PHYSICS OF THE $N = Z$ AND $N = Z + 1$ NUCLEI IN THE $A = 80$–100 REGION*

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A review of the experimental work performed at the GASP array with the purpose of the identification and first spectroscopic measurements of the heaviest even–even $N = Z$ and odd-A $N = Z + 1$ nuclei (mass larger than 80) is made. Systematic experiments in this mass region led to the first study of seven such nuclei: ^{88}Ru, ^{81}Zr, ^{85}Mo, ^{89}Ru, ^{91}Rh, ^{93}Pd, and ^{95}Ag, and extensive data on many other nuclei in their neighborhood. The systematic evolution of the level structures in both even–even and odd-A nuclei, between $N \approx Z \approx 40$ and $N \approx Z \approx 47$ is briefly presented. The possibility that effects of the neutron–proton pairing have been observed, as well as the type of collectivity observed in this region are discussed.

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1. Introduction

Nuclei with $N = Z$ are unique objects of study in Nuclear Physics due to their exceptional symmetry: equal numbers of neutrons and protons. Of special interest are: many nuclear structure phenomena and their evolution with $N,\ Z$, and spin, arising from the fact that protons and neutrons occupy the same orbitals; the neutron–proton pairing — a genuinely new form of nuclear superfluidity; the study of the isospin symmetry and its breaking;

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and the role of these nuclei in certain astrophysical processes (see previous reviews [1]). In the heavier mass region, just before ^{100}Sn, the heaviest bound $N = Z$ nucleus, the $N = Z$ nuclei are at, or very close to the stability limit, therefore their experimental approach becomes difficult. Here is presented an overview of the progress made in the study of the nuclei along the $N = Z$ and $N = Z + 1$ lines, with the mass above 80.

2. Experiments

Most of the nuclei in this exotic region were studied with the GASP γ-ray array, and a brief survey of these experiments will be given first. The performed experiments are listed in Table I.

TABLE I

The experiments performed with the GASP array, and the most interesting channels measured, bringing new information on the specified $N = Z$ and $N = Z + 1$ nuclei. Except for ^{84}Mo, for which the energy of the first excited 2^+ state was known [12] at the time of our first measurement [2], no spectroscopic information existed for the other nuclei. Studies simultaneous with ours were published for ^{93}Pd [13] and ^{95}Ag [14].

Reaction	Target	Channel	Studied nucleus	$\sigma(\mu$b)	$\sigma(\%\sigma_F)$	Ref.
^{28}Si+^{58}Ni	2×0.5 mg/cm^2	$2n$	^{84}Mo	∼7	$\sim 4\times10^{-5}$	[2,3]
90 MeV		αn	^{81}Zr	∼300	$\sim 2\times10^{-4}$	[4,5]
^{32}S+^{58}Ni	1.1 mg/cm^2	$2n$	^{88}Ru	5–10	$\sim 4\times10^{-5}$	[6]
105 MeV		αn	^{85}Mo	∼130	$\sim 7\times10^{-4}$	[7]
^{40}Ca+^{54}Fe	6.5 mg/cm^2	αn	^{89}Ru	∼40	$\sim(1–2)\times10^{-4}$	[8]
130 MeV		$p2n$	^{91}Rh	∼65	$\sim(2–3)\times10^{-4}$	[9]
^{40}Ca+^{58}Ni	6.0 mg/cm^2	αn	^{93}Pd			[10]
135 MeV		$p2n$	^{95}Ag			[11]

Each of the four fusion-evaporation reactions had as main purpose the study of the even–even $N = Z$ nucleus populated by the $2n$ channel; however, the ^{92}Pd and ^{96}Cd nuclei could not be observed, possibly due to population cross-sections lower than a few μb. The incident energies were chosen rather close to the Coulomb barrier, such as to favor the two-particle evaporation channels over the three-particle ones. The weakest measured channels (^{84}Mo and ^{88}Ru) are about 4×10^{-5} from the fusion cross-section — this being the limit of the sensitivity of these experiments. In the same reactions, $N = Z+1$ nuclei also not known at the time of these studies, were populated in the channels αn or $p2n$, with cross-sections at least one order of magnitude higher (Table I). The γ-rays were detected with the GASP (40 HPGe detectors with a total efficiency of ~ 3 % at 1.3 MeV, and a 80 BGO detectors multiplicity filter). Charged particles were detected with the ISIS ball (40 Si $\Delta E - E$ telescopes), with typical efficiencies of 56–60 % for protons, and 35–38 % for alpha particles. In some experiments, neutrons were detected with N-ring — an array of six liquid scintillator detectors which replaced 6 BGO elements of the multiplicity filter, in the forward direction, having an efficiency of 3–5 %. Gamma-rays were assigned to a nucleus by studying γ–γ coincidence matrices with different conditions on the type and number of evaporated particles (protons, alphas, neutrons), and level schemes were deduced from coincidence relationships observed in such matrices and γ–γ–γ cubes. Experimental details for each case are given in Refs. [2-11].

3. State of the knowledge of $N \approx Z$ nuclei above mass 80

Fig. 1 shows a map of $N \approx Z$ nuclei with mass greater than 80.

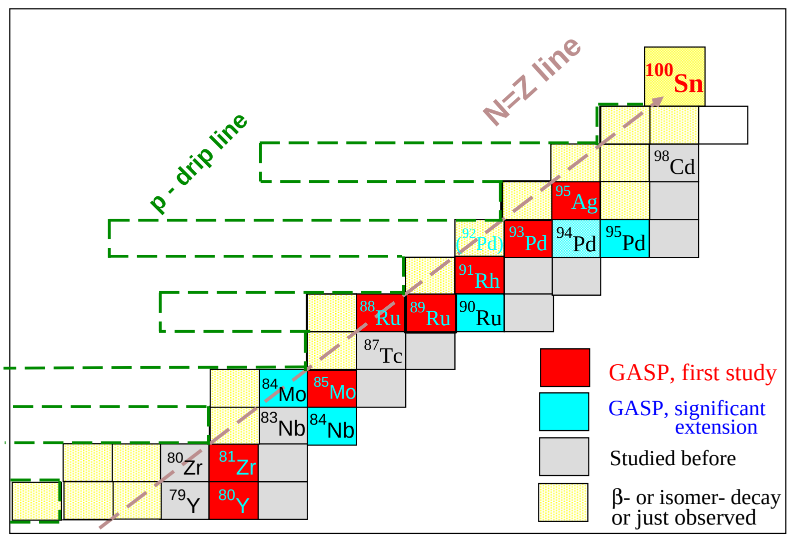

Fig. 1. State of the knowledge of the heaviest nuclei with $N \approx Z$. The proton drip line was calculated in Ref. [15].

Highlighted with different shades are nuclei for which *(i)* spectroscopic studies were performed with the GASP; *(ii)* the GASP studies brought significantly new spectroscopic information; *(iii)* either β-decay or isomeric decay were observed, or were found as bound by observation after an isotope separator (*e.g.*, [16]); and *(iv)* spectroscopic information was available from other studies. The heaviest studied $N = Z$ even–even nucleus is ^{88}Ru [6]), while odd–odd $N = Z$ nuclei are very little studied (see, *e.g.*, ^{86}Tc [17]);

nuclei with $N < Z$ are not known, therefore study of the isospin symmetry in this region is not possible yet; many nuclei predicted as bound were not reached yet. As a rule, for the studied nuclei the existing experimental information are poorer than those usually available for nuclei closer to stability. Below, we present several points of actual interest which can be discussed to a certain depth on the basis of the existing information.

3.1. The $N = Z$ even–even nuclei: Delayed band crossing

The heavy $N = Z$ nuclei are expected to present strong effects of the neutron–proton pairing correlations, which cannot be observed in nuclei closer to stability because of the dominance of the like nucleon correlations. The competition between the pairing and Coriolis forces modifies the moment of inertia at high spins, therefore properties of pairing are observable in the high-spin behaviour. It is expected that effects due to the $T = 0$ np pairing component, which is more robust to rotation (there is no Coriolis antipairing effect in this case), are observable in $N = Z$ nuclei, where they could cause a delay in the rotational frequency of the pair breaking and alignment [18]. The search for such an effect became the main point in the study (both experimental and theoretical) of the heavy $N = Z$ nuclei.

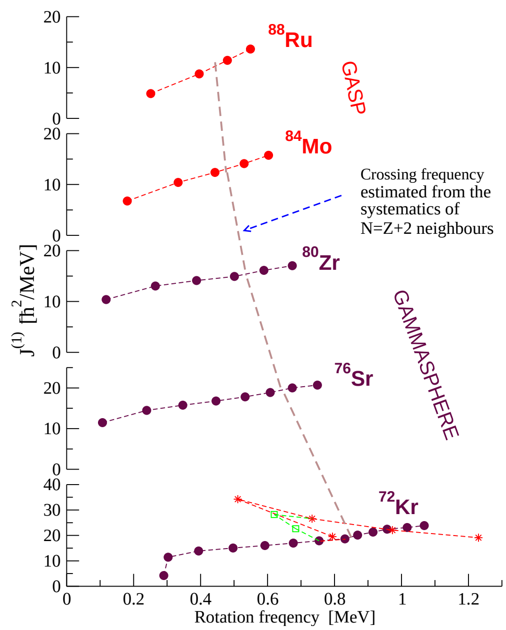

Fig. 2. Kinematic moment of inertia for the yrast bands of the heaviest studied $N = Z$ even–even nuclei. The dashed line shows the expected position of the nucleon pair breaking frequency, as estimated from the $N = Z + 2$ neighbors.

Fig. 2 shows the backbending plot for the yrast bands of the $N = Z$ nuclei above ^{72}Kr. The GAMMASPHERE data are from [19] (^{72}Kr) and [20] (^{76}Sr, ^{80}Zr). No definite evidence for a delayed crossing was finally found for ^{72}Kr [19]. For the heavier nuclei, the figure shows that there may be a systematic delay in the alignment frequency, although for a more precise statement a few more experimental points should be added in each case. It is not clear at present whether the observed hint of delayed crossing, especially in ^{84}Mo and ^{88}Ru, may be taken as an indication of an effect of the $T = 0$ np pairing field. Shifts in the alignment frequencies may be also caused by shape changes, therefore more detailed experiments and selfconsistent microscopic theoretical calculations for these nuclei are needed.

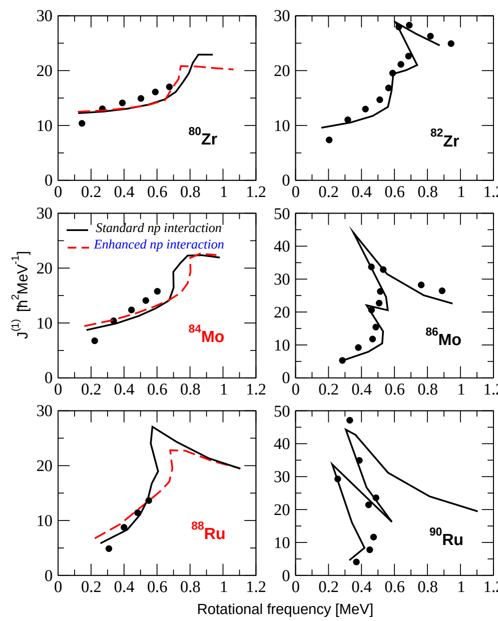

Fig. 3. Experimental backbending plots compared to predictions of the Projected Shell Model (PSM); for the $N = Z$ nuclei, two predictions are shown, one with "standard" parameters (as used for the $N = Z + 2$ nuclei, right-hand side), and one with an enhanced neutron-proton interaction (dashed line).

In Fig. 3 predictions based on PSM (projected shell model) are presented [3]. The experimental features of nuclei with $N > Z$ in this mass region are very well described by such calculations with a "standard" set of parameters, as shown here for the $N = Z + 2$ isotopes. On the other hand, to push the alignment frequency at a higher value, as observed for the $N = Z$ nucleus ^{72}Kr, an *enhanced* residual np interaction (which may mimic the np pairing interaction, absent in these calculations) was needed [21]. For the $N = Z$ nuclei, this type of prediction is also shown in Fig 3; a delay in the alignment frequency is predicted for ^{84}Mo and ^{88}Ru, while for ^{80}Zr the effect is smaller and opposite. Calculations with a spherical shell model with a $P + QQ$ Hamiltonian [22] showed also that in order to describe the ^{88}Ru data one needs an enhancement of the *pn* quadrupole interaction — it is emphasized that the α-like ($T = 0$) $2p$–$2n$ correlations hinder the single nucleon pair alignment until a simultaneous alignment of both proton and neutron pairs takes place at spin $16\hbar$. Thus, while the possible delayed alignment seen in Fig. 2 is intriguing, more work is needed in order to clear up whether these data show indeed effects of the *np* pairing. Experimentally, the yrast band of these nuclei must be measured up to higher spins, and measurements of the deformation along this band (lifetimes) would be needed too, for a non-ambiguous interpretation.

3.2. The $N = Z + 1$ nuclei

3.2.1. Multiple bands in ^{81}Zr

The $N = Z + 1$ nuclei, as neighbors of the $N = Z$ ones, may provide also information about the *np* pairing interactions and their study is easier due to the larger population cross sections (Table I). In the case of ^{81}Zr we obtained rather rich experimental information: three rotational bands [5] assigned to the [422]5/2, [301]3/2, and [431]1/2 Nilsson orbitals, by similarity with structures from its isotone ^{79}Sr [5,23]. The Nilsson single-particle level scheme shows large gaps for $N = 38$ and 40, at a deformation $\beta_2 \approx 0.4$. Due to the position of the Fermi level, one expects that the [422]5/2 band will behave as a "hole" band, *i.e.*, a neutron-hole coupled to the heavier even–even core (^{82}Zr and ^{80}Sr for ^{81}Zr, ^{79}Sr, respectively), whereas the other two bands will be of the "particle" type, a neutron coupled to the lighter core (^{80}Zr, ^{78}Sr).

In Fig. 4 the dynamic moments of inertia of the three bands in ^{81}Zr and ^{79}Sr are compared to those of the neighboring even–even cores, and it is seen that these expected similarities are well obeyed in ^{79}Sr and in the case of the [422]5/2 band in ^{81}Zr. The $g_{9/2}$ proton pair alignment is also observed in the [301]3/2 band of ^{81}Zr, which allows the speculation that this band crossing at $\hbar\omega \approx 0.61$ MeV is an indication on where should be found the backbending in the ^{80}Zr g.s.b. Two intriguing questions require further investigations: *(i)* why this band crossing is *not* observed in ^{80}Zr, and *(ii)* why the [431]1/2 band in ^{81}Zr does not show this band crossing, but evolves smoothly up to higher frequencies. In ^{85}Mo, the [422]5/2 band was observed too, and another band was assigned as [303]5/2 but it was observed only below backbending [7].

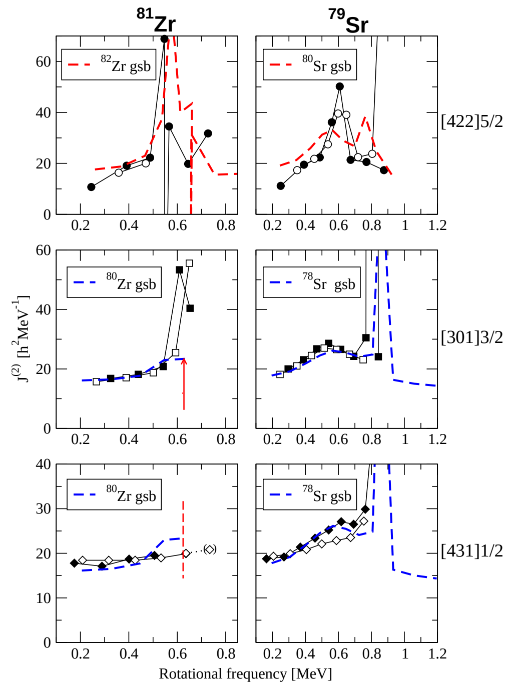

Fig. 4. Dynamic moment of inertia for the three bands in ^{81}Zr and ^{79}Sr, compared with that of the yrast bands in the neighboring even-even nuclei (thick dashed lines) — see text for details.

3.2.2. Higher mass $N = Z + 1$ nuclei

For the studied heavier nuclei, starting with ^{89}Ru, the observed level schemes are not so rich due to lower cross sections [8–11]; in general, only the positive parity yrast levels (based on the $g_{9/2}$ orbital) were observed up to moderately high spins. In ^{95}Ag, due to proximity to $N = 50$ shell closure, a spin-gap isomeric state $(23/2^-)$ predicted long ago by shell model calculations [24] was observed [11, 14]. The ^{89}Ru, ^{91}Rh, ^{93}Pd nuclei show reduced collectivity, and the main features observed could be accounted for by spherical shell model calculations, performed with OXBASH in the $(\pi\nu 2p_{1/2}, 1g_{9/2})$ model space, and using various available residual interactions (a short overview is presented in [9]). However, the positive-parity yrast states are not sensitive to details of the residual interactions (the $p_{1/2}$ orbital is, practically, completely filled in their configurations) and thus do not offer a critical test of all two-body matrix elements.

3.3. Evolution of collectivity and symmetries

Fig. 5 shows the evolution of the yrast states for the even–even $N = Z$ nuclei. For each nucleus are indicated the quadrupole deformation (measured values, or estimated with the Grodzins relation — when marked with the tilde symbol), and the value of the ratio $R_{4/2} = E(4_1^+)/E(2_1^+)$.

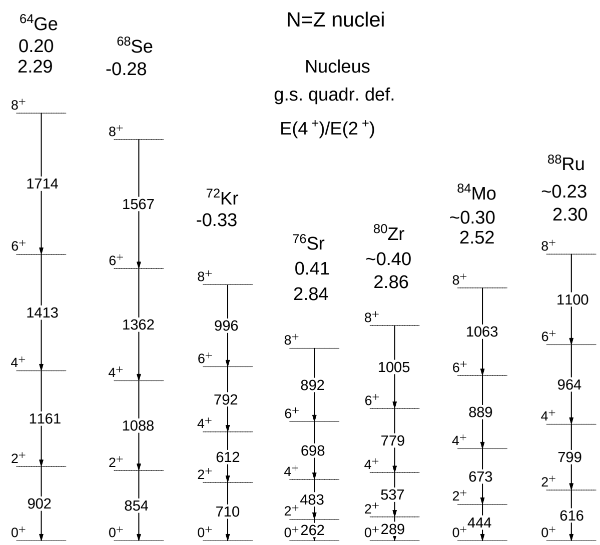

Fig. 5. Systematic of the yrast band of the even–even $N = Z$ nuclei.

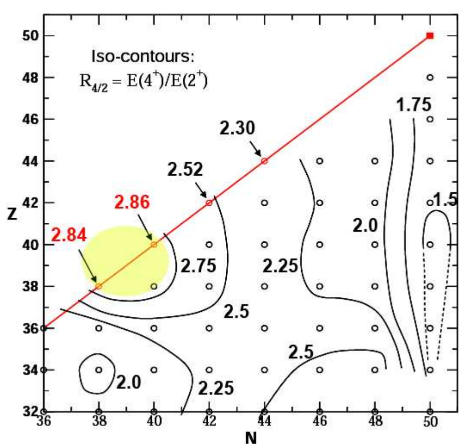

Fig. 6. Map of the variation of the ratio $R(4/2) = E(4_1^+)/E(2_1^+)$ in the region of the heaviest $N \approx Z$ nuclei. The continuous lines are iso-contours of this quantity in steps of 0.25, and particular values are marked for several $N = Z$ nuclei.

A maximum of collectivity is observed for ^{76}Sr and ^{80}Zr, then, with increasing mass, the structure evolves gradually towards that of a vibrator. Fig. 6 shows an alternative view of this evolution. Nuclei in the vicinity of $N = Z = 38, 40$ form a region ("island") of deformation, with a rather large quadrupole deformation at low spin, $\beta_2 \approx 0.40$.

In spite of this, the $R_{4/2}$ values (around 2.85) show that these nuclei are still far from good rotors (3.33), therefore a natural question is what kind of "transitional" structure do they realize. Note that this $R_{4/2}$ value is close to 2.91, the prediction of the X(5) symmetry [25], the critical point of the phase shape transition between the dynamical symmetries SU(3) — symmetric rotor and U(5) — anharmonic vibrator. An examination of the yrast (ground state) bands of nuclei in this mass region shows indeed that ^{76}Sr, ^{78}Sr, and ^{80}Zr are closer to the X(5) prediction than to that of rotor or vibrator. However, other specific predictions of the model must be investigated for a more precise statement. A more comprehensive survey of the low-spin properties of nuclei in this region was performed. The data collected in the experiments listed in Table I allowed the assignment of the quasi-γ bands in some nuclei in which they were not known. Thus, several states of the quasi-γ bands were determined for the first time in ^{78}Sr, ^{86,88}Mo, and additional states were found in ^{80}Sr, ^{82,84}Zr. Then, the Sr, Zr, and Mo isotopes with $N \leq 46$ were investigated within the IBA model. A consistent-Q Hamiltonian was used for this purpose, which, up to a normalization constant is:

$$H = (1-\zeta)\hat{n}_d - \frac{\zeta}{4N}(\hat{Q}\cdot\hat{Q}) \quad \text{with} \quad \hat{Q} = s^\dagger\tilde{d} + d^\dagger s + \chi[d^\dagger\tilde{d}]^{(2)}\,.$$

The two parameters ζ and χ were determined by minimizing a merit function which considered energies and energy ratios in both the yrast (g.s.b.) and quasi-γ band, as well as the branching ratios of the low-lying states in the quasi-γ band. We define new parameters

$$x = \zeta\,\frac{1}{1+\frac{|\chi|}{\sqrt{7}/2}}\,, \quad y = \frac{\zeta\,|\chi|}{\sqrt{7}/2}\,.$$

The results for these nuclei can be represented in the (x, y) plane, and compared to the "points" representing different symmetries, and this is shown in Fig. 7. The lighter Sr and Zr isotopes are close to the X(5) point. Thus, the $N, Z \approx 38, 40$ region appears as a "X(5) island", with nuclei that may approximate X(5) symmetry better than in other mass regions.

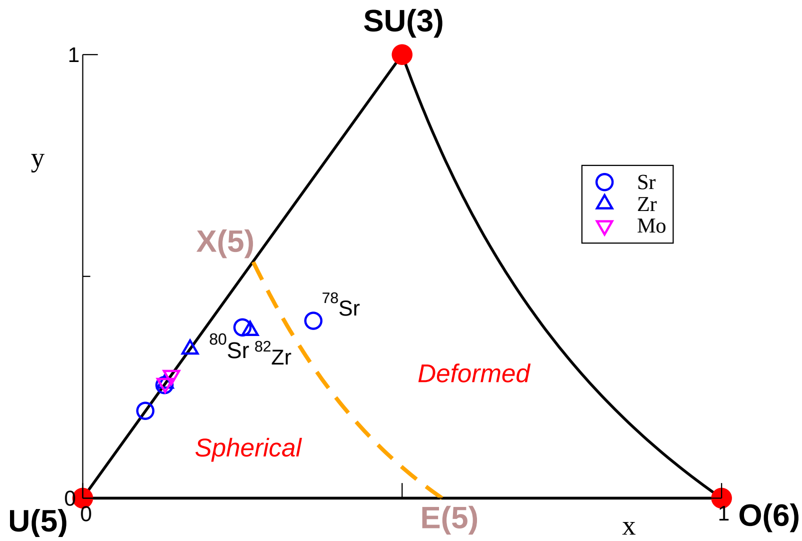

Fig. 7. Placement of the Sr, Zr, and Mo nuclei with $N \leq 46$ within the symmetry triangle, drawn in the (x, y) plane (see text).

4. Conclusions

Experiments during the last few years extended considerably our knowledge of the heaviest $N = Z$ and $N = Z + 1$ nuclei (Fig. 1). The study of these nuclei by fusion-evaporation reactions with stable ion beams is, however, difficult due to the low population cross-sections. The available experimental data allowed a glimpse on subjects of actual interest in this region. The quest for the neutron–proton pairing requires observation of the yrast bands of the $N = Z$ even–even nuclei and of bands in neighbouring deformed odd-mass nuclei at still higher spins; measuring the deformation of these states is also highly desirable. Shell model predictions could be tested for several $N = Z + 1$ nuclei with $N \geq 45$. The structure evolution in this region reveals that at $N \approx Z = 38, 40$ there may be an "island" with X(5) critical point properties. Spectroscopic studies of the odd–odd $N = Z$ nuclei, also important for the np pairing problem, are waited for.

New results such as, *e.g.*, the extension of the yrast bands of ^{84}Mo and ^{88}Ru at higher spins, or the identification of excited states in ^{92}Pd, could be obtained at present with stable beams and existing γ-ray arrays. On the other hand, future experiments with radioactive ion beams and next generation γ-ray arrays will bring significant contributions to a more detailed knowledge of this exotic nuclear region.

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