ROTATING N=Z NUCLEI — A PROBE TO THE t=0 AND t=1 PAIRING CORRELATIONS*

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A study of heavy N=Z nuclei including t=1, t_z=±1 pairing only clearly reveals the shortcoming of that model in T_z=0 nuclei. We present a simple model in which we study the response of isoscalar t=0 and isovector t=1 pairing correlations to rotational motion. In particular, we address the role played by the t=1 and t=0 pair gaps with respect to the band crossing frequency. We argue that the t=1 neutron-proton pair field is of limited importance in even-even nuclei. For the t=0 pair field, we introduce two different pairing modes. One is invariant with respect to signature symmetry and one is not. The signature conserving mode results in a delay of the band crossing frequency, whereas the signature breaking part enhances the rigidity of the moment of inertia.

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1. Introduction

During the very last years there has been a remarkable progress in the study of high spin states of heavy N=Z nuclei. Experimental data of excited states is now available up to ^{88}Ru [1]. Since the proton and neutron wave functions are essentially identical in N=Z nuclei, one may expect in addition to standard isovector (t=1) the presence of isoscalar (t=0) pairing [2, 3]. The field of high spin physics has played an important role in the investigation of isovector t=1, t_z=±1 pairing correlations [4]. The recent

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experimental development will now allow us to investigate in a similar manner the significance and role played by $t{=}0$ pairing correlations. There are two basic high spin observables which in particular may serve as a probe to static pairing correlations: *(i)* the size of the moment of inertia and *(ii)* the frequency at which the first pairs of particles align their angular momentum (band crossing frequency).

In an early experiment on ^{72}Kr, it was shown that the crossing frequency between the ground state and S-band appeared to be shifted [5]. These findings were later on corroborated by data from Gammasphere [6]. It was suggested that the shift could be viewed as an evidence for neutron–proton (np) pairing correlations although other mechanisms could not be ruled out [5].

In this paper we will first discuss results of Total Routhian Surface (TRS) calculations for rotational states of $N{=}Z$ nuclei from ^{68}Se to ^{88}Ru. These calculations are restricted to $t{=}1$ $t_z{=}\pm1$ pairing only. In the following section, we present a simple model in which we can study the response of the $t{=}1$ and $t{=}0$ pair field to rotation. In particular, we will address the role played by the two different components of the isoscalar pairing field.

2. High spin states in $N{=}Z$ nuclei

The force acting on a pair of particles moving in time reversed orbits in a rotating field is analogous to the force acting on an electronic Cooper pair in a magnetic field. The frequency at which a pair of particles align is determined by the competition of the pairing force, keeping the particles in time reversed orbits and the Coriolis force that tends to break the pairs, see *e.g.* the discussion in Ref. [4]. The band crossing frequency, therefore, is an indicator on the size of pairing correlations — the pair gap. Unfortunately, other factors, like the deformed mean field will affect the band crossing frequencies as well. Nevertheless, a systematic observation of a delayed band crossing in $N{=}Z$ nuclei as compared to their $N{\neq}Z$ neighbours, may indicate, that pairing correlations are, at least partially, responsible for it. Particularly, that in our previous paper on $T_z{=}1$ nuclei [7] it was shown that our TRS calculations were rather successful in describing the high spin data in this mass region. Therefore, the comparison of our calculations with recent data on $N{=}Z$ nuclei is crucial in order to set a benchmark on the validity or limitations of the model.

In a series of recent experiments at Gammasphere, Euroball and GASP, high spin states of $N{=}Z$ nuclei were studied up to ^{88}Ru. In the following we comment on those cases, where we show the limitations of calculations including $t{=}1$ pairing only. In these extended TRS-calculations, the shape of the nucleus is minimized with respect to the quadrupole and hexadecapole deformations. Pairing channel includes $t{=}1$ $t_z{=}\pm1$ monopole and double stretched quadrupole forces and is treated by means of the Lipkin–Nogami (LN) approximate number projection, see [8, 9] for further details. We start the discussion with the data on ^{68}Se, which was reported in [10]. Two rotational bands have been observed in that nucleus, that were interpreted in terms of an oblate and prolate structure. An alignment in the prolate band at $\hbar\omega \approx 0.55\,\mathrm{MeV}$ was associated with the simultaneous breaking of $g_{9/2}$ neutron and proton pairs [10].

Results of our calculations are depicted in Fig. 1. The energy difference between the prolate (p) and oblate (o) ground state band of ^{68}Se is quite well reproduced in our calculations although the moment of inertia does not agree so well. This is not surprising since the deformation is rather small, corresponding to a more transitional like nucleus. However, in our calculations, the prolate band is not crossed by the weakly deformed S-band, but by more deformed structures (d1 and d2). The difference between the deformed bands relates to the gamma-degree of freedom, d2 (d1) having $\beta_2 \sim 0.327(0.340)$ and $\gamma \sim -18^\circ(+32^\circ)$, respectively.

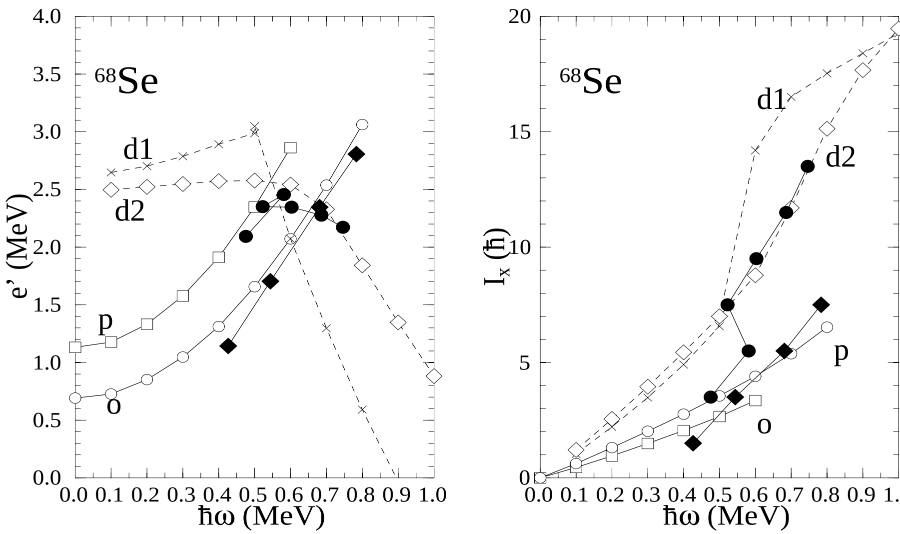

Fig. 1. Routhians (left part) and aligned spin (right part) for ^{68}Se. Experimental values are shown with filled circles for the prolate band and filled boxes for the oblate band. See text for further details.

The alignment gain when going from the less deformed to the more deformed band agrees quite nicely with experiment. Indeed, if this band crossing would be associated with the alignment of $g_{9/2}$ protons and neutrons at small deformation the angular momentum gain would be considerably larger than what is observed. The shape coexistence calculated for this particular nucleus (four different shapes close to the Fermi surface) points to the importance of shape degree of freedom in this mass region (see also Ref. [11] and references quoted therein) and, unfortunately, renders quite some uncertainty to our calculations. To discuss band crossing frequencies without controlling the shape variables does not appear very meaningful.

From the calculations, Fig. 1, one can clearly see, that the deformed band with positive gamma is lowest in energy and is crossed by the aligned S-band at $\hbar\omega \approx 0.55\,\mathrm{MeV}$, whereas the band in experiment is seen up to $\hbar\omega > 0.7\,\mathrm{MeV}$ without any band crossing. The moment of inertia agrees with the deformed band (at negative gamma-values) but the calculated band crossing is obviously absent. The situation thus resembles that of ^{72}Kr [5], where there exist also an uncertainty related to the varying shapes.

The case of ^{72}Kr has been discussed already [5]. The new data from Gammasphere seems to confirm the previous GASP experiment [6], but there exist still some uncertainty concerning the highest spins. There is no doubt, however, that the calculated band crossing frequency deviates strongly from experiment. This is in clear contrast to the case of ^{74}Kr and ^{76}Kr, where the calculated frequency agrees very well with experiment. The calculated shape change adds of course some uncertainty, but at the same time, one should note that for the case of ^{74}Kr, the predicted shape change has been confirmed by experiment [12].

The Gammasphere experiment also reports data on ^{76}Sr and ^{80}Zr [6]. Below we present our calculations for the two nuclei and compare to experiment, Fig. 2. One may conclude that the calculations with $t{=}1$ pairing only, agree quite well with experiment and that there is little evidence for the presence of $t{=}0$ pairing. However, these nuclei belong to the most deformed prolate nuclei in this mass region. The large deformation results by itself in a very smooth alignment, from which it is difficult to draw any conclusions concerning the shift of the band crossing frequency, see Fig. 2. For the case of ^{76}Sr, it would be very valuable to observe another two transitions, in order to be able to address this question. For the case of ^{80}Zr, one is still far from the alignment and the data is therefore not at all conclusive.

Very recently, ^{88}Ru data was reported from a GASP experiment [1]. Since the nuclei beyond ^{80}Zr are less deformed, one would expect to observe the $g_{9/2}$ alignment at a lower frequency. Again, comparing with neighbouring isotopes, there appears a clear shift to be present in the band crossing frequency [1]. Below, we show the calculations for ^{84}Mo and ^{88}Ru, see Fig. 3.

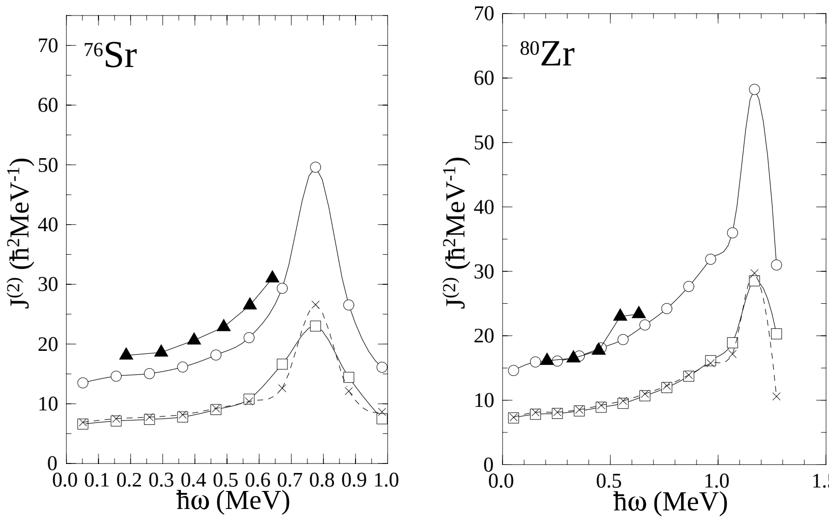

Fig. 2. Dynamical moment of inertia, $J^{(2)}$, as a function of frequency for ^{76}Sr and ^{80}Zr. Experimental (theoretical) values are depicted by ▲ (∘). We also show the contribution of protons (□) and neutrons (×) to the total calculated values. The calculated crossing frequency is indicated by arrow. Note the smooth alignment process.

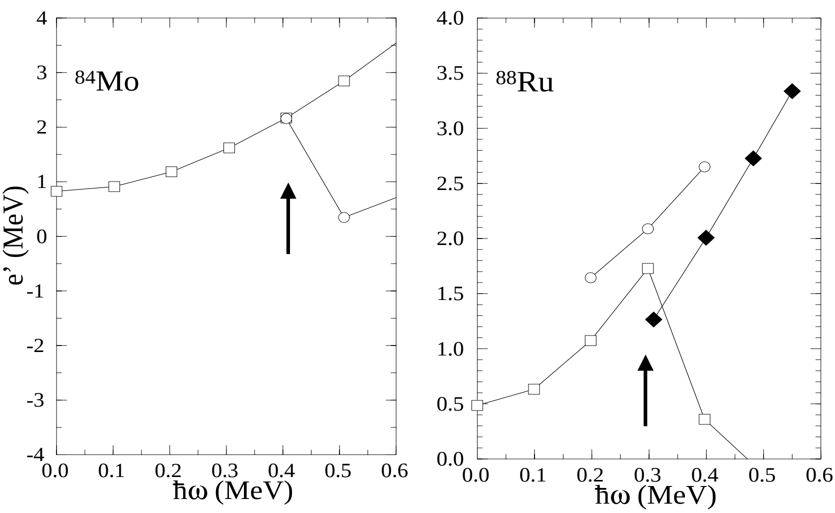

Fig. 3. Calculated (open symbols) and experimental (filled symbols) routhians as a function of frequency. For the case of ^{84}Mo, no data is available yet. The calculated crossing frequencies are indicated with arrows. Note, that for the case of ^{88}Ru there is no sign of any band crossing in the data.

Data for ^{84}Mo would be of high interest as well as higher lying states for the case of ^{88}Ru. In the calculations, the $g_{9/2}$ alignment occurs quite early, in clear contrast to experiment.

3. Pairing correlations and the rotational field

When constructing a pairing force that can encompass both t=1 and t=0 correlations, one immediately is faced with the difficulty of their entirely different angular momentum dependence. For a short range interaction, like the δ-force, it is well known that the 0^+ matrix element is strongly attractive and dominates over higher angular momentum matrix elements. Then, even in a case of deformed nuclei (strong configuration mixing) a structureless seniority-type force, $-GP^\dagger P$, where $P^\dagger = \sum_{\alpha>0} a^+_\alpha a^+_{\tilde\alpha}$ and the index α and $\tilde\alpha$ correspond to states of opposite signature, offers a reliable approximation of an *effective* pairing force. This force is easily generalized as to include t=1 np−correlations:

$$\begin{aligned} H^{t=1}_{\rm pair} &= -G^{t=1} P^\dagger_{1t_z} P_{1t_z} \, , \\ P^\dagger_{1t_z} &= \sum_{\alpha>0, m_\tau} < 1/2 \; m_\tau \; 1/2 \; m'_\tau | 1 \; t_z > a^+_{\alpha \; m_\tau} a^+_{\tilde\alpha \; m'_\tau} \, , \end{aligned} \tag{1}$$

where m_τ is $+1/2(-1/2)$ for neutrons (protons), respectively [2, 3, 13].

In contrast, for a pair of particles in identical orbits, the t=0 interaction is essentially as attractive for the J=1 as the J=2j states, see *e.g.* the compilation in [14]. Since our model is entirely based on the spontaneously broken spherical symmetry (deformed mean field), angular momentum is not a conserved quantity. Therefore on top of the deformed mean field we can construct two entirely different pairing modes creating t=0 np pairs that involve scattering of pairs *(i)* in states of opposite signature – the $\alpha\tilde\alpha$ mode similar to the t=1 pairing, and *(ii)* in states of the same signature, the $\alpha\alpha$ mode. In terms of the spherical shell model the $\alpha\tilde\alpha$ mode would correspond to low angular momentum matrix elements, whereas the $\alpha\alpha$ pairs can carry large angular momenta. The force takes the following form (see also discussion in Ref. [15]):

$$\begin{aligned} H^{t=0}_{\rm pair} &= -G^{t=0}_1 P^\dagger_1 P_1 - G^{t=0}_2 P^\dagger_2 P_2 \, , \\ P^\dagger_1 &= \frac{1}{\sqrt{2}} \sum_{\alpha>0} \left(a^+_{\alpha n} a^+_{\tilde\alpha p} - a^+_{\alpha p} a^+_{\tilde\alpha n} \right) \, , \\ P^\dagger_2 &= \frac{1}{\sqrt{2}} \sum_{\alpha>0} \left(a^+_{\alpha n} a^+_{\alpha p} \pm a^+_{\tilde\alpha n} a^+_{\tilde\alpha p} \right) \, . \end{aligned} \tag{2}$$

Further details of the model will be discussed in a forthcoming publication [16]. The ratio of $G_1^{t=0}$ and $G_2^{t=0}$ is an open problem, and cannot be determined in our approach. Let us recall, however, that $\alpha\alpha$ pairs carry angular momentum. Since adjacent deformed Nilsson orbits usually have different angular momenta, the pair scattering in this pairing mode implies that angular momentum conservation is severely broken. This implies that this mode must be strongly suppressed with respect to the $\alpha\tilde{\alpha}$ mode *i.e.* $G_1^{t=0} > G_2^{t=0}$. Indeed the latter resembles much the standard t=1 pair scattering in which there is essentially no angular momentum violation during the scattering process. One can therefore conclude that only at high spins, may the $\alpha\alpha$ mode become important, see also the discussion in Ref. [17]. The t=0 pairing at low angular momenta is therefore expected to be dominated by the $\alpha\tilde{\alpha}$ mode. In fact, we have found that $\alpha\tilde{\alpha}$ hardly mix with $\alpha\alpha$ mode. More precisely, at low spins there exist only $\alpha\tilde{\alpha}$ pairing. At high spin, after the alignment, a transition into the $\alpha\alpha$ mode might occur provided that the $G_2^{t=0}$ strength is over certain critical value [17].

Two possibilities for the phase relation exist for the $\alpha\alpha$ pairing, see definition of $P_2^\dagger$ in Eq. (2), which leads to the same phase for $\alpha\alpha \longrightarrow \beta\beta$ but opposite phases for $\alpha\alpha \longrightarrow \tilde{\beta}\tilde{\beta}$ scattering processes. Thus far we were unable to find a physical difference between them. However, we found that $\alpha\alpha^{(-)}$ mode can mix with $\alpha\tilde{\alpha}$ but only in the high spin transition region while $\alpha\alpha^{(+)}$ and $\alpha\tilde{\alpha}$ solutions seem to be always exclusive.

3.1. Response of the t=1 field.

The response of the t=1 pair field to rotations is well known and has been studied to quite some extent. Indeed, the observation of the reduced moment of inertia in rotating nuclei with respect to the rigid body value was essential in order to establish the theory of superfluidity and the introduction of the BCS-formalism to nuclear physics [18]. Since in standard BCS-theory, the t_z=0 component of the t=1 pairing force is omitted, it was suggested that the shift in the crossing frequency may be due to the t=1, np-component of the force. Two different mean field mechanisms were proposed: *(i)* the explicit isospin symmetry breaking at the level of the Hamiltonian with and ad hoc strong t=1, t_z=0 component of the pairing force [19] and *(ii)* the spontaneous isospin symmetry breaking [20]. We propose here a different mechanism where the delay is caused essentially by the $\alpha\tilde{\alpha}$ t=0 field.

In the work of [19], the Δ_{10} pair gap was artificially increased without decreasing the corresponding values of Δ_{1-1} and Δ_{11} which is equivalent to introducing a t_z dependent t=1 pairing force and the explicit violation of isospin symmetry. This results in an artificial increase of the total pairing gap $\Delta_1 = \sqrt{\Delta_{1-1}^2 + \Delta_{11}^2 + \Delta_{10}^2}$ as compared to the value calculated for an isospin conserving Hamiltonian where the value of Δ_1 is insensitive to the direction in isospace $\vec{\Delta}_1 \equiv (\Delta_{1-1}, \Delta_{11}, \Delta_{10})$. Since the band crossing frequency is related to the size of the total gap this mechanism naturally produces a shift.

In the work of Ref. [20] it was argued that the spontaneous symmetry breaking of the t=1 pairing is the main cause of the delay in the band crossing frequency and that there is no effect from t=0 $np-$pairing [20]. The physics mechanism behind this idea can be expressed as follows: the spontaneous breaking and subsequent restoration of isospin symmetry should lower ground state band, where pairing correlations are larger, with respect to S-band where pairing is supposed to be suppressed due the pair alignment which obviously would lead to a delayed band crossing. However, the shift was never estimated quantitatively for a realistic case. In addition, part of this effect is already taken into account by standard particle number projection. Moreover, it was shown later on that the conclusion of a zero effect of the t=0 pairing force is correct only within a single$-j$ shell, and as soon as one increases the strength of the J=1 component in the pairing field, one will indeed shift the crossing frequency in N=Z nuclei [21]. The physical motivation for this increase is of course that in heavy nuclei, the Fermi surface is placed among several subshells, like $f_{5/2}$, $p_{3/2}$, $g_{9/2}$, $p_{1/2}$ and one expects therefore a coherence in the J=1 component of the force, whereas the J=2j part is fragmented over several shells [21]. This is analogous in our model to the expected coherence of the $\alpha\tilde{\alpha}$ (low J) with respect to the $\alpha\alpha$ (high J) pairing mode.

3.2. Response of the t=0 field

The wave function of the nucleus in a rotating system is usually classified by means of the signature quantum number, which is conserved by the rotating field. However, the t=0 pairing has a component that breaks that symmetry, namely the $\alpha\alpha$ field. Therefore, one is dealing with two different components of the pair field, one that preserves signature and one that is breaking it. To understand the effect of the two different t=0 pair fields, we perform a case study for the nucleus ^{72}Kr, which was the first where a delay of the band crossing frequency was reported and also interpreted as being caused by the lowering of the ground state band energy due to possible t=0 correlations. To quantify these suggestions, we have performed calculations at fixed deformation in spite of the fact that deformation changes play a large role in this region. In this respect one has to view this study on a qualitative level.

In Fig. 4, we show the angular momentum I_x as a function of frequency for three different cases: *(i)* standard t=1 pairing correlations ($\circ$) (let us recall that in our LN calculations t=1, t_z=0 component plays a redundant role [17, 22]) *(ii)* t=1 and t=0 $\alpha\tilde{\alpha}$ (•) and *(iii)* t=1 and t=0 $\alpha\alpha$ (×) pairing. For the case of standard t=1 pairing, we see the sudden rise in the calculated I_x at $\hbar\omega = 0.4\,\text{MeV}$, corresponding to the breaking of a pair of protons and neutrons in the $g_{9/2}$ orbits. As soon as we switch on the t=0 $\alpha\tilde{\alpha}$ pairing, the frequency of this alignment, the band crossing frequency $\hbar\omega_c$ becomes actually shifted by $\Delta\hbar\omega_c \sim 0.2\,\text{MeV}$, which is quite a sizeable amount. The strength of the pairing used for this case is $G_1^{t=0}$=$1.3\,G^{t=1}$, which slightly exceeds the strength expected from the study of the Wigner energy [17, 23]. The shift scales directly with the strength. Of course, the effect will appear only for values above critical, *i.e.* $G_1^{t=0} > 1.1G^{t=1}$. Clearly, if there is a coherent t=0 pair field, it will affect the band crossing frequencies, see also [21]. The shift is easily understood. Since the $\alpha\tilde{\alpha}$ pair field couples proton and neutron pairs in signature inversed orbits, these pairs resist the alignment in a similar fashion like in standard t=1 pairing. Since the t=0 pair field constitutes a new degree of freedom, there is no need to invoke a symmetry violating Hamiltonian. The situation is quite similar to the discussion concerning the mass excess in N=Z nuclei, which can be accounted for by means of t=0 correlations, without any need of charge symmetry breaking Hamiltonian [17].

On the other hand the response of the $\alpha\alpha$ pair field to rotation is quite different. These pairs couple to high angular momentum and therefore, the Coriolis force does not at all tend to break them. The Coriolis and centrifugal force only tend to smoothly align those pairs along the rotational axis. The response to rotation resembles fully that of a classical rigid body. Sometimes it is suggested, that a nucleus without pairing correlations resembles that of a rigid body. This notation is correct only in the limit of small frequencies, where rotation can be treated by means of perturbation theory. As soon as particles start to align, the moment of inertia in general starts to drop due to the limited angular momentum available for a given configuration. In contrast, the nucleus in an $\alpha\alpha$ condensate actually continuously aligns its angular momentum, since there is no hindrance to scatter pairs into higher lying orbits by means of the t=0 $\alpha\alpha$ pair field. There is no drop in the pair field with increasing frequency, it actually increases. No backbend can occur. In a recent paper by Goodman [24], the case of ^{80}Zr was discussed, in which the t=0 solution crossed the t=1, and where there was no backbend obtained for the t=0 solution. There the t=0 pairing was essentially built upon the J=5 component of the t=0 field and no reduction of the pair field with frequency was obtained. Clearly, this solution is quite analogous to our seniority $\alpha\alpha$ mode, although there is no explicit angular momentum dependence present in our model. Similar results were discussed in our paper for the case of ^{48}Cr [22], see also the discussion in [17].

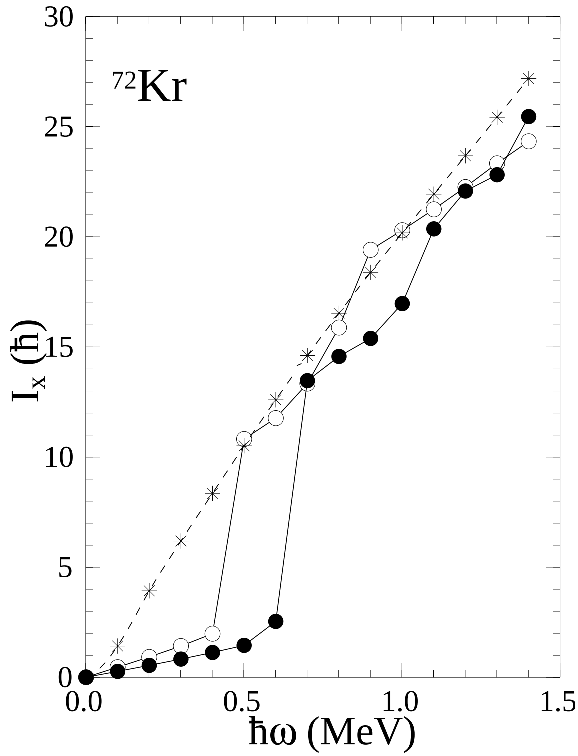

Fig. 4. Aligned angular momentum I_x as a function of $\hbar\omega$ for three different values of the pair field: (*i*) only standard t=1 (∘), (*ii*) t=1 and t=0 $\alpha\tilde{\alpha}$ (•) and (*iii*) t=1 and t=0 $\alpha\alpha$ pairing (⋆).

4. Summary

The comparison with the present data and calculations including t=1 pairing only is quite instructive but also limited in scope. The general picture that emerges is that although the TRS-calculations are quite successful in reproducing the rotational spectra in $T_z = 1$ nuclei [7] and other nuclei in this mass region [25], there appears a general shortcoming with respect to the band crossing frequency in T_z=0 nuclei. The presence of a static t=0 $\alpha\tilde{\alpha}$ pair gap will result in a shift of the band crossing frequency. In contrast, the t=1, t_z=0 pair gap will have little effect on the rotational spectrum of even-even nuclei. The t=0 $\alpha\alpha$ mode results in a pair gap, that is increasing with frequency, in which the nucleus becomes like a rigid body. No sudden alignment can occur. Due to the limited phase space, it is questionable whether such a mode does exist in nature, possibly at very high angular momenta [17].

To treat both isoscalar and isovector pairing on the same footing in TRS calculations is beyond this presentation. It requires a more thorough investigation especially on the deformation dependence of isoscalar pairing as well as its feedback on the deformed potential. Since isoscalar pairing is much stronger than isovector pairing, it is not at all clear, whether it can be included on top of a deformed single particle potential as is done with isovector pairing. In calculations for ^{48}Cr including isoscalar and isovector pairing correlation, the deformed potential becomes soft with increasing isoscalar pairing, until the deformed minimum disappears when $G_1^{t=0} > 1.3\, G^{t=1}$. In contrast, in self-consistent HFB calculations involving the Skyrme SIII force, the nucleus ^{48}Cr became somewhat *more* deformed in the presence of $t=0$ pairing [26]. The difference may be attributed to the lack of feedback of the pairing interaction to the deformed field and also to the simple type of pairing force used in our approach. For the proper treatment of rotational states at high angular momentum, the time-odd component of the pairing force is essential [8, 27]. This requires an extension of our model to include the quadrupole pairing force in the isoscalar channel. It is not obvious at all, whether such extensions will be successful, or whether this is the limit of simple model calculations, where the next step will require fully self-consistent HFB-calculations in order to make not only qualitative but also quantitative comparisons. This certainly is an urgent task for the future as well as further experimental investigations of $N=Z$ nuclei.

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