EXCITED 0^+ STATES IN NEUTRON RICH Zr AND Mo ISOTOPES

T.A. Khan, W.D. Lauppe, G. Sadler, H.A. Selic, H. Lawin and K. Sistemich

Institut für Kernphysik, Kernforschungsanlage Jülich, 5170 Jülich, F.R. Germany

Abstract

The low lying 0_2^+ levels in even nuclei in the transitional region around mass 100 have been investigated by means of the fission product separator JOSEF. An excited 0^+ state at 331 keV has been discovered in the nucleus ^{100}Zr. Electron lines of energies 313, 675, 715, 836 and 1576 keV have been observed in singles and X/e^- coincidence spectra. The E0 character of these transitions and their assignment to specific nuclides has been unambiguously established. From delayed γ/e^- coincidences a lifetime of 78 ± 10 nsec for the 0_2^+ state in ^{98}Zr has been measured. Using the empirical correlation between the E0 strength parameter and the quadrupole deformation, a value of $\beta_2 \sim 0.12$ is suggested for ^{98}Zr. In the light of the present results a decay scheme is proposed for ^{100}Zr and its implications discussed.

1. Introduction

The occurence in even nuclei of first excited 0^+ states is relatively rare. Such states above the ground state but below the pairing gap are considered as characteristic of the change between spherical and deformed equilibrium shapes. There is particular interest in the nature and the systematics of excited 0^+ states in the zirconium and molybdenium isotopes since despite some interesting attempts[1,2] their character is still not fully understood. For example Sheline et al.[1] have proposed that these states have the nature of deformed band heads due to the existence of a second minimum in the nuclear potential surface whereas Burch et al.[3] have regarded the 0_2^+ levels of some even zirconium isotopes as states orthogonal to the ground state.

Direct spectroscopic information about such levels has been scanty due to the very short lived nature of the nuclides involved and the fact that their observation requires the detection of totally converted E0 transitions in the presence of a large β-particle background. It was therefore considered of interest to utilize the high fission product intensities and short separation times of the gas filled separator JOSEF to:

a) Unambiguously assign these 0_2^+ states so that one could have confidence in their systematics as one moved through the transitional region.
b) Measure their lifetime so that one could have a better understanding of their character.
c) Search for new ones. Thus it was conjectured that if an excited 0_2^+ state were to be discovered in ^{100}Zr, in the manner shown in fig. 1, it would not only fit in with the systematics of the lighter even isotopes, but also remove the very puzzling transition in nuclear behaviour between ^{98}Zr and ^{100}Zr, where the energy of the first 2^+ state seems to change from 1223 keV to 213 keV.

2. Experimental Procedure

The experimental arrangement is shown in fig. 2. The fission product beam from the separator impinged on the tape of a tape transport device for an irradiation time chosen to suit the decay time of the parent isotope. The irradiated spot was then moved rapidly to the measuring position 30 cm above. While the measurement proceeded a new area of the tape was irradiated. In the measuring position the γ-ray/electron and X-ray/electron spectra were recorded in singles, coincidence and delayed coincidence modes. Ge(Li) and intrinsic germanium detectors were used for the γ-rays and X-rays respectively while the electron detector was a windowless 300 mm^2 x 3 mm thick Si(Li) detector of resolution 3 keV in the actual experimental conditions.

3. Results

Two of the electron spectra recorded during the first series of measurements are shown in fig. 3. The irradiation times for the two spectra were 2 sec and 11 sec respectively. Also shown is a γ-ray spectrum accumulated simultaneously with the 11 sec electron spectrum for a period of one hour. It is seen that only the strongest electron transitions are clearly observed due to the high β-particle background. The fact that these are totally converted transitions may be seen from the γ-ray spectrum which shows no corresponding γ-lines. Moreover the K/L ratios are also compatible with E0 transitions.

In order to assign the lines to specific nuclides the intensity of the electron lines as a function of the magnetic rigidity $B\rho$ of the gas filled magnet was obtained. The value of $B\rho$ at maximum intensity was then compared with the calibration curves previously established using known γ-rays from short lived fragments. The calibration for the light fission product group is shown in fig. 4. It is seen that for each value of $B\rho$ a number of mass charge combinations are possible. However the difference in K and L electron energies in the singles electron spectra and the X-ray/electron coincidences gave an independent determination of the charge. Thus a completely unambiguous assignment of the transitions to specific nuclides was possible. The lifetimes of the β-decaying levels populating these excited 0_2^+ states were obtained by measuring the intensity of the electron lines as a function of time.

The E0 transitions observed during the first series of measurements are shown in fig. 5. By means of procedures described elsewhere[4] it was possible to show that two β-decay modes exist in each of the parents and to determine the relative population of the 0_2^+ states by the two modes. The lifetime of the 0_2^+ state at 854 keV in ^{98}Zr has been measured by delayed γ-electron coincidences as 78 ± 10 nsec, which gives a value of 0.11 for the E0 strength parameter ρ [5]. From the empirical correlation between ρ and the quadrupole deformation β_2 observed by Andrews et al.[6] (see fig. 6) a value of $\beta_2 = 0.12$ is suggested for ^{98}Zr. In fig. 7 the energies of the 2_1^+ states and of β_2 for the even zirconium isotopes are shown[7,8]. The neutron shell and subshell closures at N = 50 and N = 56 may be observed. It is seen that the suggested value of β_2 for ^{98}Zr fits in quite well with these systematics.

4. An Excited 0^+ State in ^{100}Zr

A search for an excited 0^+ state in the region of ^{100}Zr has also been carried out. The search was first made in electron singles measurements but was unsuccessful due to the intense β-particle background[4]. It emerged, however, that the possible 0_2^+ state in ^{100}Zr was unlikely to be a first excited state in the manner suggested in fig. 1. since in that case the level would be populated by the very strong[9,10]

213 keV transition and the depopulating E0 transitions should have been strong enough to be observed above the background.

Very recently it has been possible, by use of techniques to mitigate the background, to observe a totally converted transition in ^{100}Zr. The evidence is shown in figures 8, 9 and 10. Fig. 8 shows the results of the X-ray/electron coincidences. Three strong electron lines are seen to be in coincidence with the zirconium K X-ray. Apart from the 836 keV line due to the 0_2^+ to 0_1^+ transition in ^{98}Zr, the other two lines are at energies 194 and 313 keV. In fig. 9 the electron and γ-ray singles spectra obtained simultaneously are shown. In the γ-ray spectrum the 213 keV line, which is complementary to the 194 keV electron line, is strongly apparent. However there is no γ-ray at 331 keV which is complementary to the 313 keV electron line, thus establishing it as a totally converted transition. Its assignment to the nucleus ^{100}Zr may be seen in fig. 10 where the intensity versus magnetic rigidity distributions of the relevant electron and γ-lines are plotted. It is seen that the maximum of the 313 keV line is situated at the same position as that for the 213 keV line which has previously been unambiguously assigned to ^{100}Zr. The $(B\rho)_{max}$ values for the 836 keV electron line in ^{98}Zr and the 296 keV γ-line in ^{102}Mo are also consistent with the assignment of the 313 keV line to ^{100}Zr.

The discovery of a 0_2^+ state at 331 keV in ^{100}Zr, together with the information from our X-ray/γ and γ/γ coincidence measurements, has considerably clarified the situation with regard to this nucleus which has hitherto been something of a puzzle. The previous information with regard to this nucleus was obtained from 3 parameter γ-ray and conversion electron experiments[9,10] which showed that a cascade of transitions of energies 213, 352 and 498 keV existed in this nucleus, the 213 keV transition having an E2 multipolarity[10]. Since then by means of the γ-ray singles measurements at the separator LOHENGRIN and the γ/γ[11] and X/γ coincidences at JOSEF it has been possible to assign transitions at 118 and 667 keV to ^{100}Zr and to confirm the existence of the 213 keV and 352 keV cascade. In our electron/γ-ray measurements we have looked for coincidences between these γ-rays and the 313 keV electron line. Although the statistics are poor, the 313 keV line does not seem to be in coincidence with these γ-rays while the 194 keV electron line (complementary to the 213 keV transition) is seen in coincidence with the 118 keV and 352 keV γ-rays. The results of these measurements, together with the information obtained from the γ/γ and X/γ coincidences, suggest the scheme depicted in fig. 11 for the lower levels in ^{100}Zr. It may be noted that according to this scheme the 213 keV and 352 keV cascade is still based on the ground state so that the drastic change in the energy of the 2_1^+ states between ^{98}Zr and ^{100}Zr remains. However, in other respects the behaviour of ^{100}Zr appears to be quite analogous to the transitional molybdenium isotopes[12] and other transitional nuclei such as ^{150}Sm[13] (see fig. 12).

Although the present results have not yet been fully evaluated and a number of other experiments are called for, one may at this stage come to the tentative conclusions; firstly, that the excited 0_2^+ state in ^{100}Zr is probably not a shape isomeric state of the type suggested by Sheline et al.[1] since it seems to decay by fast transitions to the first 2^+ and the ground state. Secondly, in analogy to other transitional nuclei such as ^{150}Sm, the excited 0_2^+ state may very likely be the band head of a β-vibrational band, as seems to be the case for the transitional molybdenium isotopes[12].

References

1) Sheline, R.K., Ragnarsson, I., Nilsson, S.G., Phys. Lett. 41B (1972) 115
2) Hadermann, J., Rester, A.C., Nucl. Phys. A231 (1974) 120
3) Burch, D., Russo, P., Swanson, H., Adelberger, E.G., Phys. Lett. 40B (1972) 357
4) Khan, T.A., Lauppe, W.D., Selic, H.A., Sistemich, K., Sadler, G., Lawin, H., Z. Physik A275 (1975) 289
5) Church, E.L., Weneser, J., P.R. 103(4) (1956) 1035
6) Andrews, H.R., Geiger, J.S., Graham, R.L., Ward, D., BAPS (1972) 514, Washington meeting.
7) Stelson, P.H., Grodzins, L., Nuc. Data A1 (1965) 21
8) Wood, J., Kernforschungszentrum Karlsruhe, report KFK 1/71-1
9) Cheifetz, E., Jared, R.C., Thompson, S.G., Wilhelmy, J.B., Phys. Rev. Lett. 25, (1970) 38
10) Khan, T.A., Hofmann, D., Horsch, F., Nucl. Phys. A205 (1973) 488
11) Contribution A 49, these proceedings
12) Bohn, H., Kienle, P., Proetel, D., Hershberger, R.L., Z. Physik A274 (1975) 327
13) Husson, J.P., Jastrzebski, J., Johnson, A., Perrin, N., Henck, R., Regal, R., Siffert, P., Astner, G., Kjelberg, A., Patzelt, P., Höglund, A., Malmskog, S., CERN Rep. 70-30 (1970) 1031.

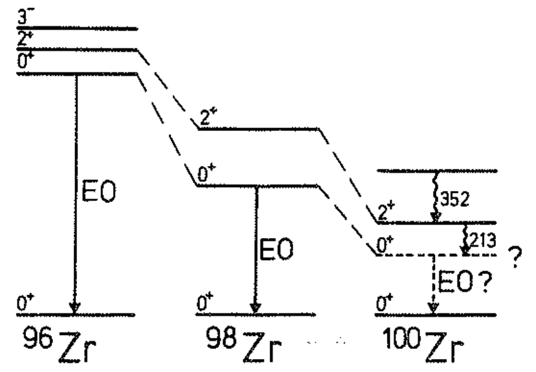


Fig. 1: Low energy level systematics of neighbouring even zirconium isotopes with the suggested position of a possible excited 0^+ state in ^{100}Zr

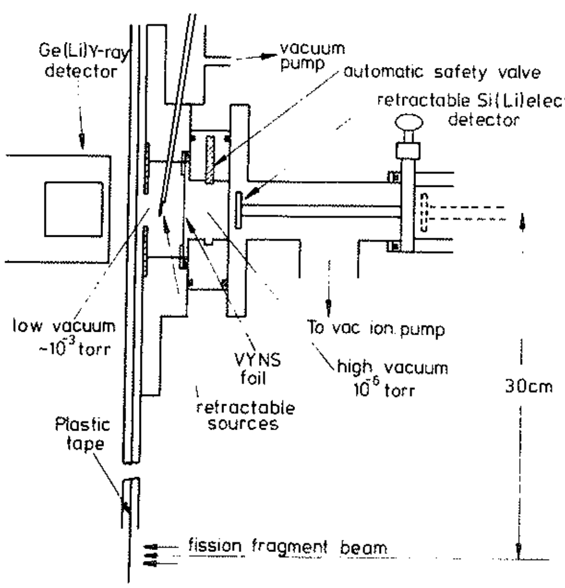


Fig. 2: Experimental arrangement

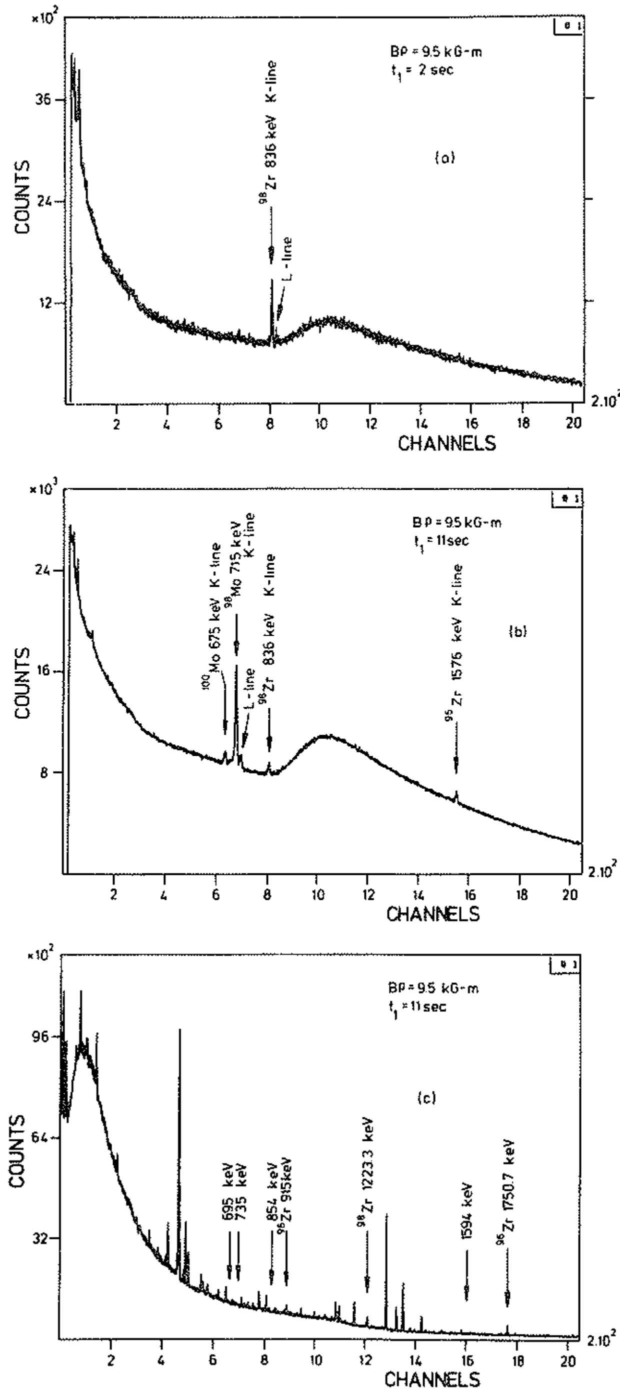


Fig. 3: Electron and γ-ray singles spectra at Bρ = 9.5 KG·m

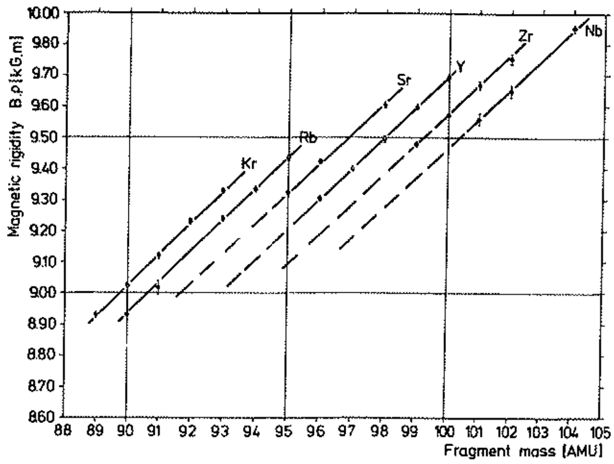


Fig. 4: Calibration curves of the separator JOSEF for the fission products of the light group, with He at 4 torr as the gas-filling.

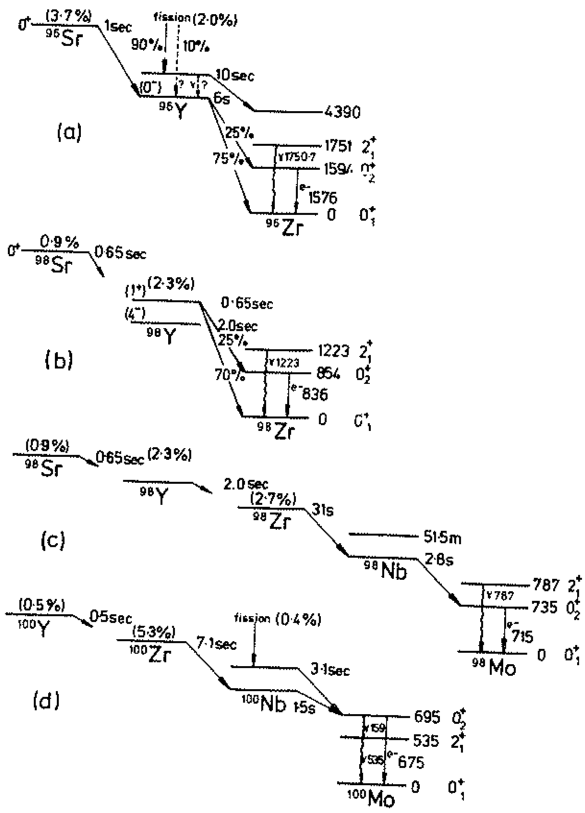


Fig. 5: Salient features of the decays leading to the $0_2^+ \rightarrow 0_1^+$ transitions.

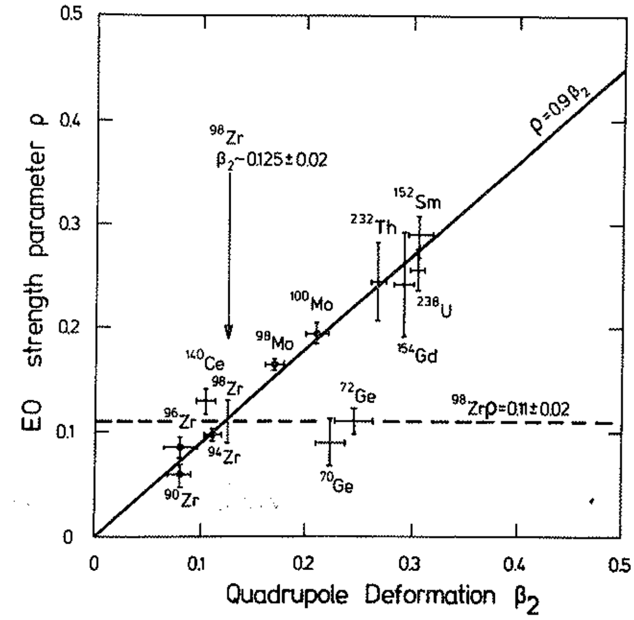


Fig. 6: The E0 strength parameter ρ versus the quadrupole deformation β_2 showing the linear correlation suggested in ref.[6]. The position for ^{98}Zr from the present work is also shown.

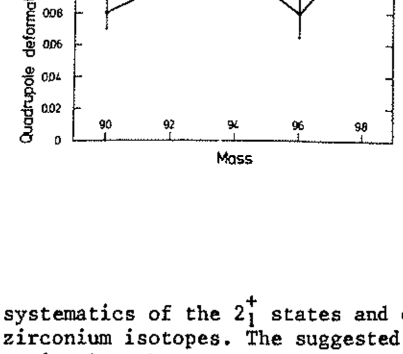


Fig. 7: The systematics of the 2_1^+ states and of β_2 in the even zirconium isotopes. The suggested value of β_2 for ^{98}Zr is also shown.

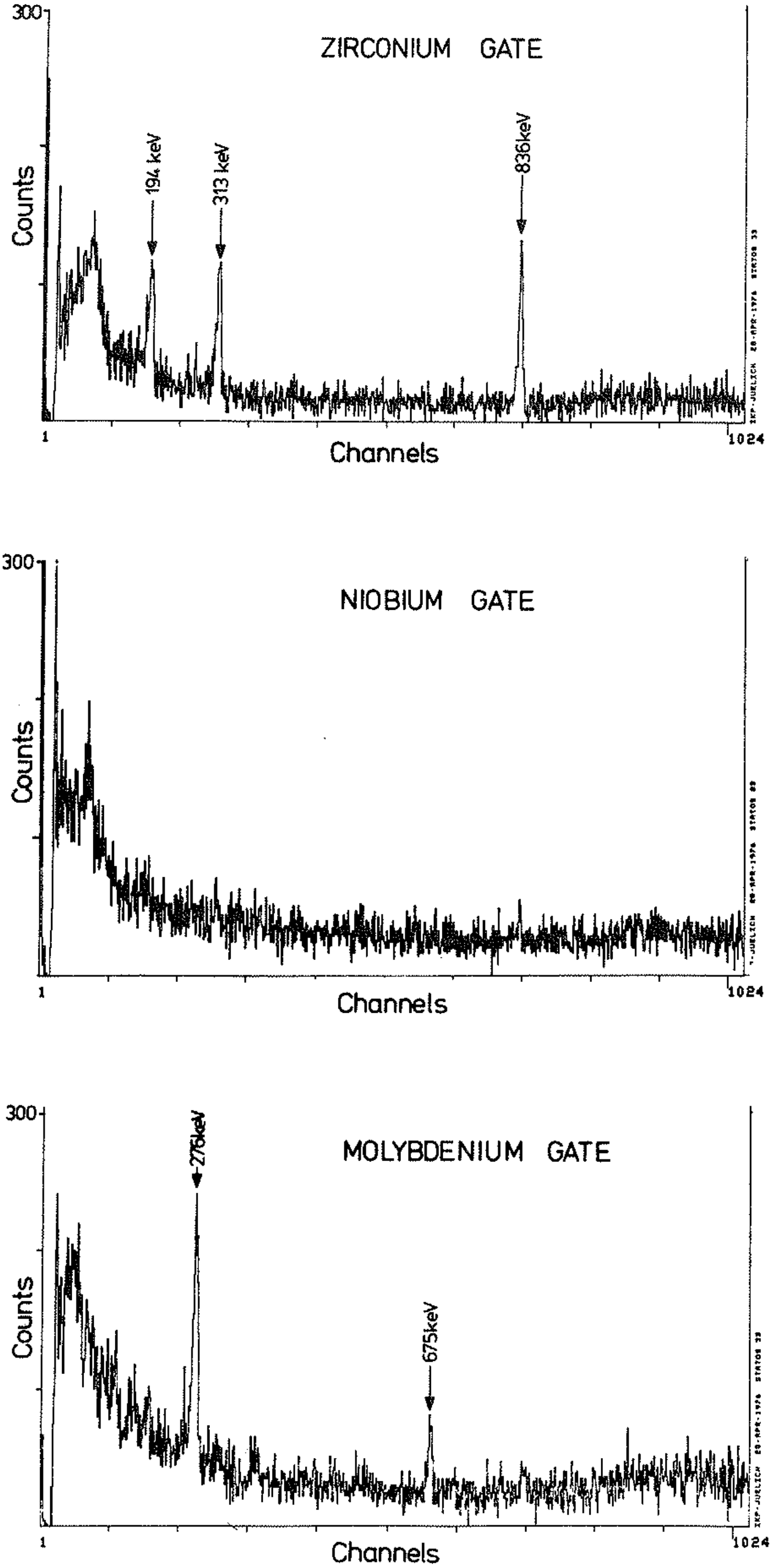
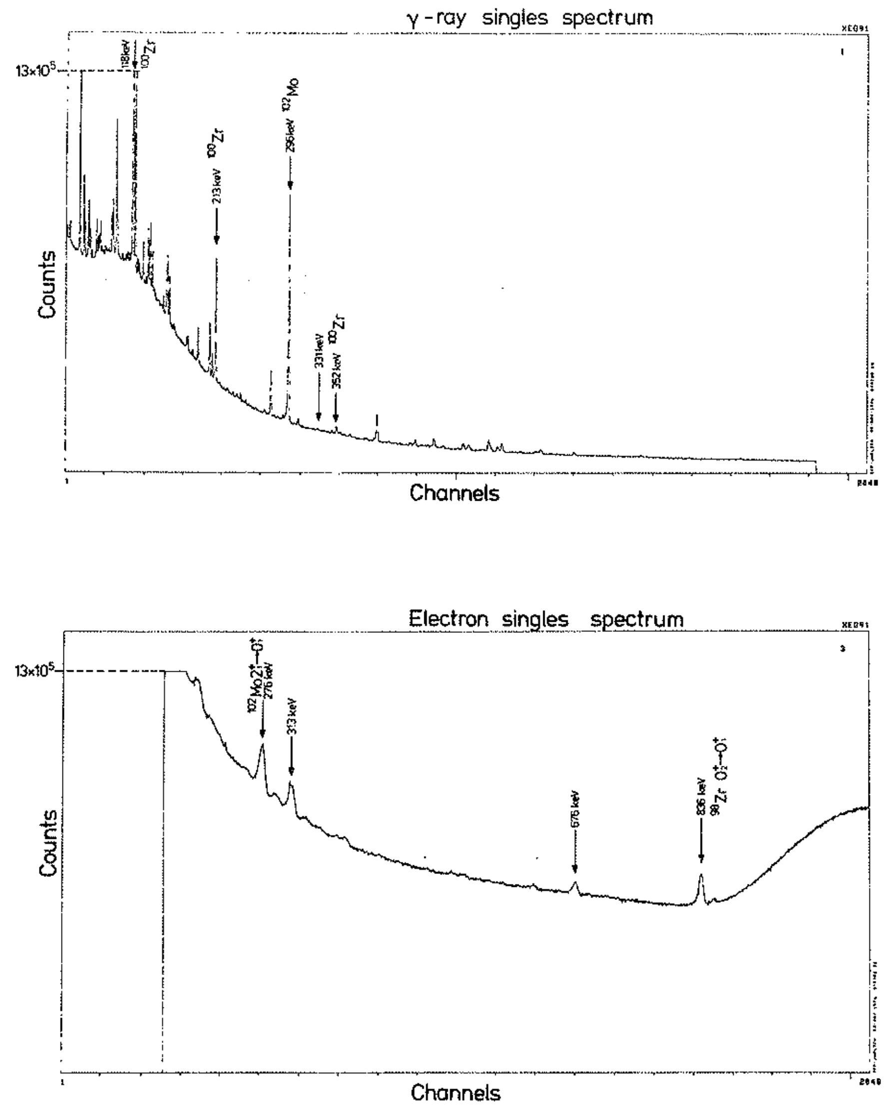


Fig. 8: Electron spectra observed in coincidence with X-rays



<u>Fig. 9:</u> The electron and γ-ray singles spectra at Bρ = 9.65 kGm

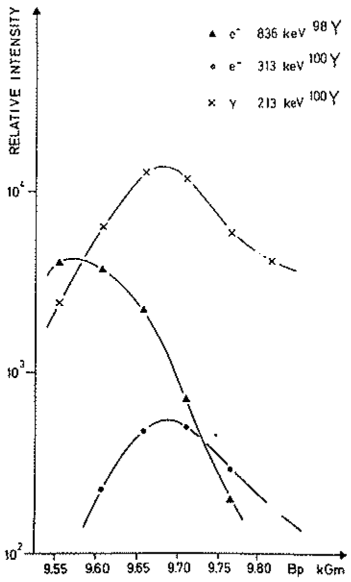


Fig. 10: The intensity versus magnetic rigidity distributions of the 836 keV, 313 keV electron lines and the 213 keV γ-line.

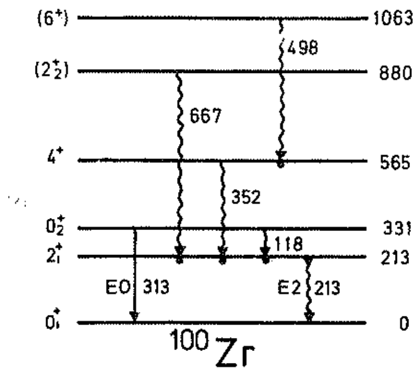


Fig. 11: The proposed decay scheme for ^{100}Zr

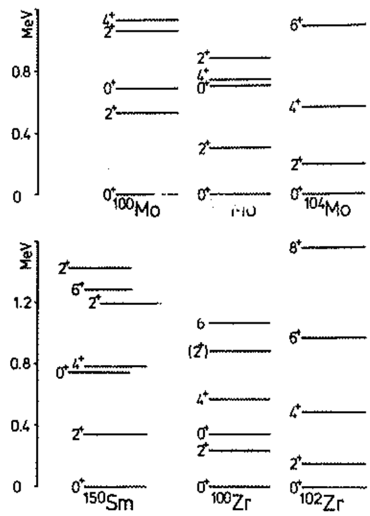


Fig. 12: The lower even parity of transitional nuclei compared with the level scheme for ^{100}Zr.