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Delayed alignments in the $N=Z$ nuclei ^{84}Mo and ^{88}Ru

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The yrast band of the $N=Z$ nucleus ^{84}Mo has been extended up to the 10^+ state. Its moment of inertia varies smoothly up to this state (rotational frequency 0.6 MeV). The new data confirm the systematic delay of the particle alignment frequency in $N=Z$ nuclei with respect to the neighboring $N>Z$ nuclei, which has been suggested as a signature of the neutron-proton pairing interaction. Projected shell model calculations performed for the heaviest $N=Z$ nuclei studied so far, ^{84}Mo and ^{88}Ru, predict that the confirmation of a possible enhancement of the neutron-proton residual interaction requires the observation of still higher spins in these nuclei.

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The study of $N=Z$ nuclei is expected to give the most relevant information about the properties of the neutron-proton (np) pairing interaction. In $N=Z$ nuclei, neutrons and protons occupy the same shell-model orbitals, and thus can have the largest probability to interact with each other. It has been thought that the np pairing interaction may be the cause of the delayed rotational alignments in the even-even $N=Z$ nuclei in the $A\sim80$ mass region, and this line of research has been actively pursued. The recently observed alignment delays in ^{72}Kr, ^{76}Sr, and ^{80}Zr may be such examples [1,2].

Experimentally, the main difficulty in extending the study of $N=Z$ nuclei at higher spins is their population with extremely low cross sections in a small number of available reactions. Progress in the development of large γ-ray arrays and associated ancillary detectors, as well as refinements of the data processing techniques, allowed recent advance in the knowledge of the heaviest $N=Z$ nuclei in general, and of their high spin behavior in particular. Theoretically, it has been suggested that the behavior of the moment of inertia of an $N=Z$ nucleus with increasing spin (rotation) would be particularly relevant in this respect. Different pairing fields (nn, pp, and np) respond differently to the Coriolis forces. The enhancement of the np interaction in $N=Z$ nuclei has in general an effect to sustain the pairing field under rotation. The real situation is, however, rather complicated, due to the fact that the spin alignment is also sensitively influenced by other factors such as deformation. Theoretical calculations, most of which are still schematic, have reached various conclusions on the role of different np interactions [3–9].

To date, consistent delays in the crossing frequencies (due to alignment of the $g_{9/2}$ particles) in the ground state bands have been observed for the $N=Z$ Kr [1,2], Sr, Zr [2], and Ru [10] nuclei. The strongest effect has been observed in ^{72}Kr where a very delayed crossing has been located at 0.85 MeV [2]. In ^{76}Sr there is a discernible effect which indicates a broad crossing shifted to 0.62 MeV (compared to ≈0.55 in $N>Z$ isotopes [2]), while for ^{80}Zr [2] and ^{88}Ru [10] the observations indicate again a delay but the crossing has not been located yet. In this chain of $N=Z$ nuclei, ^{84}Mo is the only one which has not been studied at spins higher than $4\hbar$.

In view of the present situation, which indicates a particular behavior of the $N=Z$ nuclei, extending the data on the heavier systems is a topical subject. In spite of the fact that the cross section for populating these nuclei decreases with Z, it would still be possible to observe interesting effects since the nuclei beyond ^{80}Zr are less deformed, therefore the $g_{9/2}$ alignment is expected at lower frequencies. The purpose of this work is to present new experimental data on higher spin states in the yrast band of ^{84}Mo. The experimental data on the heaviest measured $N=Z$ nuclei ^{84}Mo and ^{88}Ru will be discussed within the framework of the projected shell model [11,12].

In the present experiment we have used the same reaction as in a previous one [13], ^{58}Ni+^{28}Si, which populates the ^{84}Mo nucleus through the $2n$ channel. The 90-MeV ^{28}Si 8^+ beam with intensity of about 14 particle nA was delivered by the Legnaro XTU Tandem accelerator. The target was a stack of two 0.5-mg/cm^2 ^{58}Ni foils. The detection setup was similar to the one used in the ^{88}Ru experiment [10]: the GASP array in its standard configuration with 40 Compton-suppressed HpGe detectors and the BGO inner ball, the ISIS Silicon ball with 40ΔE-E telescopes, and the N-ring with 6 liquid scintillator neutron detectors replacing 6 of the 80 BGO elements, at forward angles. The trigger condition was that at least 2 Ge and 2 BGO detectors fired in coincidence. The efficiencies for particle detection were $\sim56\%$ for one proton, $\sim36\%$ for one α particle, and 3.1% for one neutron.

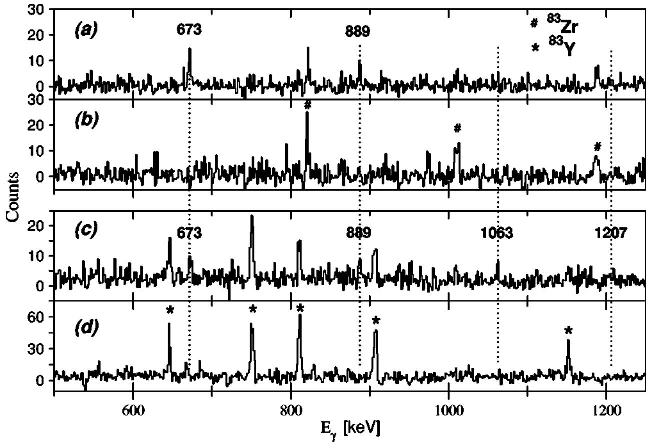

FIG. 1. Gated γ-ray spectra showing the assignment of the yrast line of ^{84}Mo. The upper two spectra are gated by the 444-keV ($2^+ \to 0^+$) transition, (a) on a γ-γ matrix with veto on the charged particles and coincident with neutrons; (b) on a γ-γ matrix coincident with both neutrons and one proton. The lower two spectra are doubly gated spectra, with a gate 444 keV/(673+889+1063 keV), (c) on a γ-γ-γ cube with veto on charged particles, and (d) on a γ-γ-γ cube coincident with protons. The lines labeled with their energy have been assigned to the yrast band of ^{84}Mo. See text for other lines indicated only with symbols in these spectra.

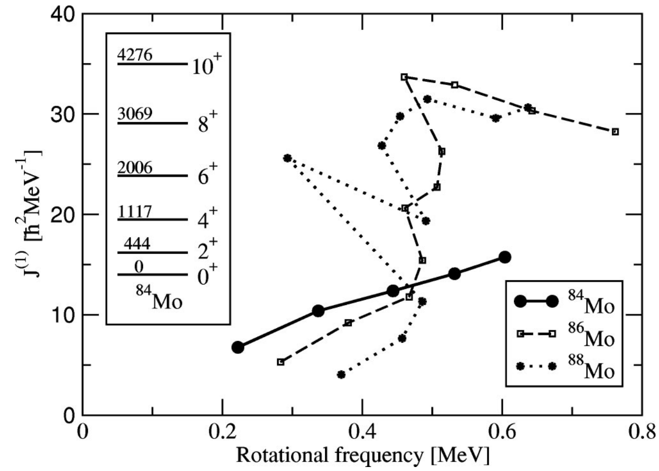

FIG. 2. Kinematic moment of inertia for the ground state bands of ^{84}Mo (present data), ^{86}Mo [17], and ^{88}Mo [18]. The inset shows the level scheme of ^{84}Mo as determined in the present work.

The off-line search for γ-ray transitions in ^{84}Mo in the data of this experiment proceeded as described in Ref. [10], on the basis of γ-γ matrices coincident with charged particles and neutrons, and using also the two lowest known yrast transitions of 444 and 673 keV [13]. The intensity of the $2n$ channel has been estimated to about 10^{-5} of the fusion cross section. The data of the older experiment [13], where we had no coincidences with the neutrons, have also been used in the construction of γ-γ-γ cubes and γ-γ matrices vetoed by, or coincident with, the charged particles. Figure 1 demonstrates the assignment of the higher yrast transitions. The upper two panels show spectra gated by the 444-keV ($2^+ \to 0^+$) transition, on a neutron-coincident *and* charged particle vetoed matrix (a) and on a matrix coincident with both neutrons and protons (b). The 673-keV ($4^+ \to 2^+$) transition assigned in Ref. [13] as the second yrast transition is reconfirmed, and the third yrast transition of 889 keV is clearly seen. These spectra contain also indications about the higher yrast transitions, but due to the low neutron detection efficiency their assignment remained uncertain. It is also seen that this gate is contaminated with transitions from a band structure of ^{83}Zr (channel $2pn$), coincident with a 442-keV line, which were not reported in the previous studies [14]. The lower two panels are doubly gated spectra, with a sum of gates 444 keV/(673+889+1063 keV) on the charged particle vetoed γ-γ-γ cube (c) and on a proton-gated cube (d). The comparison of the two spectra shows very clearly the fourth yrast transition, of 1063 keV, and an indication of the fifth transition at 1207 keV, which coincides with the one from spectrum (a). The gate shown in spectrum (c) is contaminated by the 445-keV/1065-keV coincidence from a band structure in ^{83}Y [15] (channel $3p$) as seen in the lower spectrum (d), but again the lines assigned to ^{84}Mo are not seen in the proton coincidence. Similarly to the proton-gated spectra (b) and (d) of Fig. 1, α-particle-gated spectra do not show the transitions assigned to ^{84}Mo. Thus the combined information from the spectra of Fig. 1 leads to the assignment of the transitions with the energies 673.4(5), 889.1(6), 1063.0(6), and 1207(1) keV to the yrast transitions of ^{84}Mo above the 2^+ state, up to the 10^+ state. For the $2^+ \to 0^+$ transition we found an energy of 443.9(2) keV.

Figure 2 shows the kinematic moment of inertia for the ground state band of ^{84}Mo, in comparison with that of the heavier isotopes ^{86}Mo ($N=Z+2$) [16] and ^{88}Mo ($N=Z+4$) [17]. Near closed shells, as in the case of ^{88}Mo, the nucleus may not have a stable deformation, so that the changes in moment of inertia cannot be easily analyzed in terms of particle alignments. Nevertheless, by using such a representation, the smooth behavior of ^{84}Mo up to the highest rotational frequency reached by the present experiment (0.6 MeV) appears in contrast with that of the heavier isotopes in which proton and neutron alignments occur close to each other around 0.5 MeV. This delay in the alignment frequency is consistent with the previous observations for the other $N=Z$ nuclei with Z between 36 and 44. Although the crossing frequency could not be located by the present experiment, we shall discuss in the following the possible meaning of these data.

To date, there are no quantitative calculations for high spin states in $N=Z$ nuclei above Zr. Very recently, a systematic investigation of the yrast properties of the $N=Z$, $Z+2$, and $Z+4$ Kr, Sr, and Zr nuclei has been reported [18]. The analysis was carried out using the projected shell model (PSM) approach [11,12]. These calculations described well most observables known for these nuclei, with a notable exception: the delay in the crossing frequency in ^{72}Kr claimed in the earlier reference [1]. A more detailed PSM analysis for the $N=Z$ Kr, Sr, and Zr nuclei has been subsequently performed in Ref. [9]. With the assumption that the observed rotational band in ^{72}Kr has a prolate deformation, it was shown [9] that the normal quadrupole-pairing interaction, used as one of the standard interactions in the PSM calculations, is not able to provide the substantial delay observed in ^{72}Kr [2], while calculation with an enhanced residual *np* interaction in the quadrupole-quadrupole channel improved the agreement with the data. It was conjectured that such an enhancement mimics the effect of the *np* pairing which is absent in the PSM. In the present paper, we employ the PSM for ^{84}Mo and ^{88}Ru in the same way as discussed in Refs. [9,18].

The PSM is a spherical shell model truncated in a deformed BCS multiquasiparticle basis [11]. The wave function can be written as

$$|\psi^I_M\rangle = \sum_\kappa f_\kappa \hat{P}^I_{MK_\kappa}|\varphi_\kappa\rangle, \tag{1}$$

where the index κ labels the basis states. Acting on an intrinsic state $|\varphi_\kappa\rangle$, the projection operator $\hat{P}^I_{MK}$ generates states of good angular momentum, thus restoring the necessary rotational symmetry violated in the deformed mean field. The advantage of the PSM approach is that the crossing and mixing of bands at a given angular momentum are treated fully quantum mechanically. This turns out to be crucial to study the present problem since the observed backbendings in the moment of inertia are consequences of the band crossings. A correct treatment of the band crossings is important to avoid large uncertainties in the band crossing region [19].

The Hamiltonian employed in the PSM calculation can be expressed as $\hat{H}=\hat{H}_\nu+\hat{H}_\pi+\hat{H}_{\nu\pi}$, where H_τ ($\tau=\nu,\pi$) is the like-particle pairing plus quadrupole Hamiltonian, with the inclusion of quadrupole pairing,

$$\hat{H}_\tau=\hat{H}^0_\tau-\frac{\chi_{\tau\tau}}{2}\sum_\mu \hat{Q}^{\dagger\mu}_\tau\hat{Q}^\mu_\tau-G^\tau_M\hat{P}^\dagger_\tau\hat{P}_\tau-G^\tau_Q\sum_\mu \hat{P}^{\dagger\mu}_\tau\hat{P}^\mu_\tau, \tag{2}$$

and $\hat{H}_{\nu\pi}$ is the *np* quadrupole-quadrupole residual interaction,

$$\hat{H}_{\nu\pi}=-\chi_{\nu\pi}\sum_\mu \hat{Q}^{\dagger\mu}_\nu\hat{Q}^\mu_\pi. \tag{3}$$

The interaction strengths employed in the present work are the same as those in the previous PSM calculations [9,18].

The PSM results are compared with data for $N=Z$ and $N=Z+2$ nuclei in Fig. 3 in a plot of the kinematic moment of inertia vs rotational frequency. Our calculations were performed with commonly accepted deformations for these nuclei, i.e., $\varepsilon_2=0.28$ for ^{84}Mo, 0.22 for ^{86}Mo, 0.23 for ^{88}Ru, and 0.16 for ^{90}Ru. We note that the PSM calculations are not very sensitive to the choice of the basis deformation because the input deformation parameter serves just to provide a good basis, while the real deformation will be determined dynamically by a later configuration mixing.

Two sets of theoretical calculations are presented for the $N=Z$ nuclei. The full lines are calculated by the standard PSM interaction strengths as used both in Ref. [18] and in all the early PSM calculations, whereas the dashed lines correspond to an enhanced *np* interaction by multiplying a 1.3

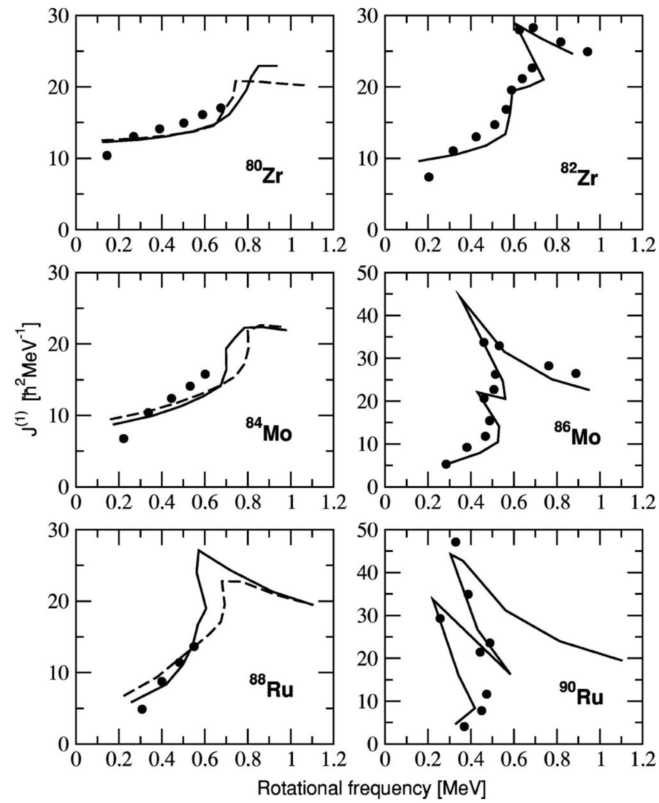

FIG. 3. Comparison of experimental data (dots) and projected shell model calculations. The experimental data are as follows: ^{84}Mo (present data), ^{86}Mo [17], ^{88}Ru [11], ^{90}Ru [20]. For continuity with the study of the $N=Z$ nuclei presented in Ref. [9], ^{80}Zr [2] and ^{82}Zr [21] are also shown. The full lines are the PSM calculations with a standard interaction, the dashed ones with an enhanced neutron-proton residual interaction (see text for details).

factor to $\chi_{\nu\pi}$ in Eq. (3). The implications of the enhanced $\hat{H}_{\nu\pi}$ were discussed in Ref. [9]. Data for the zirconium isotopes 80 and 82 are presented also in this plot to make a connection with the earlier results [9,18].

Figure 3 shows that the standard PSM calculations describe quite well the moments of inertia of the $N=Z+2$ nuclei up to the highest measured spin. They also predict well the known (low spin) data for the $N=Z$ nuclei. For the nuclei studied in this paper, the standard calculations do not differ significantly from those with enhanced *np* interaction. The difference is seen only at higher spins. Unfortunately, experimental data are not available at present to support one of the two calculations. Thus for ^{84}Mo the standard PSM predicts the alignment at $\hbar\omega\approx0.7$ MeV, while with the enhanced $\hat{H}_{\nu\pi}$ the alignment should occur at $\hbar\omega\approx0.8$ MeV; the experimental data are known only up to $\hbar\omega\approx0.6$ MeV. The situation is similar for ^{88}Ru, where the enhanced $\hat{H}_{\nu\pi}$ pushes the alignment from ≈0.6 MeV to ≈0.7 MeV, while the data stop at ≈0.55 MeV. Thus, although the existing experimental data show delays in the alignment frequency in comparison with the neighboring $N=Z+2$ nuclei, one cannot immediately relate this to an enhancement of the *np* interaction. From Fig. 3 one may conclude that at least two or three more yrast transitions are desired in these $N=Z$

nuclei for a better testing of the PSM predictions. Lifetime measurements for the yrast band would be even more restrictive for the theoretical calculations, as they would fix the value of the nuclear deformation.

Two remarks are in order. First, combining the results from the present calculations and those obtained in Ref. [9], one sees that the effect of the np interaction for the band crossing region has an isotonic dependence. Increasing the strength $\chi_{\nu\pi}$ by the same amount does not lead to the same effect in delaying the alignment. The strongest effect was seen for ^{72}Kr and a much weaker one for ^{76}Sr and ^{80}Zr [9]. For the two $N=Z$ nuclei discussed in this paper, ^{84}Mo and ^{88}Ru, the predicted effect is clear but not as pronounced as in ^{72}Kr. Moreover, as one can see in Fig. 3, while in ^{84}Mo and ^{88}Ru the enhanced np interaction causes a delay in the alignment, in ^{80}Zr one gets, on the contrary, an earlier alignment. Alignment frequencies are generally very sensitive to several factors of shape and pairing degrees of freedom [2]. Our results may indicate that at the band crossing region, the np interaction is coupled to these factors in a very complicated way and the influence on the amount of alignment delay depends strongly on the shell filling. Second, increasing the strength of the n-p QQ interaction is nothing but an empirical operation, which mimics the experimental trends and simulates the expected enhanced correlations in the np channel for these $N=Z$ nuclei. A microscopic, self-consistent treatment should include explicitly the n-p pairing term in the basis and a residual part in the Hamiltonian. This work is now under progress [22].

In summary, we have presented new experimental results for the $N=Z$ nucleus ^{84}Mo. The observation of the yrast band has been pushed up to the 10^+ state in this nucleus; its moment of inertia varies smoothly up to a rotation frequency of 0.6 MeV, which shows a delay of the alignment frequency compared to the $N>Z$ isotopes. The nuclei ^{84}Mo and ^{88}Ru have been discussed within the frame of projected shell model calculations, which were performed both with a standard interaction and with an enhanced neutron-proton residual interaction. It is concluded that a definite answer concerning the role of a possible enhanced neutron-proton interaction in the $N=Z$ nuclei above Sr requires the observation of still higher spins in the yrast bands: above spin $12\hbar$ in ^{80}Zr, $10\hbar$ in ^{84}Mo, and $8\hbar$ in ^{88}Ru, and a microscopic, self-consistent treatment in theory.

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