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Forward on the N = Z line with GASP

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Abstract. The experimental study of the proton-rich nuclei close to the $N = Z$ line is a constant challenge for nuclear spectroscopy, mainly due to the difficulty to produce them with the currently available beam/target combinations. Significant advances on this direction were obtained from experiments performed with the GASP array during the last two years: the yrast line of ^{84}Mo was extended up to 10^+, ^{88}Ru observed for the first time, and the $N = Z + 1$ line was mapped from ^{81}Zr to ^{95}Ag. These new results allow us to have a more complete image of the transition from the well-deformed shell closure at $N, Z = 40$ to the spherical-shell closure at $N, Z = 50$, and highlights some particular effects that can be observed only in the vicinity of the $N = Z$ line.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 21.10.Pc Single-particle levels and strength functions – 21.10.Re Collective levels – 23.20.-g Electromagnetic transitions

1 Introduction

Since the beginning of nuclear spectroscopy, there exists a constant interest for the experimental study of the nuclei located on or close to the $N = Z$ line. This is the only place all along the nuclide chart where one can find answers for fundamental problems of nuclear physics such as the charge independence of nuclear forces or the role of both isoscalar and isovector components of the pairing interaction in the building of nuclear superfluidity. Above $A \approx 70$ the $N = Z$ line lies very close to the proton drip line and the properties of the very proton-rich nuclei of the region are valuable tests for the predictions of the nuclear models, one good example being the nuclear shell model in the region close to the predicted doubly magic nucleus ^{100}Sn. Another scientific interest comes from nuclear astrophysics: most of the nuclei on the path of rp-process are nuclei very close to $N = Z$ region. Some of their properties (binding energy, deformation, beta-decay rates, lifetimes of low-lying isomeric states, etc.) are key ingredients for the rp-process description.

To obtain new experimental data on heavy $N \approx Z$ nuclei is not a trivial task. While below $A \approx 60$ self-conjugated isotopes are close to the stability valley and relatively easy to populate in heavy-ion fusion-evaporation reactions, with the increase of the mass number they become more and more difficult to produce with currently available beam/target combinations. The development of high-efficiency Ge arrays as GASP, GAMMASPHERE or EUROBALL and of the associated ancillary detectors gave the possibility to study nuclei produced with cross-sections of the order of few μb. In the last few years, with the use of this un-preceded resolving power, it was possible to extend the study of the $N \approx Z$ nuclei up to the region close to ^{100}Sn. This paper is intended to be a review of the recent experimental results obtained with the GASP array for the heavier $N = Z, Z + 1$ nuclei studied until now, the ones located in the 80–95 mass region.

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2 The experiments

With its 3% absolute efficiency, the GASP array [1] is not anymore on the front line of Ge arrays, dominated by GAMMASPHERE and EUROBALL arrays with absolute efficiencies of 10% and 7%, respectively. Considering also its excellent Compton rejection and energy resolution, one see that the GASP array has a good resolving power and can separate reaction channels produced with cross-section down to a few μb. In the experiments presented in the following we used a common experimental setup, consisting in GASP, coupled with the ISIS silicon telescope array for charged-particle detection, and with the Neutron Ring array for neutron detection. We obtained with ISIS experimental detection efficiencies for the charged particles in the range of 57–60% for one proton, and 33–37% for one alpha particle. The Neutron Ring array consists of six liquid scintillator (BC501A) filled detectors, which replace the six most forward of the 80 detectors of the BGO multiplicity filter. The experimental neutron detection efficiency obtained with Neutron Ring was in the range of 3.0–3.7%, depending on the reaction kinematics.

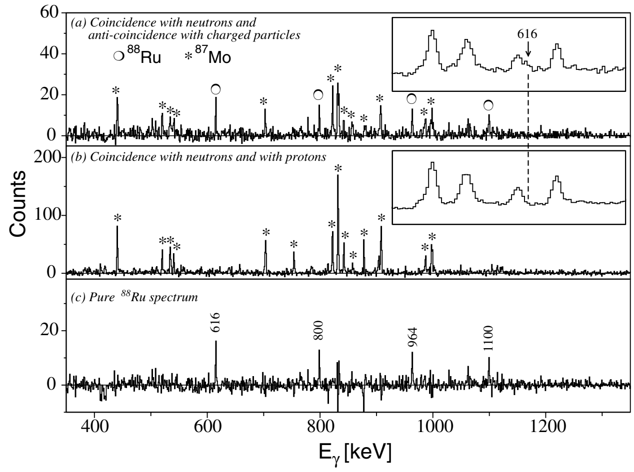

Fig. 1. Sum of gates on the 616, 800 and 964 keV lines of ^{88}Ru in γ-γ matrices (a) in coincidence with one or more neutrons and anti-coincidence with charged particles, and (b) in coincidence with any numbers of neutrons and protons. The spectrum in (c) is the difference between the upper two, normalized according to the measured proton detection efficiency. The insets show pieces of the matrix projection relevant for the situation of the 616 keV line, the $2_1^+ \rightarrow 0_1^+$ transition of ^{88}Ru.

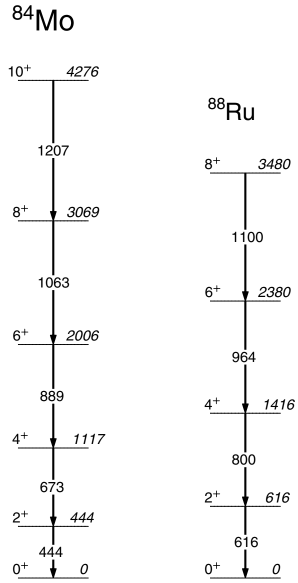

Fig. 2. Level schemes proposed for the $N = Z$ nuclei ^{84}Mo and ^{88}Ru.

We used the following reactions to populate proton-rich nuclei in the mass region 80–100:

^{28}Si(90 MeV) + ^{58}Ni, thin target;
^{32}S(105 MeV) + ^{58}Ni, thick target;
^{40}Ca(130 MeV) + ^{54}Fe, thick target;
^{40}Ca(135 MeV) + ^{58}Ni, thick target.

One common feature in all these experiments is the bombarding energy chosen close to the Coulomb barrier. The low incident energy limits the number of the particles evaporated from the compound nucleus, and makes possible to obtain clean selection for almost all isotopes produced in reaction using neutron and charged-particle coincidence.

3 N = Z nuclei

The recent construction of the Neutron Ring array brought significant increase in the resolving power of GASP for the study of very proton-rich nuclei. In one of the first experiments performed after the commissioning of Neutron Ring, the reaction ^{32}S(105 MeV) + ^{58}Ni, we identified for the first time γ transitions from ^{88}Ru [2], until now the heaviest $N = Z$ nucleus studied by γ-ray spectroscopy. The spectra shown in fig. 1 are relevant for the good quality of experimental data: four gammas belonging to ^{88}Ru (the $2n$ channel) are clearly observed in coincidence with neutrons and in anti-coincidence with charged particles. We estimated from data that ^{88}Ru is produced at the level of $\sim 4 \cdot 10^{-5}$ of the summed intensity of all reaction channels, which means 5–10 μb if we normalize to the total fusion cross-section calculated with CASCADE.

The other $N = Z$ nucleus studied was ^{84}Mo. In a previous GASP + ISIS experiment [3] the $4_1^+ \rightarrow 2_1^+$ γ transition of ^{84}Mo was identified. Using the Neutron Ring in our recent ^{28}Si(90 MeV) + ^{58}Ni experiment we extend its yrast line up to the 10^+ state. Details about data analysis are presented in ref. [4].

The level schemes obtained for ^{84}Mo and ^{88}Ru are shown in fig. 2. Both nuclei present regular yrast sequences, with no sign of quasi-particle alignment. This contrasts with the behaviour of their closest $N = Z + 2$ neighbouring nuclei where the alignment appears at rotational frequencies smaller than the highest ones observed in both ^{84}Mo and ^{88}Ru. Moreover, similar shifts of alignment toward higher rotational frequencies were observed in all lighter even-even $N = Z$ nuclei beginning with ^{72}Kr [5,6].

The behaviour at high spins of the heaviest even-even $N = Z$ nuclei with known excited states is illustrated in fig. 3. The dashed line marks the rotational frequency where the first back- or up-bend appears in the closest even-even $N = Z + 2$ neighbours. One must note that in this mass region the position of the first backbend (or upbend) does not change too much from an even-even nucleus to its closest even-even neighbours and the value obtained from systematics is always a good approximation. It is obvious that the five $N = Z$ nuclei represented in fig. 3 do not obey this rule and the first quasi-particle alignment, when identified, appears significantly delayed with respect to the neghbouring nuclei.

4 N = Z + 1 nuclei

Prior to our experiments the heaviest $N = Z + 1$ nuclei studied were ^{77}Sr, ^{83}Nb, and ^{87}Tc. We identified ^{81}Zr from our first ^{28}Si(90 MeV) + ^{58}Ni experiment [3], and a

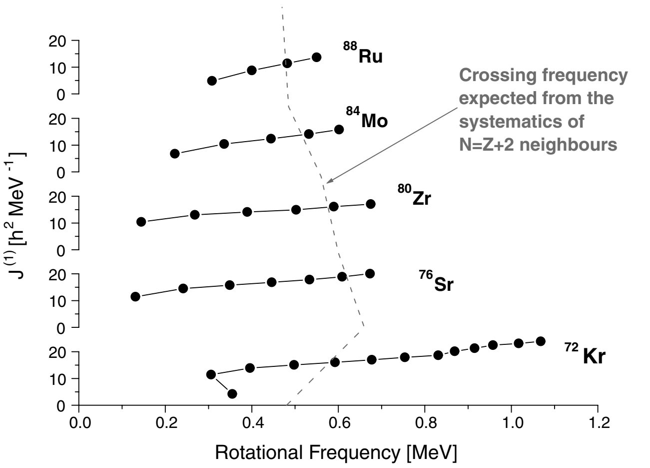

Fig. 3. Systematics of the dynamic moment of inertia function of rotational frequency for the even-even $N = Z$ nuclei from ^{72}Kr to ^{88}Ru. Experimental data for ^{72}Kr, ^{76}Sr and ^{80}Zr are taken from [6].

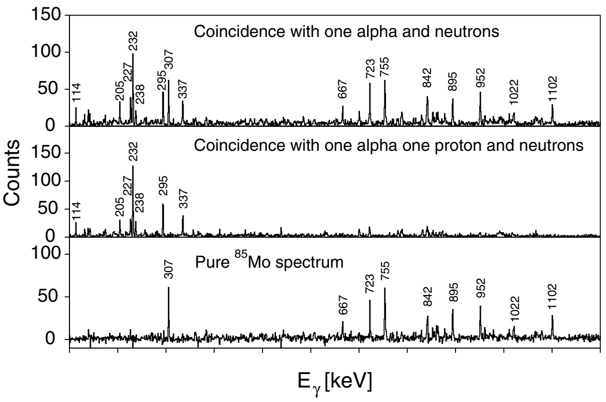

Fig. 4. Spectra demonstrating the assignment of γ-rays to ^{85}Mo, αn channel in the reaction ^{32}S(105 MeV) + ^{58}Ni.

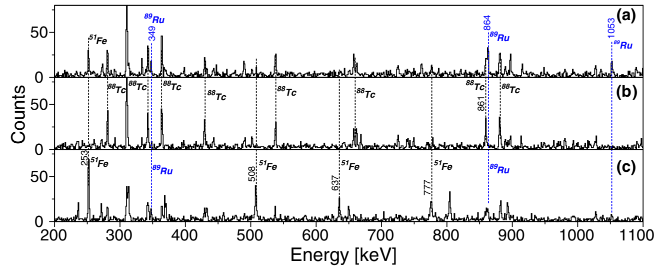

Fig. 5. Spectra demonstrating the assignment of γ-rays to ^{89}Ru, αn channel in the reaction ^{40}Ca(130 MeV) + ^{54}Fe: (a) spectrum coincident with one α-particle and neutrons and non-coincident with protons with low oxygen contamination in the target, (c) the same but with strong oxygen contamination and (b) spectrum coincident with one α-particle, one proton and neutrons.

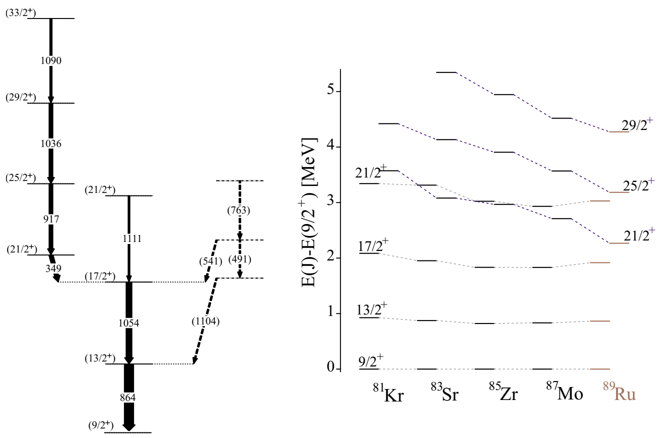

Fig. 6. The level scheme proposed for ^{89}Ru and the systematic of positive-parity yrast states in odd-A $N = 45$ isotones.

level scheme for this nucleus was published in ref. [7]. This level scheme was significantly extended from the most recent ^{28}Si(90 MeV) + ^{58}Ni experiment. The analysis of this nucleus is still in progress and will be presented in a forthcoming paper.

The ^{85}Mo nucleus was populated as αn channel in the reaction ^{32}S(105 MeV) + ^{58}Ni. First, γ-rays belonging to this nucleus were identified in the γ spectrum coincident with one α-particle and neutrons, shown in fig. 4. Afterwards, the level scheme of this nucleus was built from the analysis of γ-γ coincidences. From experimental data we deduced that the cross-section for ^{85}Mo was about 7×10^{-4} of the fusion cross-section. Details about data analysis and the level scheme proposed for ^{85}Mo were published in ref. [8].

The ^{89}Ru nucleus was populated as αn channel in the reaction ^{40}Ca(130 MeV) + ^{54}Fe. As for the ^{85}Mo, the most intense γ-rays of ^{89}Ru were identified in the spectrum coincident with α-particles and neutrons. Since the oxygen accumulated in the ^{54}Fe target during the experiment, in the spectrum are present also γ-rays from ^{51}Fe, the αn channel in the reaction on ^{16}O. The γ-rays belonging to ^{89}Ru were thus firmly established by comparing a spectrum coincident with one α-particle and neutrons and non-coincident with protons, obtained from a subset of data where the oxygen contamination was small, with a spectrum coincident with one α-particle, one proton and neutrons from the same data sub-set, and with a spectrum coincident with one α-particle and neutrons and non-coincident with protons from a data sub-set in which the oxygen contamination was strong. These spectra are shown in fig. 5. The intensity of the αn channel was estimated from experimental data to be about 2×10^{-4} of the fusion cross-section.

The level scheme deduced for ^{89}Ru fits well in the systematics of odd-A, $N = 45$ isotopes (fig. 6). The positive-parity yrast sequence is based on the $1g_{9/2}$ orbital and is crossed by a 3-qp band at spin $21/2^+$. One observes from the systematics that the 3-qp band comes lower in energy with increasing Z, this effect being stronger in ^{89}Ru than in any of its isotones.

The ^{91}Rh nucleus was populated as $p2n$ channel in the same reaction. The first identification of γ-rays from the decay of this nucleus was done using the coincidence with charged particles and neutrons. Several γ-rays, marked

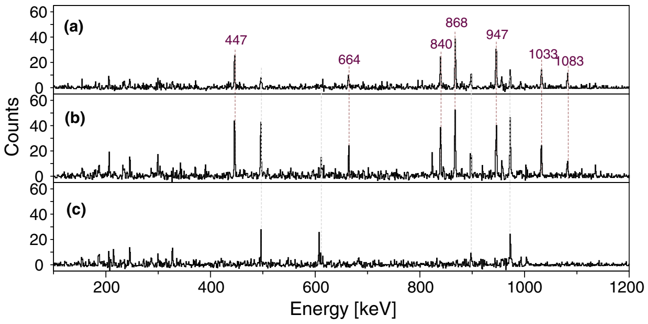

Fig. 7. Spectra demonstrating the identification of ^{91}Rh: sum of gates on marked γ-rays in matrices in coincidence with neutrons and (a) zero charged particles, (b) one proton, and (c) two protons.

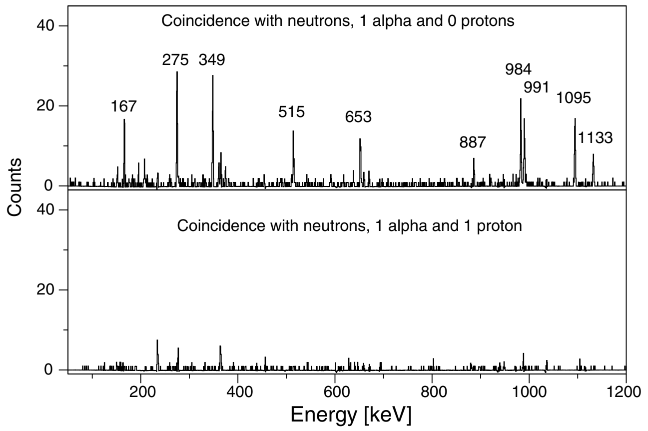

Fig. 8. Sum of gates on γ transitions assigned to ^{93}Pd in γ-γ matrices in coincidence with neutrons and one α-particle (top panel), and neutrons, one α-particle and one proton (bottom panel). The γ-rays marked by their energy belong to ^{93}Pd and are not present in coincidence with protons.

with their energy in fig. 7, were observed in coincidence with one proton and neutrons, and they were not observed in coincidence with two protons or α-particles. For a γ-ray, the neutron multiplicity can be obtained from the ratio of its intensity when observed in coincidence with neutrons to total intensity. For the transitions marked in fig. 7 this ratio is consistent with neutron multiplicity two, thus they were firmly assigned to the $p2n$ channel, the nucleus ^{91}Rh. The intensity of this reaction channel was deduced to be about 4×10^{-4} of the fusion cross-section.

The ^{93}Pd nucleus was produced as αn channel in the ^{40}Ca(135 MeV) + ^{58}Ni reaction. As for ^{85}Mo and ^{89}Ru, the most intense γ-rays of ^{93}Pd were identified from the γ spectrum obtained by setting coincidence conditions with one α-particle and neutrons (see fig. 8). Afterwards, the level scheme was completed from the analysis of γ-γ coincidences. The multipolarities for the γ-ray transitions were obtained from the analysis of angular distributions, leading to the tentative spin and parity assignments given in fig. 9.

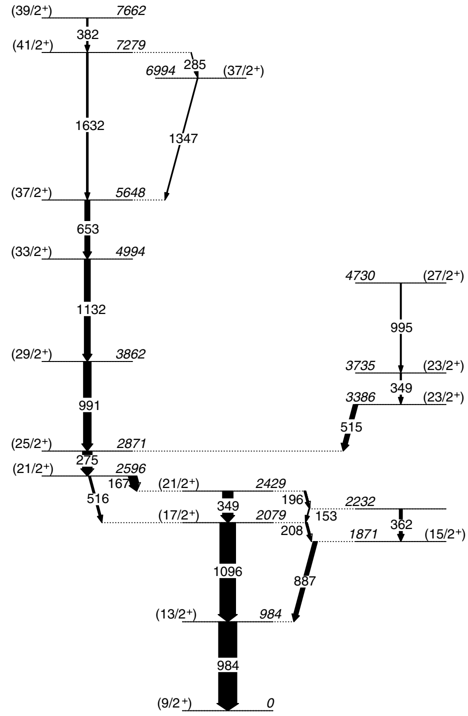

Fig. 9. The level scheme proposed for ^{93}Pd.

5 Spin-gap isomeric states

Shell model calculations in the $(p_{1/2}, g_{9/2})$ subshells have shown that spin-gap isomers could possibly occur in proton-rich Pd-Ag-Cd isotopes [9,10]. This is a direct consequence of the properties of effective interaction between protons and neutrons in the $1g_{9/2}$ orbit and it was shown to depend rather critically on the value of the two-body matrix element $\langle g^2_{9/2}|V_{pn}|g^2_{9/2}\rangle_{J=9}$ [9]. The first $21/2^+$ state of ^{95}Pd, the first $23/2^+$ state of ^{95}Ag, and the yrast 16^+ state of ^{96}Cd were theoretically predicted to be spin-gap isomers.

In ^{95}Pd, a high-spin isomeric state with a half-life of 14 s decaying by both β^+/EC and β-delayed proton emission has been discovered [11,12]. On the basis of its β^+-decay pattern, this state was assigned as being the $21/2^+$ isomer predicted by shell model calculations. Later γ-ray spectroscopic investigations have assigned excited states above this isomeric level but its real position has still remained unknown, as the excited states above the ground state could not be observed [13]. Recently, several low-spin states in ^{95}Pd were reported from the β^+/EC-decay of the ground state of ^{95}Ag [10]. The β^+/EC-decay from the predicted spin-gap isomeric state of ^{95}Ag was not observed, suggesting that, if exists, this state should decay by γ transitions.

The ^{95}Pd nucleus was populated as $2pn$ channel in our experiment ^{40}Ca(135 MeV) + ^{58}Ni. We observed the 1262 keV γ-ray, which comes from the decay of the lowest excited state known in this nucleus directly to the ground state. A relatively strong 1351 keV transition was observed in coincidence with two protons an one neutron, thus belongs to the $2pn$ channel. The presence of a transition at

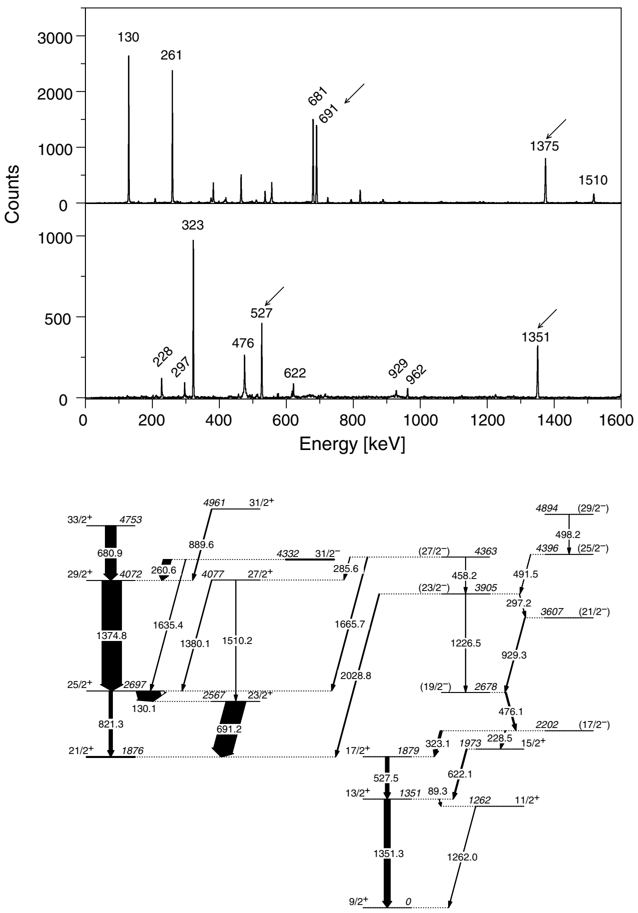

Fig. 10. Top: sum of gates on γ transitions (indicated with arrows) above and below the $21/2^+$ isomer of ^{95}Pd from γ-γ matrix in coincidence with two protons and one neutron, and bottom: the low-spin part of the level scheme deduced for ^{95}Pd.

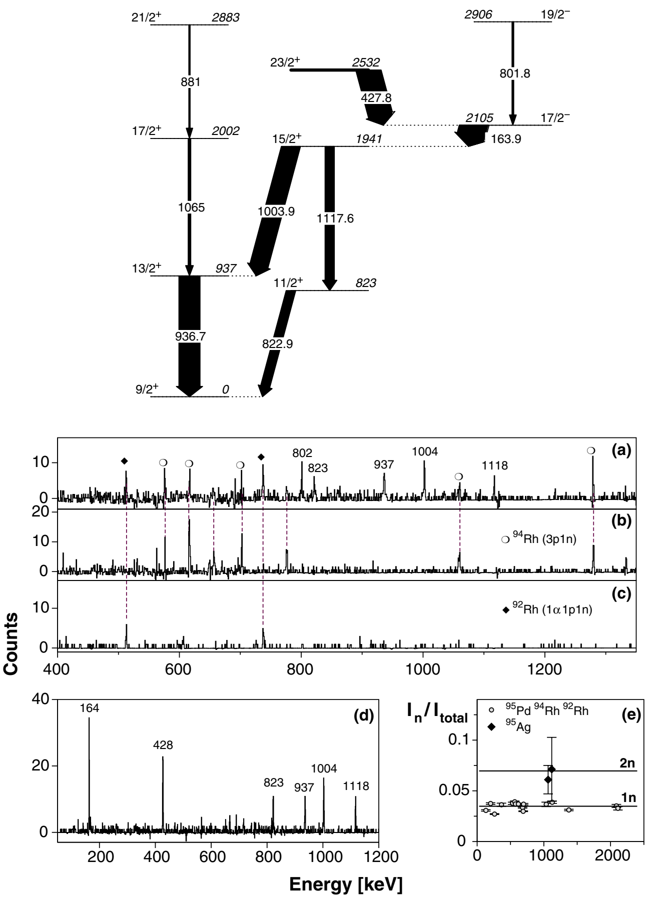

Fig. 11. Top: the level scheme proposed for ^{95}Ag and bottom: spectra that support its deduction. (a) A gate on the 164 keV transition, on a matrix coincident with neutrons and zero or one protons; (b) a gate on the same line on a matrix coincident with neutrons and at least two protons; (c) the same gate on a matrix coincident with neutrons and α-particles; (d) sum of double gates on different transitions assigned to ^{95}Ag, on a cube vetoed by charged particles. (e) Relative neutron multiplicity estimated for the 1065 and 1118 keV transitions assigned to ^{95}Ag and for transitions from channels with one evaporated neutron.

89 keV in coincidence with the 1262 keV line proves the existence of the 1351 keV level in ^{95}Pd, that decays mainly to the ground state. Starting from this observations, we have built up the level scheme of ^{95}Pd starting from the ground state. We identified several γ-rays that connect the states from the part of the level scheme built on the ground state with states from the part of the level scheme built on the isomeric level. Consequently, the excitation energy of the $21/2^+$ isomer was firmly established to be 1876 keV, with 3 keV lower than the excitation energy of the yrast $17/2^+$ state (see fig. 10).

In the same reaction, the $N = Z + 1$ nucleus ^{95}Ag was populated as $p2n$ channel. Several γ-rays were observed as being in prompt coincidence with one proton and neutrons and were absent in coincidences with two protons or α-particles. On the basis of the proton and neutron multiplicities, these transitions were assigned to the prompt decay of ^{95}Ag. Five of these γ transitions were observed to be in coincidence with a 428 keV line, only if we asked for anti-coincidence with charged particles and neutrons. Given the high efficiency achieved for charged particle detection, this anti-coincidence condition selects the γ cascades following the decay of isomeric states with lifetimes larger than 10 ns. These cascades are delayed with respect to the reaction, thus cannot come in prompt coincidence with charged particles. Consequently, the lines shown in the spectrum (d) from fig. 11 must come following the decay through the 428 keV γ transition of an high-spin isomeric state of ^{95}Ag. This isomeric state was tentatively identified with the $23/2^+$ isomeric state predicted in ^{95}Ag [9,10].

6 Summary

Following a campaign of four GASP experiments performed in the last two years, we obtained many new experimental results for the heaviest $N = Z, Z + 1$ nuclei studied until now by γ-ray spectroscopy. On the $N = Z$ line, the yrast sequence of ^{84}Mo was extended up to 10^+

and excited states were identified for the first time in ^{88}Ru. With the first observation of excited states in ^{81}Zr, ^{85}Mo, ^{89}Ru, ^{93}Pd and ^{95}Ag, the experimental study of the $N = Z + 1$ nuclei was extended up to the region close to the double magic nucleus ^{100}Sn. The previously unknown excitation energy of the $21/2^+$ isomeric state observed in ^{95}Pd was firmly established and it was demonstrated that this state is a spin-gap isomer. A high-spin isomeric state was identified in ^{95}Ag and it was identified with the $23/2^+$ spin-gap isomer predicted by shell model. All this new experimental data allows to test the predictive power of the actual nuclear-structure models and contributes to the understanding of the physics of this exotic region located far away from the stability line.

In this review were shown results that are coming from the work of many physicists, and the author likes to thank all who contributed to the experiments presented here: C. Rossi Alvarez, D. Bucurescu, C.A. Ur, D. Bazzacco, S. Lunardi, G. de Angelis, M. Axiotis, E. Farnea, A. Gadea, M. Ionescu-Bujor, A. Iordăchescu, W. Krolas, Th. Kröll, S.M. Lenzi, T. Martinez, R. Menegazzo, D.R. Napoli, P. Pavan, M. De Poli, B. Quintana, P. Spolaore, R. Venturelli and J. Wrzesinski.

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