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Reorientation precession measurements on ^{100,104}Ru

by

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Abstract

The quadrupole moments of the first excited 2^+ states in ^{100,104}Ru have been measured using the reorientation precession technique. In ^{104}Ru the sign of the Coulomb interference term $P_4 = M_{02_1^+} M_{02_2^+} M_{2_2^+2_1^+} M_{2_1^+2_1^+}$ was found to be $P_4 < 0$. The quadrupole moment in ^{104}Ru was determined to be -0.76±0.19 eb. In ^{100}Ru the measurements revealed a quadrupole moment of -0.40±0.12 eb independent of the sign of P_4. The experimentally determined values are compared with theoretical calculations.

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Introduction

Measurements of quadrupole moments and transition rates in nuclei reveal fundamental properties of the nuclear system. In the mass region $42 \leq Z \leq 48$ and $50 \leq N \leq 68$ rather extensive studies have been performed of properties of low excited states for the even isotopes. Coulomb excitation methods have shown that the nuclei in their first excited 2^+ states have a prolate shape. The ordering of the energy levels and the B(E2)-values indicate that the underlying structure is of a vibrational character. More experimental data are, however, needed in order to have a complete view of the systematics for isotopes and isotones in this region.

A few years ago we started measurements of $Q(2_1^+)$ using the reorientation precession technique, REPREC. Results of $Q(2_1^+)$ and B(E2)-values in the even Pd isotopes have been reported 1,2). The results show that the Pd-nuclei in their first excited 2^+ states become more prolate in going from ^{102}Pd to ^{110}Pd. From the trends of the values of $B(E2;\ 0_1^+ \rightarrow 2_1^+)$ in the even Ru isotopes the same type of systematics can be expected. However, measurements of $Q(2_1^+)$ have only been reported for ^{102,104}Ru 3,4,5). Since REPREC can be used to determine the sign of the Coulomb interference term P_4 and since this method has some advantages over the reorientation technique we decided to perform not only measurements in the isotopes where $Q(2_1^+)$ was unknown but also in ^{104}Ru. A measurement of $P_4 = M_{0_1^+2_1^+} M_{0_1^+2_2^+} M_{2_1^+2_2^+} M_{2_1^+2_1^+}$ in ^{102}Ru has already been reported 6).

With the recently introduced Interacting Boson Approximation (IBA) of Arima and Iachello [7] one has obtained a good agreement with experimental data for both positive and negative parity states for nuclei in this mass region 8). This collective model describes the even-even nuclei in terms of bosons where the boson number equals the number of proton- and neutron pairs outside closed shells. In ref. 2 we applied the IBA-model to ^{102,104}Pd and the fits obtained were promising. However, the large number of parameters and the relatively few experimental values imply that detailed comparisons are difficult. Comparisons with experimental data for a large number of nuclei can however give some insight in the theoretical interpretation.

Experiment and results

In the polarized state of an excited nucleus produced in Coulomb excitation there is a change in magnetic sublevel population due to the interaction between the scattered projectile and the quadrupole moment of the excited state. This can be seen in the gamma ray angular distribution as a precession which is proportional to the magnitude and sign of the quadrupole moment. The reorientation precession technique, REPREC, implies a determination of this precession. The influence of the quadrupole moment on the distribution will be largest for particles scattered around 90° and for gamma rays detected in the reaction plane.

The experimental setup consists of a scattering chamber where two particle detectors are placed at ±90° to the beam in the lab system and two NaI detectors at ±22.5° to the beam. The accuracy in the detector angles is better than 0.1°. The precession of the gamma ray angular distribution $W(\theta_\gamma)$, can be determined by measuring the number of coincidences for different combinations of the particle- and gamma ray detectors. In our experiment we determine two ratios of coincidences:

$$R = \frac{W(22.5^\circ)}{W(157.5^\circ)} = \frac{N_c(\text{part.}90^\circ\text{-}\gamma 22.5^\circ)}{N_c(\text{part.}270^\circ\text{-}\gamma 22.5^\circ)} = \frac{N_c(\text{part.}270^\circ\text{-}\gamma 337.5^\circ)}{N_c(\text{part.}90^\circ\text{-}\gamma 337.5^\circ)}$$

A more detailed presentation of REPREC is given in ref. 1.

The experimental methods for determination of quadrupole moments using Coulomb excitation make use of detailed knowledge of this excitation process. However,a reliable analysis of the experimental data needs a number of transition matrix elements to be known. It has been shown that especially the second 2^+ state and the first 4^+ state will have an influence in this respect 1). So, for example, one obtains two values of $Q(2_1^+)$ for different signs of the Coulomb interference term P_4. REPREC, is however, not as sensitive to this type of interference as the conventional technique. Furthermore, REPREC, provides a way to measure the sign of P_4. This is done by determining the ratio $R' = W(22.5^\circ)/W(157.5^\circ)$ for the transition $2_2^+ \rightarrow 0_1^+$.

The theoretical calculations are performed using the Winther-de Boer computer code 9). Since this program is based on a semiclassical treatment of the excitation process the calculated R values have to be quantum mechanically corrected. These corrections are made using the Pelte-Smilansky coupled channel code 10).

The experiments were performed using beams of ^{16}O projectiles with energies between 37-48 MeV accelerated in the EN tandem Van de Graaff accelerator in Uppsala. Thick targets were prepared by rolling enriched ^{100}Ru (97.24%) and ^{104}Ru(99.35%) respectively on 10 mg/cm^2 Cu backings. The Cu backings are used to prevent deorientation of the nuclei. The data were recorded event by event and stored on magnetic tapes. In the off-line analysis digital windows were put in the time spectrum and the particle spectrum and the resulting γ-ray spectrum was analyzed. Two or three particle windows were used from each run. The mean energies for ^{100}Ru were 31.8, 35.3, 35.8 and 38.5 MeV and for ^{104}Ru 29.4, 33.2 and 37 MeV. In the case of ^{104}Ru we also made an additional run at an effective energy of 45.3 MeV in order to determine the sign of P_4. The energies used are believed to be safe bombarding energies 11). A coincidence spectrum in the case of ^{104}Ru is shown in Fig. 1. In Fig. 2 we present the experimental results on P_4 for ^{104}Ru together with the theoretically calculated values. The direct determination of P_4 in ^{104}Ru thus gives $P_4<0$ which is in accordance with the results found for ^{102}Ru 6) and $^{108,110}Pd$ 1). In the case of ^{100}Ru the excitation probability of the second 2^+ state was too low for such a determination.

The results for the $Q(2_1^+)$ measurements are presented in Fig. 3. The solid lines in the figure correspond to calculations with the matrix element $M_{22} = 0$ and the value of M_{22} giving the best fit to our experimental data. All the curves are quantum mechanically corrected. The matrix elements used in the calculations are taken from ref. 12 and are included in Fig. 3.

For ^{104}Ru a quadrupole moment of -0.76 ± 0.19 eb was obtained using $P_4 < 0$. In the case of ^{100}Ru both signs of the Coulomb interference term gave the same result and $Q(2_1^+)$ was found to be -0.40 ± 0.12 eb. The results are summarized in Table 1 where also results from measurements using the reorientation technique are given.

Discussion

The direct determinations of the sign of $P_4 = M_{0_1^+2_1^+} M_{0_1^+2_2^+} M_{2_2^+2_1^+} M_{2_1^+2_1^+}$ in ^{102}Ru 6) and ^{104}Ru have given $P_4 < 0$. This is in accordance with nuclear model predictions22). In the case of ^{100}Ru a determination of P_4 was not possible but on the other hand a REPREC measurement turned out to be insensitive to the signs of these matrix elements.

Experimentally determined values of $Q(2_1^+)$ in $^{100-104}$Ru are given in Table 1 and Fig. 4 displays $B(E2;\ 0_1^+ \rightarrow 2_1^+)$ and $Q(2_1^+)$. In Fig. 4 we have also included the meanvalues of $Q(2_1^+)$ as well as the rotational values calculated according to the formula $|Q(2_1^+)|_{rot} = 0.9059 \sqrt{B(E2;\ 0_1^+ \rightarrow 2_1^+)}$. As can be seen from this figure $Q(2_1^+,\ ^{104}\mathrm{Ru})$ is of the same magnitude as the rotational value, while the other isotopes have quadrupole moments which are significantly smaller.

Fig. 5 gives the present situation of B(E2; $0_1^+ \rightarrow 2_1^+$) and Q(2_1^+) for the isotones with N = 56, 58 and 60 respectively. Also in this figure we have included the meanvalues as well as the rotational values of the quadrupole moments. As is seen, the systematics forB(E2)-values and values of Q(2_1^+) are quite consistent. We note that for N = 60 the absolute values of B(E2) and Q(2_1^+) decrease with increasing Z-value. For N = 58 the trend has been smeared out but $|Q(2_1^+, {}^{106}\mathrm{Cd})|$ seems to be smaller than $|Q(2_1^+, {}^{100}\mathrm{Mo})|$ as indicated by the B(E2) values. For N = 56 and N = 58 $|Q(2_1^+)| \approx \sqrt{B(E2;\ 2_1^+ \rightarrow 0_1^+)}$ and thus $|Q(2_1^+)|$ have a magnitude which is one half of the rotational value. This relation is also valid for ^{94,96}Mo as well as for therest of the Cd isotopes. For N = 60 and for ^{108,110}Pd the magnitudes of $|Q(2_1^+)|$ have increased but the values are smaller than what can be expected from the rotational model, except in the case of ^{104}Ru.

Very few theoretical calculations of energy- and B(E2)-values have been performed for the Ru isotopes. Anharmonicities in the harmonic vibrator through mixing of the one- and two-phonon states have been considered by Singh et al.$^{23)}$ for ^{100}Ru and ^{104}Ru. In ^{100}Ru the calculated values of B(E2, $2_2^+ \rightarrow 2_1^+$), B(E2; $2_2^+ \rightarrow 0_1^+$) and Q(2_1^+) are all within the experimental values, while in the case of ^{104}Ru, especially B(E2; $2_2^+ \rightarrow 0_1^+$) is overestimated.

De Voigt et al.$^{24)}$ have studied the energy levels in ^{100}Ru through the ^{100}Mo(α,4n)^{100}Ru reaction. They conclude that good fits can be obtained for both positive and negative parity bands using the interacting boson approximation (IBA) of Arima and Iachello. Calculations using this model have also been performed in ^{102,104}Pd $^{2)}$. The agreement between the theoretical and experimental values were promising, but due to the large number of parameters used, no detailed comparison between theory and experiment were performed. Since then the Groningen group$^{25)}$ has performed more calculations in $^{104-110}$Pd. They obtain good agreement between theory and experiment and a smooth change in the parameters in going from ^{104}Pd to ^{110}Pd. The one-phonon changing terms in $^{104-110}$Pd, for example followed the trend of the experimental ratios of $B(E2;\ 2_2^+ \rightarrow 0_1^+)/B(E2;\ 2_1^+ \rightarrow 0_1^+)$. For $^{100-104}$Ru we tried to perform fits using as input values one- and two-phonon changing terms from the trends obtained for the Pd isotopes. In this way it was possible to obtain good fits for $^{100-102}$Ru, but not for ^{104}Ru. The reason for the failure to fit ^{104}Ru in this way is not clear. It might be a consequence of too few experimental values, but it might also be due to other reasons. In fact plots of $B(E2;\ 0_1^+ \rightarrow 2_1^+)$, $Q(2_1^+)$, $B(E2;\ 2_1^+ \rightarrow 4_1^+)$, $B(E2;\ 2_1^+ \rightarrow 2_2^+)$ and $B(E2;\ 0_2^+ \rightarrow 2_1^+)$ as functions of the total number of proton and neutron pairs show an almost perfect agreement for ^{100}Ru - ^{104}Pd and ^{102}Ru - ^{106}Pd while the data for ^{104}Ru - ^{108}Pd do not agree.

The results of the calculations from the IBA model are presented in Fig. 6 together with experimental values. The fit presented for ^{104}Ru was not obtained using one- and two-phonon changing terms from the trends in the Pd isotopes. The experimental energy levels are taken from the compilation of Sakai$^{26)}$

and the B(E2) values are taken from Refs. 12 and 14. The parameters used are given in Table 2.

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Table captions

Table 1. Experimentally determined values of $Q(2_1^+)$ in $^{100-104}$Ru.

Table 2. Parameters obtained from the fits in $^{100-104}$Ru using the IBA. For the meaning of the parameters we refer to ref. 7.

Figure captions

Fig. 1. A coincidence spectrum of ^{104}Ru where the transition $2_2^+ \rightarrow 0_1^+$ can be seen.

Fig. 2. The experimentally determined R' value in ^{104}Ru together with calculated values from the Winther-de Boer programme.

Fig. 3. Experimental results for R in ^{100,104}Ru. The solid lines, correspond to calculations with $M_{22}=0$ and the M_{22} value giving the best fit to our experimental data. Also included are the matrix elements used in the calculations.

Fig. 4. Experimental results of $B(E2;\ 0_1^+ \rightarrow 2_1^+)$ and $Q(2_1^+)$ for $^{96-104}$Ru. The B(E2) values are taken from ref.12.

Fig. 5. Experimental results of $B(E2;\ 0_1^+ \rightarrow 2_1^+)$ and $Q(2_1^+)$ for the isotones N=56, 58 and 60. The B(E2) values are taken from ref. 13 (Mo), 12(Ru), 1(^{102,104}Pd), 14(^{106}Pd) and 15(Cd). The values of $Q(2_1^+)$ correspond to a constructive interference.

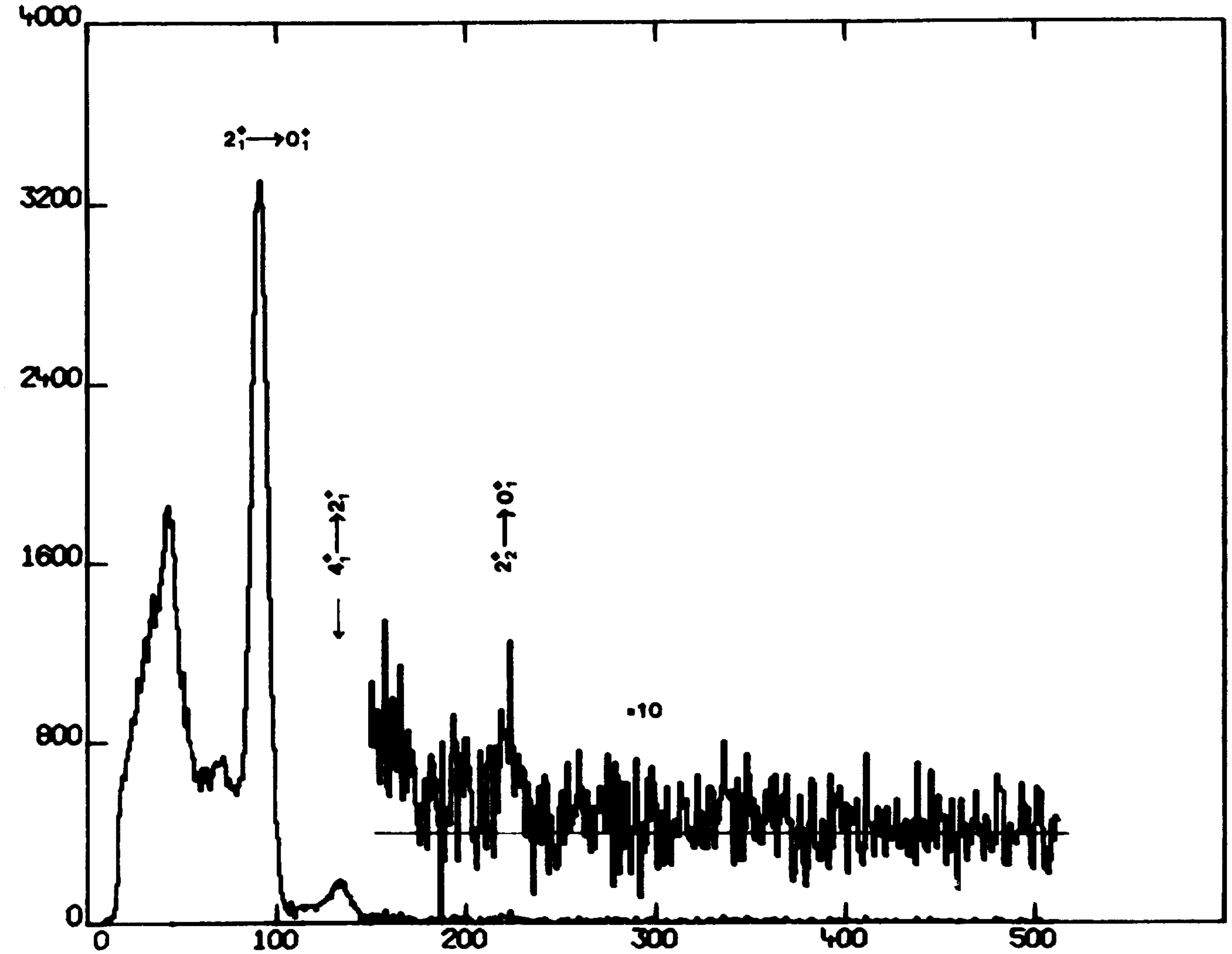
Fig. 6. Theoretical and experimental results in $^{100-104}$Ru.

Table 1.

		$Q(2_1^+)$ eb			
		Present	Ref.3	Ref.4	Ref.5
^{100}Ru	$P_4 < 0$	-0.40 ± 0.12			
	$P_4 > 0$	-0.40 ± 0.12			
^{102}Ru	$P_4 < 0$ deduced		-0.37 ± 0.24	-0.4 ± 0.1	
^{104}Ru	$P_4 < 0$ deduced	-0.76 ± 0.19	-0.84 ± 0.21		-0.63 ± 0.20

Table 2.

	ε	C_0	C_2	C_4	1ph	2ph	q_2	q_2'
^{100}Ru	.501	-.440	.075	.081	.08	-.109	.959	-.310
^{102}Ru	.567	-.271	-.124	.064	.065	-.08	.975	-1.372
^{104}Ru	.258	.74	-.151	.118	.069	-.141	1.032	-1.926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3200
2400
1600
800
0
0
100
200
300
400
500
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$4_1^+ \rightarrow 2_1^+$
$2_2^+ \rightarrow 0_1^+$
×10

Fig 1

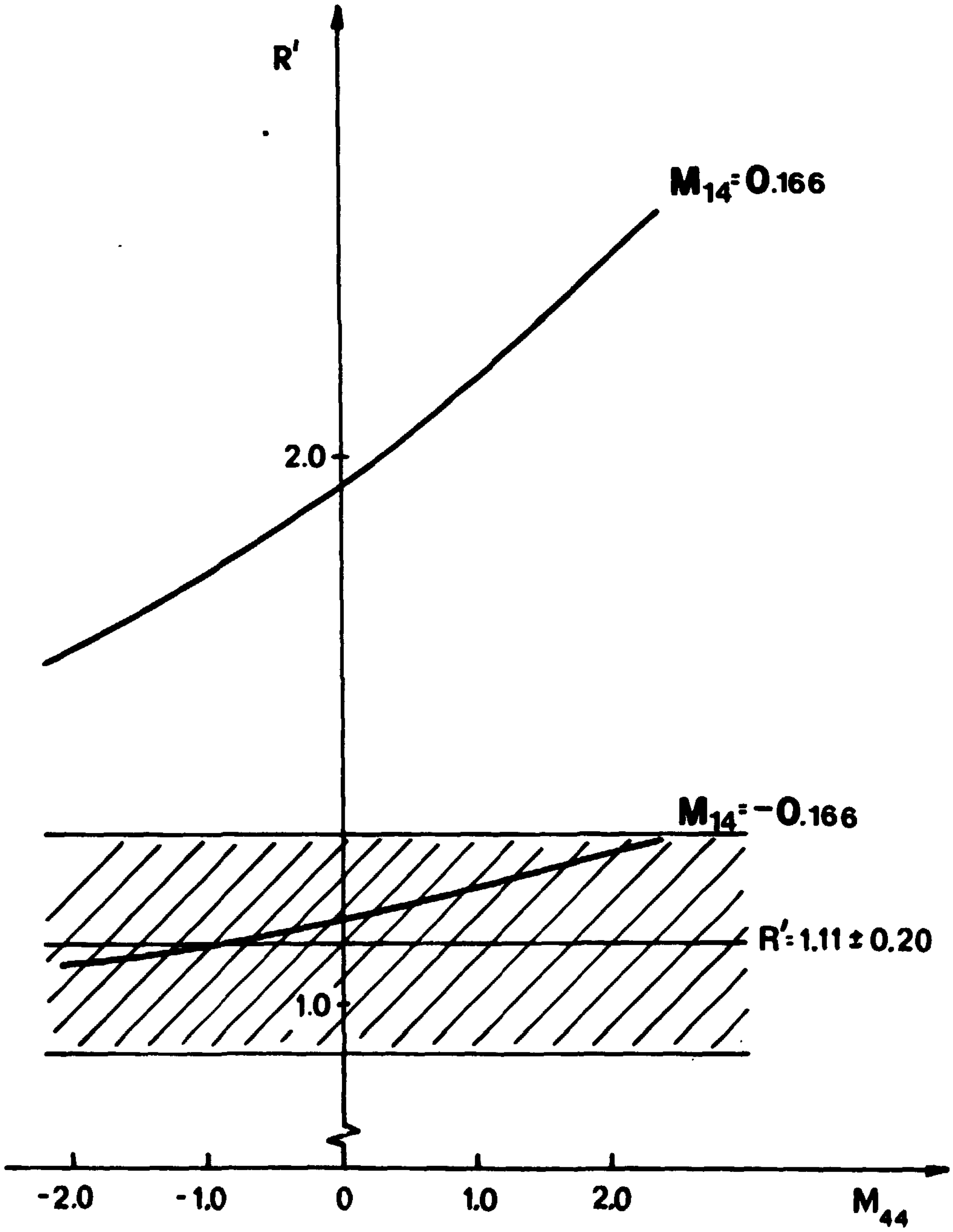
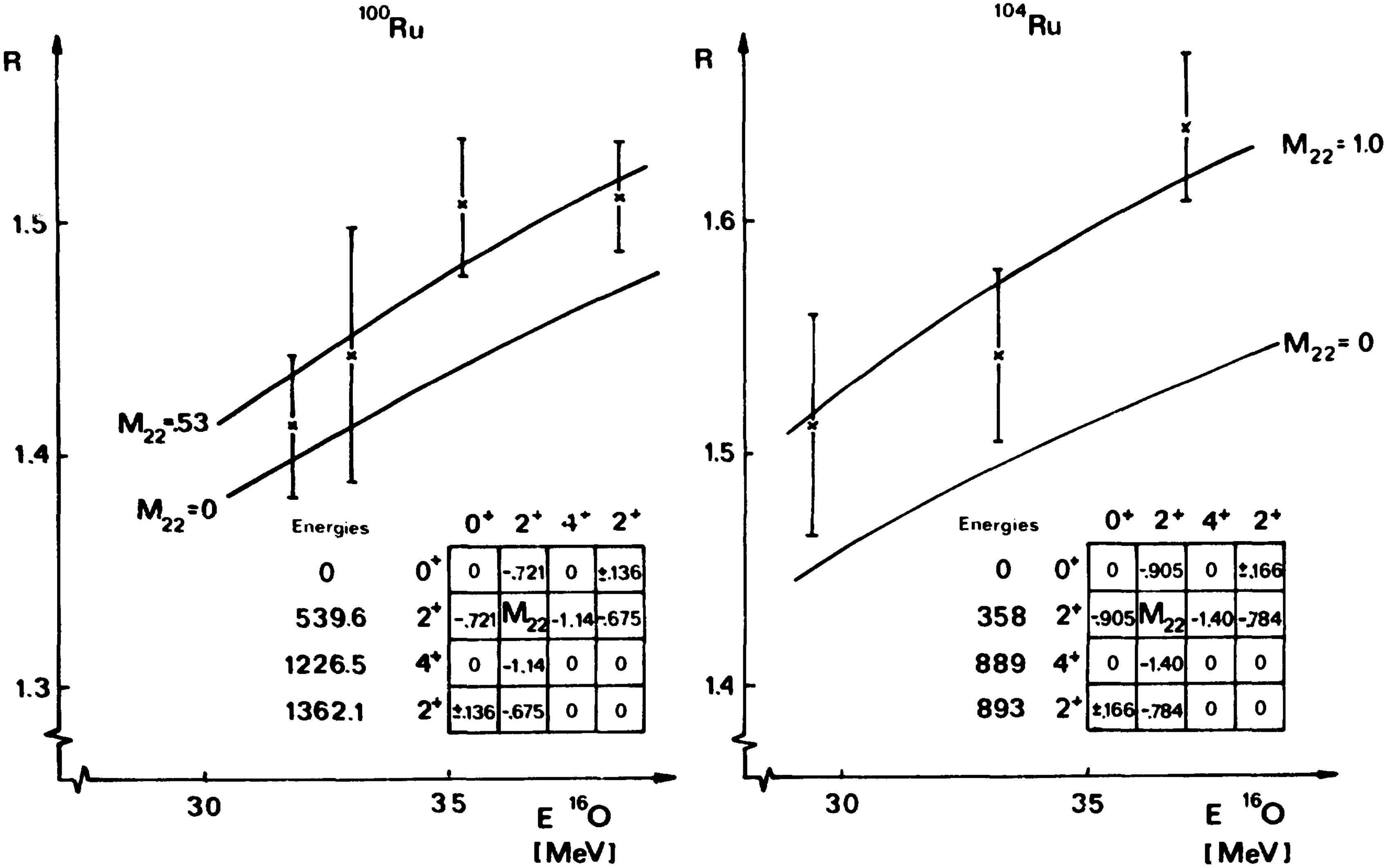


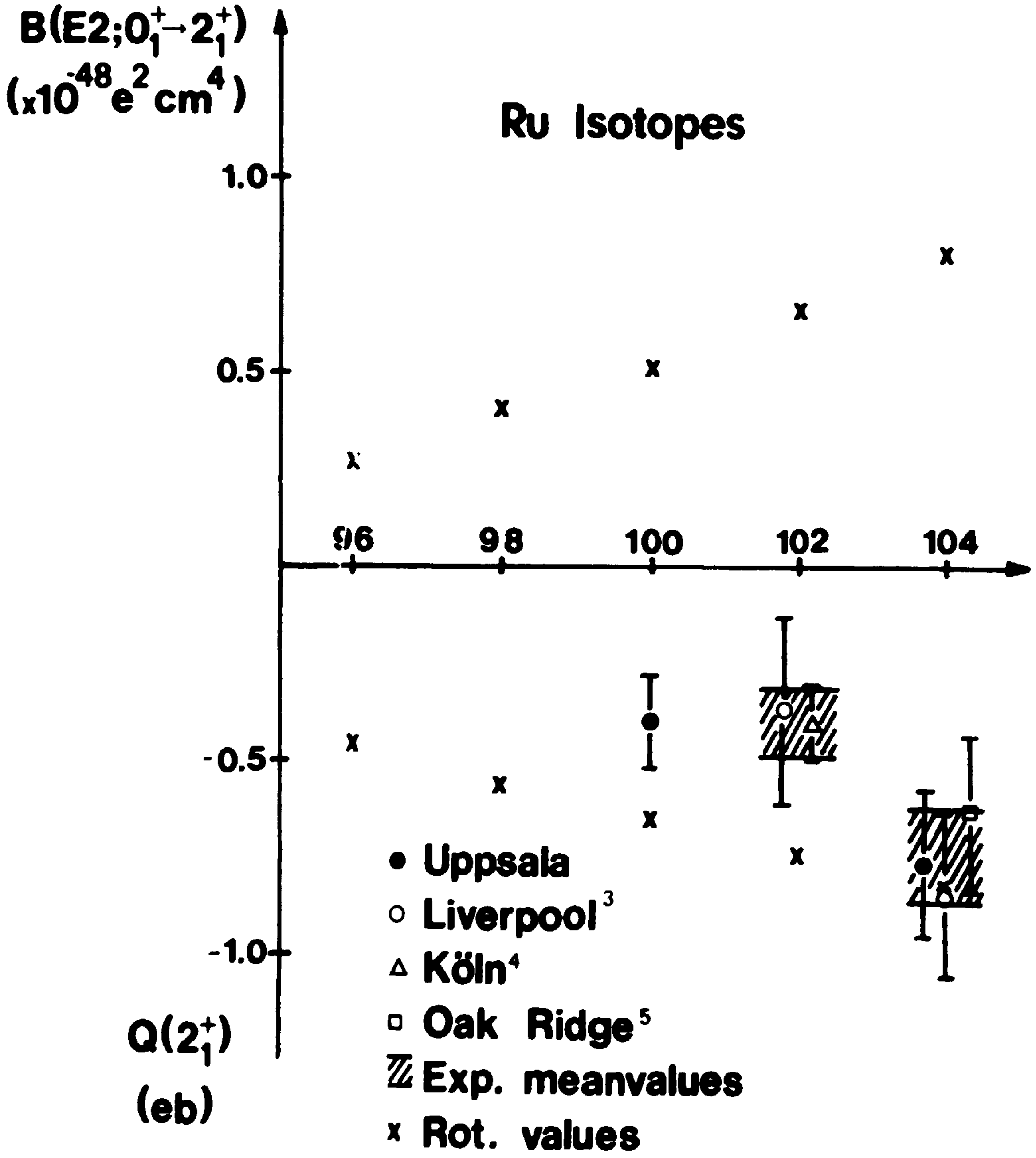
Fig 2



Energies		0^+	2^+	4^+	2^+
0	0^+	0	-.721	0	±.136
539.6	2^+	-.721	M_{22}	-1.14	-.675
1226.5	4^+	0	-1.14	0	0
1362.1	2^+	±.136	-.675	0	0

Energies		0^+	2^+	4^+	2^+
0	0^+	0	-.905	0	±.166
358	2^+	-.905	M_{22}	-1.40	-.784
889	4^+	0	-1.40	0	0
893	2^+	±.166	-.784	0	0

Fig 3



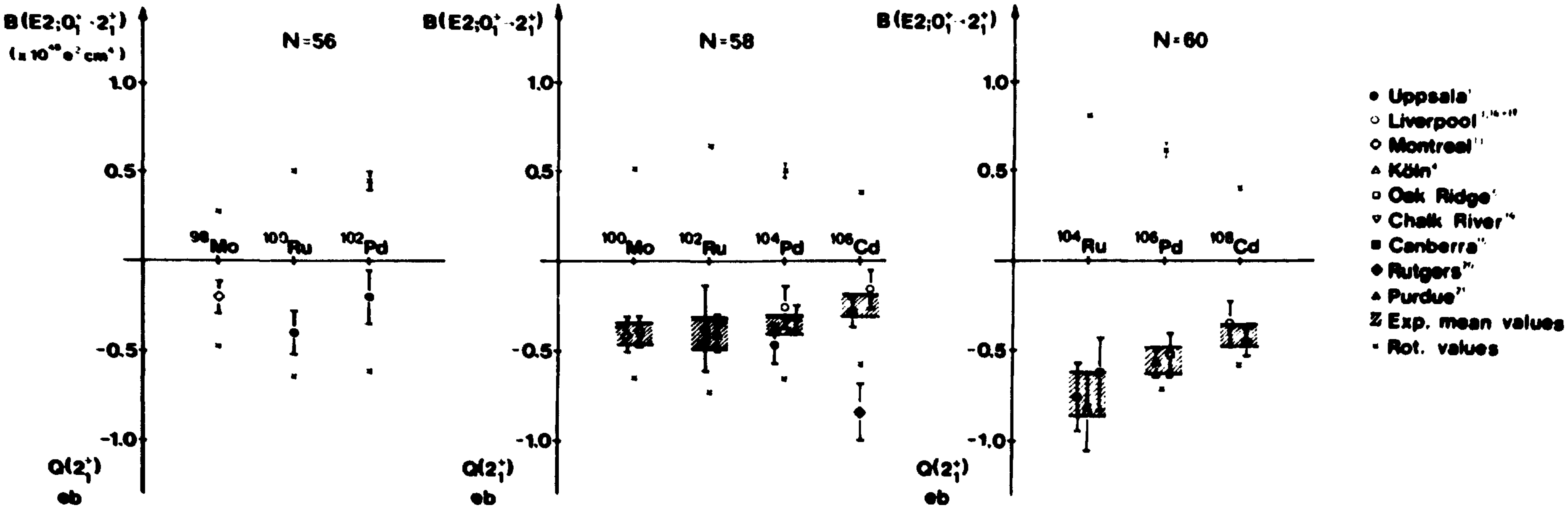
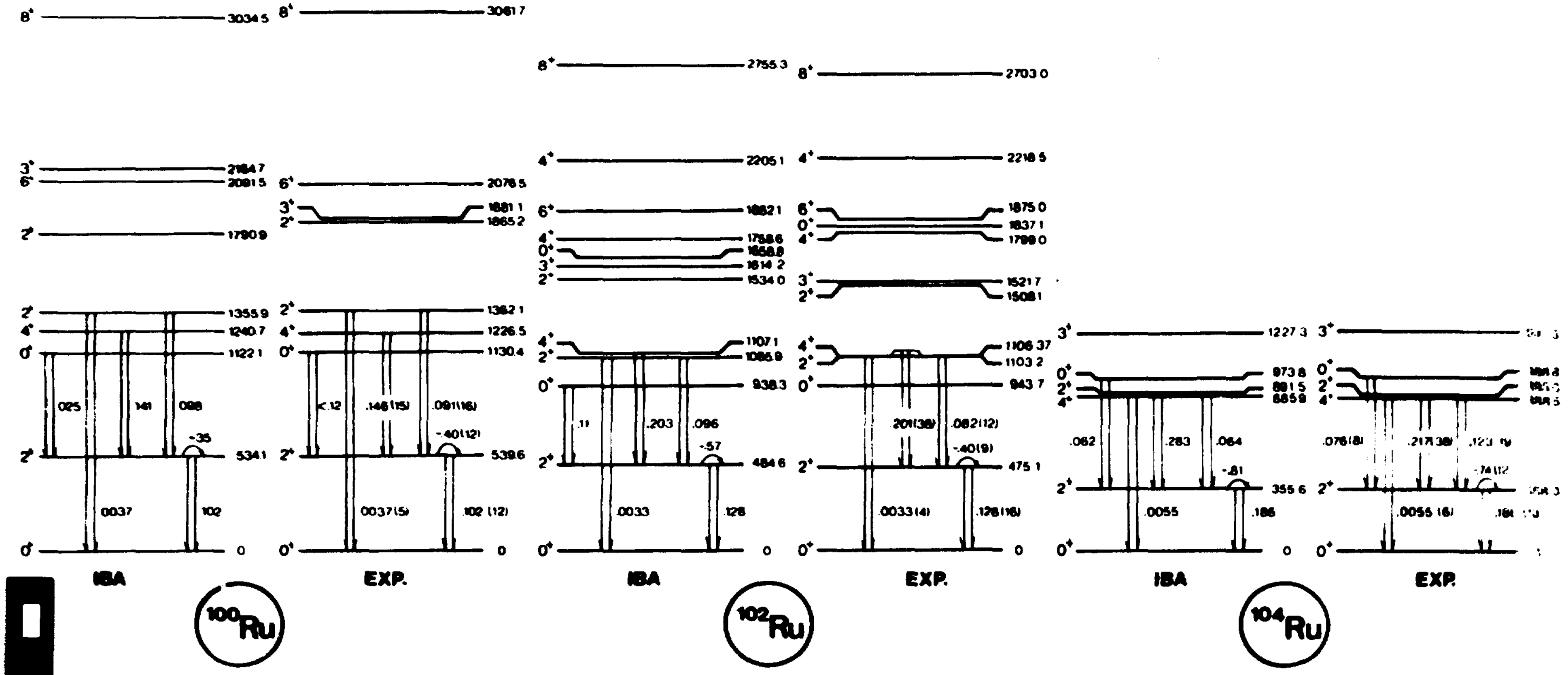

B(E2;0₁⁺→2₁⁺)
(x 10⁻⁴⁸ e² cm⁴)
N=56
N=58
N=60
1.0
0.5
-0.5
-1.0
Q(2₁⁺)
eb
⁹⁸Mo
¹⁰⁰Ru
¹⁰²Pd
¹⁰⁰Mo
¹⁰²Ru
¹⁰⁴Pd
¹⁰⁶Cd
¹⁰⁴Ru
¹⁰⁶Pd
¹⁰⁸Cd
● Uppsala
○ Liverpool
◇ Montreal
△ Köln
□ Oak Ridge
▽ Chalk River
■ Canberra
◆ Rutgers
▲ Purdue
▨ Exp. mean values
▪ Rot. values

Fig 5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6+ 2081 5
2+ 1790 9
2+ 1355 9
4+ 1240 7
0+ 1122 1
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.141
.098
-.35
2+ 534 1
.0037
.102
0+ 0
IBA
8+ 3061 7
6+ 2076 5
3+ 1881 1
2+ 1865 2
2+ 1362 1
4+ 1226 5
0+ 1130 4
<.12
.146(15)
.091(16)
-.40(12)
2+ 539 6
.0037(5)
.102 (12)
0+ 0
EXP.
100Ru
8+ 2755 3
4+ 2205 1
6+ 1882 1
4+ 1758 6
0+ 1658 8
3+ 1614 2
2+ 1534 0
4+ 1107 1
2+ 1086 9
0+ 938 3
.11
.203
.096
-.57
2+ 484 6
.0033
.128
0+ 0
IBA
8+ 2703 0
4+ 2218 5
6+ 1875 0
0+ 1837 1
4+ 1799 0
3+ 1521 7
2+ 1508 1
4+ 1106 37
2+ 1103 2
0+ 943 7
.201(38)
.082(12)
-.40(9)
2+ 475 1
.0033(4)
.128(16)
0+ 0
EXP.
102Ru
3+ 1227 3
0+ 973 8
2+ 891 5
4+ 885 9
.062
.283
.064
-.81
2+ 355 6
.0055
.186
0+ 0
IBA
3+
0+
2+
4+
.076(8)
.217(38)
2+
.0055 (6)
0+
EXP.
104Ru

Fig 6