γ -band of ^{104}Ru as deduced from the present experiment and calculated by different collective models (see text)

	present	GCM	IBA-2	AR
experiment				
$\frac{B(E2, 2^+_2 \rightarrow 0^+_1)}{B(E2, 2^+_2 \rightarrow 0^+_1)}$	.037(6)	.026	.034	.049
$\frac{B(E2, 4^+_2 \rightarrow 2^+_1)}{B(E2, 4^+_2 \rightarrow 2^+_1)}$	.0063(4)	.0043	.0071	.049
$\frac{B(E2, 6^+_2 \rightarrow 4^+_1)}{B(E2, 6^+_2 \rightarrow 4^+_1)}$	.60(2)	.67	.52	.73
$\frac{B(E2, 8^+_2 \rightarrow 6^+_1)}{B(E2, 8^+_2 \rightarrow 6^+_1)}$	.00023(7)	.00063	.0052	.0027
$\frac{B(E2, 10^+_2 \rightarrow 8^+_1)}{B(E2, 10^+_2 \rightarrow 8^+_1)}$	.30(12)	.32	.28	.16