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TWO-QUASIPARTICLE BANDS IN $A = 100$ REGION OF NEUTRON-RICH NUCLEI*

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In the present work triple, prompt γ-ray coincidence data following the spontaneous fission of ^{248}Cm have been used to search for excited bands in neutron-rich nuclei based upon two-quasiparticle intrinsic structures. Such bands have been found in several even–even nuclei from ^{96}Sr to ^{112}Pd. Careful analysis of double-gated spectra has been performed in order to determine branching ratios within the bands. These branching ratios are then used to establish the magnetic properties of the intrinsic structure, permitting, in many cases, the determination of which Nilsson orbits (and whether they are neutron or proton states) are contributing to the excitation. The results of the investigation are presented, and the single-particle states involved in the two-quasiparticle excitations in some of the nuclei studied are identified. The lowest-lying two-quasiparticle states will be at an excitation energy of approximately 2Δ above the even–even ground state. If these lowest-lying bands are systematically populated, then it would allow us to determine the single-particle orbits at the Fermi surface as the nuclear mass number and deformation varies. One interesting feature that arises from the present study is that the population mechanism in fission plays an important role in deciding what two-quasiparticle states are actually observed.

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1. Introduction

The existence of large multi-detector arrays such as EUROBALL and GAMMASPHERE has made possible the detailed study of the spectroscopy of neutron-rich nuclei through the observation of discrete, prompt γ rays emitted following fission [1,2]. The use of the spontaneously fissioning isotopes ^{248}Cm and ^{252}Cf has been the most prolific method for providing new information on previously unobserved states in neutron-rich nuclei over a wide mass range. These prompt γ-ray investigations have built upon and complemented the study of neutron-rich nuclei through the β decay of fission products. A considerable amount of data has now been accumulated on particularly interesting mass regions: the $A = 90$–100 shape transition region; nuclei near doubly magic ^{132}Sn; and isotopes that exhibit features of octupole degrees of freedom in the Ba–Ce region.

The sensitivity and efficiency of the large arrays has meant that not only can many new excited states be discovered, but also adaptations of standard spectrosopic techniques can be applied to reveal more detailed structural information. Angular correlation and linear polarisation measurements have been made in order to determine spins and multipolarities [3]; lifetime measurements using Doppler effects (γ-ray lineshapes and differential plunger techniques) have lead to transition quadrupole moments being determined [4,5]; and implantation into magnetic hosts has enabled g-factors to be measured [6].

A large proportion of the information obtained from prompt γ-ray spectroscopy of fission fragments has concerned yrast states and (in the case of non-spherical nuclei) collective excitations. This concentration of information is a reflection of the population mechanism in fission, which strongly favours yrast and near-yrast states. Despite this feature of the fission process, a considerable amount of information on the structure of neutron-rich nuclei has been obtained. In the present paper we shall concentrate on nuclei in the $Z = 38$ to 46 region.

This region of neutron-rich nuclei is characterised by particularly interesting evolution of nuclear shape, not only as a function of proton and neutron number, but also as a function of angular momentum. The $_{38}$Sr and $_{40}$Zr isotopes exhibit [7] a rapid change in their ground-state deformation between $N = 58$ and 60. This has been interpreted as a crossing of "spherical" and highly-deformed structures between these two neutron numbers. Recently Urban *et al.* [8] have been able to track, at least partially, the evolution of each of these structures through the transition region. The results of Ref. [8] indicate that the deformation of both structures changes gradually between $N = 56$ and $N = 60$. Lifetime measurements [5] of the excited states of the ground-state bands of ^{100}Zr suggest that, after the shape change, the highly-deformed isotopes are axially symmetric and stable in shape as a function of angular momentum. The neutron-rich $_{42}$Mo isotopes display features consistent with their being γ soft: low-lying γ bands; a near-harmonic double γ-phonon band [9]; and reducing transition quadrupole moments [5] in the ground-state band as a function of angular momentum. Evidence has been presented [10] showing that $^{108-114}$Ru have properties consistent with predictions of a simple model of a rigid triaxial rotor. The trend in shape evolution continues through the transitional palladium isotopes [11], and the spherical $Z = 48$ cadmium nuclei as doubly-magic $_{132}$Sn is approached.

It is evident that a lot has been learnt about the ground-state configurations of neutron-rich nuclei from fission fragment spectroscopy. Further information on the structure of these nuclei can be gained if it would be possible to study systematically excited states formed by breaking specific pairs in the vacuum state *i.e.* two-quasiparticle configurations. We would be able to identify the single-particle levels near the Fermi surface; to investigate core polarisation phenomena by determining the deformation of the two-quasiparticle intrinsic state; and to measure the strength of pairing in neutron-rich nuclei. With these aims in mind we have searched for excited bands in neutron-rich nuclei based upon two-quasiparticle intrinsic structures.

2. Two-quasiparticle bands in the $A = 110$ region

If the intrinsic configuration of a two-quasiparticle state has an axially-symmetric deformation then a "good" rotational band will be built upon the intrinsic state. This implies that the rotational model can be used to determine parameters related to the quasiparticle structure of the band. In particular, the branching ratio of $\Delta J = 1$ to $\Delta J = 2$ transitions within the band can be used to determine [12] the modulus of $(g_K - g_R)/Q_0$, where g_K and g_R are single-particle and collective gyromagnetic ratios; and Q_0 is the quadrupole moment of the intrinsic structure.

In an axially-symmetric even–even nucleus, the K quantum number of a two-quasiparticle band can only be $K = \Omega_1 \pm \Omega_2$, where $\Omega_{1,2}$ are the usual Nilsson quantum numbers of single-particle states. As a consequence, the g_K parameter determined by the branching ratios is given by:

$$g_K K = g_{\Omega_1} \Omega_1 \pm g_{\Omega_2}\ \Omega_2 \,.$$

Thus we see that the branching ratios within the two-quasiparticle bands, and hence the modulus of $(g_K - g_R)/Q_0$, provide information on the quasiparticles that form the intrinsic state, given that one can calculate [13] the values of g_Ω of the single particles. Good estimates of the intrinsic quadrupole moment are provided by recent lifetime measurements of yrast states (see for example Ref. [5]).

Figure 1 shows a schematic section of a Nilsson diagram, illustrating how, for a given nucleon number, the configuration of a two-quasiparticle can change with deformation. At the lower deformation a two-quasiparticle band will have the $\frac{5}{2}[413] \times \frac{3}{2}[411]$ configuration, leading to bands with $J^\pi = (1,4)^+$. On the other hand, at the higher deformation the configuration $\frac{5}{2}[532] \times \frac{3}{2}[411]$ will be formed, leading to bands with $J^\pi = (1,4)^-$.

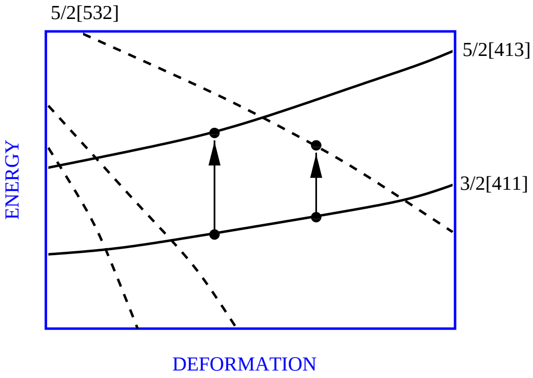

Fig. 1. Schematic section of a Nilsson diagram showing how the spin and parity of a two-quasiparticle band for a given nucleon number could vary with deformation.

In this example, angular correlation data can be used to determine the angular momentum of the band-head, but linear polarisation measurements would be needed to decide between the two possible parities. Often linear polarisation and angular correlation measurements do not give unique J^π assignments. However, the branching ratios within the band can be used to distinguish between two candidate configurations since the values of $(g_K - g_R)/Q_0$ can be quite different.

Two-quasiparticle bands have been observed in several nuclei ranging from ^{96,98}Sr to ^{112}Pd. Figure 2 gives one example of a band in the isotope ^{102}Zr. The level scheme shown is a partial decay scheme only, concentrating on the relevant two-quasiparticle band. The nucleus ^{102}Zr has properties consistent with it being axially-symmetric. Therefore it is expected that K will be a good quantum number. This fact is reflected by the rather complex decay out from the band-head state.

Careful analysis of double-gated coincidence spectra has been performed in order to determine the branching ratios within the observed bands. In most cases this analysis has lead to unambiguous assignment of the configuration of the intrinsic states.

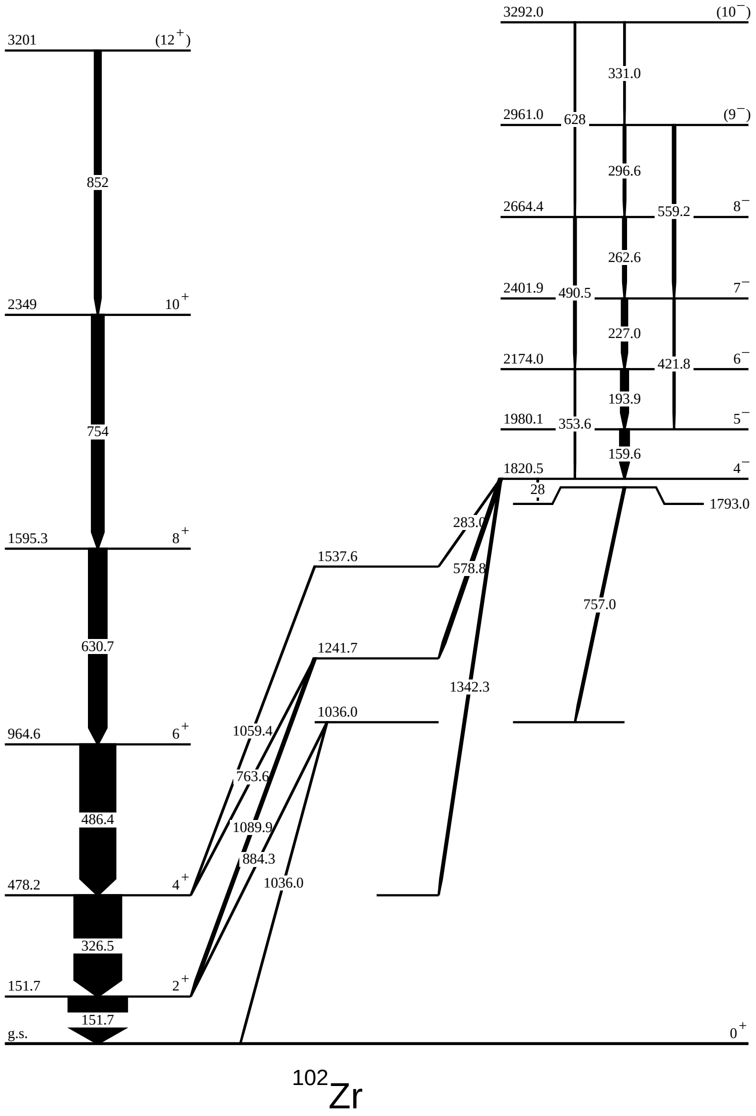

Fig. 2. Partial decay scheme of ^{102}Zr.

2.1. *The $N = 62$ nuclei ^{102}Zr and ^{104}Mo*

In both ^{102}Zr and ^{104}Mo two-quasiparticle bands have been observed the bandheads of which have been determined, by angular correlation measurements, to have $J = 4$. Linear polarisation measurements suggest that the ^{102}Zr band has negative parity, whereas the ^{104}Mo band has positive parity. The portion of the Nilsson diagram for neutron single-particle states relevant to these two nuclei is that shown in figure 1. The Fermi level for neutrons lies just above the $\frac{3}{2}[411]$ orbital for the deformation range expected for these two nuclei. Whether the two-quasiparticle band will have positive or negative parity will depend upon whether the actual deformation is lower or higher than the deformation at which the $\frac{5}{2}[413]$ and $\frac{5}{2}[532]$ orbitals cross. There are of course other configurations (both neutron and proton) that could lead to the observed spins and parities. It transpires that the determinations of $(g_K - g_R)/Q_0$ from the measured branching ratios confirm that the ^{102}Zr band arises from the $\frac{5}{2}[532] \times \frac{3}{2}[411]$ configuration, and the ^{104}Mo band from the $\frac{5}{2}[413] \times \frac{3}{2}[411]$ configuration.

The values of the modulus of $(g_K - g_R)/Q_0$ for ^{102}Zr and ^{104}Mo are 0.14(1) and 0.115(5) $\mu_N eb^{-1}$, respectively. The experimental value for ^{102}Zr can be compared to the calculated numbers for the three configurations that could give rise to a $J^\pi = 4^-$ band. The calculated values are set out in Table I. The assignment of the $\frac{5}{2}[532]$ x $\frac{3}{2}[411]$ configuration to the two-quasiparticle band in ^{102}Zr is supported by the properties [12] of the $N = 61, 63$ isotopes of Zr. The values of $(g_K - g_R)/Q_0$ for the $K^\pi = \frac{3}{2}^+$ and $K^\pi = \frac{5}{2}^-$ ground-state bands of ^{101}Zr and ^{103}Zr lead to an experimentally based prediction for the two-quasiparticle band in ^{102}Zr of 0.15(2), in good agreement with the observed value of 0.14(1).

TABLE I

Calculated values of $(g_K - g_R)/Q_0$ for the configurations that could give rise to a $J^\pi = 4^-$ band in ^{102}Zr.

Configuration	$\frac{g_K - g_R}{Q_0}$
$\nu\frac{5}{2}[532] \times \frac{3}{2}[411]$	-0.16
$\nu\frac{5}{2}[413] \times \frac{3}{2}[541]$	-0.05
$\pi\frac{5}{2}[422] \times \frac{3}{2}[301]$	$+0.03$

For the case of ^{104}Mo, the calculated value of the modulus of $(g_K - g_R)/Q_0$ is $+0.10$ for the $\frac{5}{2}[413] \times \frac{3}{2}[411]$ configuration, which is the only candidate to explain the experimentally observed band.

As a result of this comparison between experiment and calculation it can be deduced that the two-quasiparticle band in ^{102}Zr has a larger deformation than that in the isotone ^{104}Mo. This simple example is illustrative of the spectroscopic information that can be obtained from the properties of two-quasiparticle bands.

2.2. Other two-quasiparticle bands observed

Two-quasiparticle bands have also been found in ^{96,98}Sr, ^{100}Zr, ^{106}Mo, ^{108,110,112}Ru and ^{112}Pd. In all cases except ^{98}Sr only the bands built upon the higher angular momentum intrinsic state have been seen *i.e.* the state arising from the parallel coupling of the individual particles' angular momentum, Ω. This is a consequence of the population mechanism in the fission process, whereby yrast and near-yrast levels are favoured. It appears that, for a two-quasiparticle band to be observed, the actual or extrapolated $J = 12$ member of the band must be near-yrast.

In the case of ^{98}Sr, bands based on both the $K^\pi = 3^+$ and 6^+ couplings of the $\frac{9}{2}[404] \times \frac{3}{2}[411]$ neutron configuration have been identified. This results from the Gallagher–Moskowski interaction which lowers the $K^\pi = 3^+$ intrinsic state by 696 keV relative to the $K^\pi = 6^+$ intrinsic state, thus enabling both bands to fulfil the criterion for significant population. The identification of these two excited bands is consistent with the proposal of Meyer *et al.* [14] that the two three-quasiparticle intrinsic states seen in $^{99}_{39}$Y (an isotone of ^{98}Sr) have the structure: $\pi\ \frac{5}{2}[422] \times \nu\ \frac{9}{2}[404] \times \frac{3}{2}[411]$. The importance of the $\nu\ \frac{9}{2}[404]$ single-particle orbit in the $N = 59, 60$ region is also evidenced by the recent discovery [15] of a $K^\pi = \frac{9}{2}^+$ band, based on an isomeric intrinsic state, in ^{99}Zr.

3. Summary

Two-quasiparticle bands have been seen in several neutron-rich nuclei in the mass range $A = 96$ to 112. Although the ground-state structures of the nuclei concerned differ in nuclear shape, all the two-quasiparticle bands observed have the properties of good rotational bands. It appears that the breaking of a pair of nucleons (usually neutrons) has the effect of stabilising the nuclear shape to be axially symmetric.

The configurations of the two-quasiparticle bands have been determined by calculations of their magnetic properties deduced from in-band branching ratios. The neutrons occupying Nilsson orbitals based on the spherical $h\frac{11}{2}$ and $g\frac{9}{2}$ single-particle states are the main contributors to the intrinsic structure of the two-quasiparticle bands.

A systematic determination of the excitation energies of the lowest-lying two-quasiparticle states would provide data to investigate the strength of the pairing interaction in this mass region. Which two-quasiparticle states are actually seen is determined by the population mechanism of the fission process. This may make it more difficult to learn about pairing. Future experiments with accelerated fission fragments may provide a complementary method for populating a wider range of two-quasiparticle configurations.

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REFERENCES

[1] I. Ahmad, W.R. Phillips, *Rep. Prog. Phys.* **58**, 1415 (1995).
[2] J.H. Hamilton *et al.*, *Prog. Nucl. Part. Phys.* **35**, 635 (1995).
[3] M. Jones, W. Urban, W.R. Phillips, *Rev. Sci. Instrum.* **69**, 4120 (1988).
[4] A.G. Smith *et al.*, *Phys. Rev. Lett.* **77**, 1711 (1996).
[5] A.G. Smith *et al.*, *J. Phys. G: Nucl. Part. Phys.* **28**, 2307 (2002).
[6] A.G. Smith *et al.*, *Phys. Lett.* **B453**, 206 (1999).
[7] G. Lhersonneau *et al.*, *Z. Phys.* **A337**, 143 (1990).
[8] W. Urban *et al.*, *Nucl. Phys.* **A689**, 605 (2001).
[9] A. Guessous *et al.*, *Phys. Rev. Lett.* **75**, 2280 (1995).
[10] J.A. Shannon *et al.*, *Phys. Lett.* **B336**, 136 (1994).
[11] M. Houry *et al.*, *Eur. Phys. J.* **A6**, 43 (1999).
[12] M.A.C. Hotchkis *et al.*, *Nucl. Phys.* **A530**, 111 (1991).
[13] E. Browne, F.R. Femenia, *Nucl. Data Tables* **10**, 81 (1971).
[14] R.A. Meyer *et al.*, *Nucl. Phys.* **A439**, 510 (1985).
[15] W. Urban *et al.*, to be published.