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# Two-quasiparticle bands in neutron-rich nuclei

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**Abstract.** The large multi-detector arrays such as EUROBALL and GAMMASPHERE have made possible the study of the spectroscopy of neutron-rich nuclei through the observation of discrete, prompt $\gamma$-rays emitted following fission. Most of the information obtained has concerned yrast states and collective excitations. In the present work, a search has been made for excited bands 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 triple-coincidence 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 most cases, the determination of which Nilsson orbits (and whether they are neutron or proton states) are contributing to the excitation. Some example results from this search are presented.

**PACS.** 23.20.Lv $\gamma$ transitions and level energies – 21.60.Ev Collective models – 27.60.+j $90 \leq A \leq 149$

## 1 Introduction

The large multi-detector arrays such as EUROBALL and GAMMASPHERE used to detect discrete, prompt $\gamma$-rays from the spontaneous fission of $^{248}$Cm and $^{252}$Cf have led to considerable, new information [1,2] on previously unobserved states in neutron-rich nuclei over a wide mass range. The light-mass peak from the spontaneous fission has allowed a detailed investigation of the $A = 90$–$100$ shape transition region; the heavy-mass peak has allowed a great extension of our knowledge of nuclei near doubly magic $^{132}$Sn, and isotopes that exhibit features of octupole degrees of freedom in the Ba-Ce region.

Standard spectroscopic techniques have been developed to allow their application to the fission studies. Angular correlation and linear polarisation measurements have been made in order to determine spins and multipolarities [3]; lifetime measurements using Doppler effects (both $\gamma$-ray lineshape and differential plunger techniques) have led to transition quadrupole moments being determined [4,5]; and implantation of fission fragments into magnetic hosts has enabled $g$-factors to be measured [6] in prompt spectrsocopy.

On the whole, most of the information obtained from the prompt $\gamma$-ray spectroscopy of fission fragments has been on yrast states and simple collective excitations. This is a consequence of the population mechanism in fission, which strongly favours yrast and near-yrast states. Further information on the structure of these nuclei could be gained if it were possible to study systematically excited states formed by breaking specific pairs in the vacuum state, *i.e.* two-quasiparticle excitations. It would then be possible 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.

In the present work we shall discuss the results of a search for two-quasiparticle excitations in the $Z = 38$ to 46 region. This region is interesting because it exhibits changes in nuclear shape as a function of proton and neutron number, and as a function of angular momentum. The $_{38}$Sr and $_{40}$Zr isotopes undergo [7] a rapid change in their ground-state deformation between $N = 58$ and 60. This has been interpreted as a crossing of near-spherical and highly deformed structures between these two neutron numbers. Recently, Urban *et al.* [8] have been able to follow 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 $\gamma$ soft: low-lying $\gamma$ bands; a near-harmonic double $\gamma$-phonon band [9]; and reducing transition quadrupole moments [5] in the ground-state band as a function of angular momentum. Evidence

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has been presented [10] demonstrating that $^{108-114}$Ru have properties consistent with the predictions of a simple model of a rigid triaxial rotor. The trend in shape evolution continues through the transitional Pd isotopes [11], and the spherical $Z = 48$ Cd nuclei as doubly magic $_{132}$Sn is approached.

Given the pattern of behaviour in the $Z = 38$ to 46 region, it is clearly of interest to study the properties of two-quasiparticle excitations to see what additional information they might give.

## 2 Two-quasiparticle bands in even-even nuclei

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 $\frac{g_K - g_R}{Q_0}$, 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 $\frac{g_K - g_R}{Q_0}$, provide information on the quasiparticles that form the intrinsic state, given that one can calculate [13] the values of $g_\Omega$ 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]).

In order to compare experimental and calculated values of $\frac{g_K - g_R}{Q_0}$, it is clearly necessary to know the $K$ quantum number of the two-quasiparticle band. Angular correlation data can be used to determine the angular momentum of the band-head, and linear polarisation measurements can determine the parity. Often these measurements do not give unique $J^\pi$ assignments. However, the branching ratios within the band can sometimes be used to distinguish between two candidate configurations since the values of $\frac{g_K - g_R}{Q_0}$ can be quite different.

In the present work, two-quasiparticle bands have been found in $^{96,98}$Sr, $^{100,102}$Zr, $^{104,106}$Mo, $^{108,110,112}$Ru and $^{112}$Pd. In most cases, the combination of angular correlation and linear polarisation data with carefully measured branching ratios has allowed the unambiguous assignment of configurations to the observed bands. In all the nuclei 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, $\Omega$. This is a consequence of the population mechanism in the fission process, which favours near-yrast states. Also, despite the fact that 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.

## 3 Two-quasiparticle bands in $^{98}$Sr

The nucleus $^{98}$Sr ($N = 60$) is strongly deformed, with $\beta_2$ close to 0.4, as a consequence of the deformed, $Z = 38$ magic number. We should therefore expect to see good rotational bands based upon any two-quasiparticle configuration. Because of the proton closed shell in the Sr isotopes, we would not expect proton excitations to contribute to the low-lying two-quasiparticle bands. Guidance as to which neutron single-particle orbitals will contribute to the two-quasiparticle state should, in principle, come from the ground states of the neighbouring isotopes. This can be illustrated by $^{102}$Zr$_{62}$ in which a $K^\pi = 4^-$ two-quasiparticle band has been found with the neutron configuration $\frac{5}{2}$[532] x $\frac{3}{2}$[411]. This assignment is compatible with the observed ground-state spins and parities of $^{101}$Zr$_{61}$ and $^{103}$Zr$_{63}$ which are $\frac{3}{2}^+$ and $\frac{5}{2}^-$, respectively. The comparison can be taken further, since the branching ratios of levels in the ground-state bands of $^{101}$Zr and $^{103}$Zr have been measured [12]. The values of $\frac{g_K - g_R}{Q_0}$ 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 value of this quantity for the two-quasiparticle band in $^{102}$Zr of 0.15(2) $\mu_N$eb$^{-1}$, in good agreement with the observed value of 0.14(1) $\mu_N$eb$^{-1}$.

In the case of $^{98}$Sr$_{60}$, the situation is not so simple as the ground-state structure of $^{97}$Sr$_{59}$ is near-spherical. However, there is evidence [8] of an excited $J^\pi = \frac{3}{2}^+$ state in $^{97}$Sr upon which a rotational band is built. The ground state of $^{99}$Sr$_{61}$ is also $\frac{3}{2}^+$. It seems likely therefore that the $\frac{3}{2}$[411] Nilsson orbital may play a role in two-quasiparticle states in $^{98}$Sr.

Figure 1 shows a partial level scheme of $^{98}$Sr determined in the present work. It can be seen that two excited rotational bands have been observed based on levels at 1837.3 and 2533.1 keV. Linear polarisation measurements indicate that both these levels have positive parity. Angular correlation data show that the 1837.3 keV level has $J = 3, 4$, and the 2533.1 keV level has $J = 6, 7$, although the tentative observation of the decay to the ground-state band $J = 4$ level would make the $J = 7$ assignment unlikely. Since the band-head states are at an excitation energy of $2\Delta$ or greater, these two bands can be assigned as two-quasiparticle bands.

The magnitude of $\frac{g_K - g_R}{Q_0}$ has been determined for the band based on the 1837.3 keV level from the decay branching ratios. The value of this quantity is 0.093(9) $\mu_N$eb$^{-1}$. We can compare this experimental value with theoretical

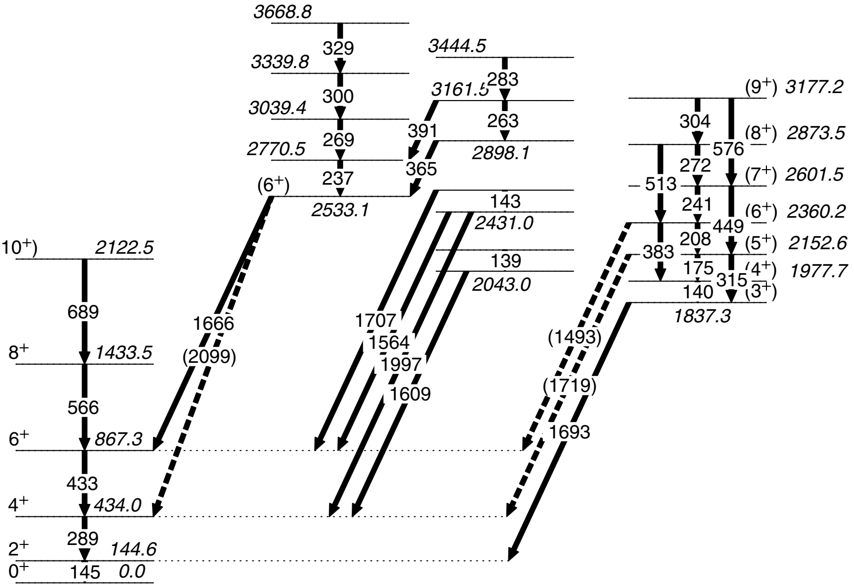

**Fig. 1.** Partial decay scheme of $^{98}$Sr.

**Table 1.** Calculated values of $\frac{g_K - g_R}{Q_0}$ for possible neutron configurations for the 1837.3 keV level in $^{98}$Sr.

| Configuration | $K^{\pi}$ | $\frac{g_K - g_R}{Q_0}$ |
|---|---|---|
| $\frac{5}{2}[532] \times \frac{3}{2}[541]$ | $4^+$ | $-0.207$ |
| $\frac{5}{2}[413] \times \frac{3}{2}[411]$ | $4^+$ | $-0.392$ |
| $\frac{9}{2}[404] \times \frac{3}{2}[411]$ | $3^+$ | $-0.106$ |

numbers calculated for all reasonable configurations that would give rise to a $K^{\pi} = 3^+$ or $4^+$ two-quasiparticle band in an $N = 60$ nucleus with a deformation around 0.4. Table 1 shows the calculated values of $\frac{g_K - g_R}{Q_0}$ for the three candidate configurations. It can be seen that only one configuration agrees with experiment: $\nu\frac{9}{2}[404] \times \frac{3}{2}[411]$, with the single-particle angular momenta $\Omega$ coupling antiparallel. Thus we see that the analysis of the branching ratios within the band resolves the ambiguity in angular momentum assignment. The assignment made involves the $\frac{3}{2}[411]$ neutron orbital, consistent with the discussion above.

No $E2$ cross-over transitions have been observed in the band based on the 2533.1 keV $J = 6, 7^+$ level. This implies that $\frac{g_K - g_R}{Q_0}$ is large for this band, and that the configuration of the intrinsic state has a large quasineutron $g$-factor. It is not possible to find a two-quasiparticle configuration that could give rise to a $K^{\pi} = 7^+$ state; a $K^{\pi} = 6^+$ state can be formed from the parallel coupled $\nu\frac{9}{2}[404] \times \frac{3}{2}[411]$ configuration. Such an intrinsic state does lead to a large quasineutron $g$-factor. We therefore assign the two band-head states at 1837.3 and 2533.1 keV to be the two partners of the $\frac{9}{2}[404] \times \frac{3}{2}[411]$ configuration.

The identification of these two excited bands is consistent with the proposal of Meyer *et al.* [14] that 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 existence of the $\nu\ \frac{9}{2}[404]$ single-particle orbit at the Fermi surface 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.

The identification of the two bands as being the two allowed couplings of angular momentum of the same configuration gives an experimental measure of the Gallagher-Moskowski interaction which lowers the $K^{\pi} = 3^+$ intrinsic state relative to the $K^{\pi} = 6^+$ intrinsic state. The measured splitting of 696 keV is somewhat larger than that which has been observed in the rare-earth region of nuclei. An average value of around 400 keV is normal in this region. We can also compare the size of the Gallagher-Moskowski splitting in $^{98}$Sr with that observed [14] in $^{99}$Y for the three-quasiparticle configuration which has a $\frac{5}{2}[422]$ proton coupled to the same neutron structure seen in $^{98}$Sr. The splitting in $^{99}$Y is 487 keV, somewhat smaller than the size of the splitting for the two-quasiparticle states. It appears that the coupling to the third nucleon moderates the magnitude of the Gallagher-Moskowski interaction.

The nucleus $^{98}$Sr is the only case in which the antiparallel coupled two-quasiparticle band is seen. It is in fact the Gallagher-Moskowski effect that makes this possible, since the lowering of the $K^{\pi} = 3^+$ band makes the higher spin members of the band near enough yrast to be populated in the fission process.

## 4 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 fact that the bands observed are good rotational bands means that the configurations of the intrinsic states can be determined by calculations of their magnetic properties deduced from in-band branching ratios, using the rotational model.

One particular example has been presented, where the analysis in terms of the magnetic properties of the bands in $^{98}$Sr has been able to resolve ambiguous spin assignments from angular correlation data. This example has also provided an experimental determination of the Gallagher-Moskowski splitting in an even-even neutron-rich nucleus.

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