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Observation of the $N=Z=44$ ^{88}Ru nucleus

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Four γ-ray transitions belonging to the ground state band of the $N=Z$ nucleus ^{88}Ru are reported for the first time. The reaction ^{58}Ni(^{32}S,$2n\gamma$) at 105 MeV has been used, and the prompt γ rays were detected with the GASP array. The assignment of γ rays to ^{88}Ru was made by combining information from GASP, the ISIS silicon ball, and the n-Ring neutron detector. The ^{88}Ru nucleus is weakly deformed, with an $E(2^+)$ energy of 0.616 MeV and $E(4^+)/E(2^+)$ ratio of 2.30. The evolution of the nuclear structure along the $N=Z$, $N=44$, and $Z=44$ lines is discussed. Unlike in other nuclei from the region, no sign of backbending is seen in ^{88}Ru at a rotational frequency of ≈ 0.5 MeV, which might be a signature of the $T=0$ neutron-proton pairing in the $N=Z$ nuclei.

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The study of nuclei with equal numbers of neutrons and protons ($N=Z$) presents a special interest due to several unique characteristics. Up to ^{100}Sn, probably the heaviest such nucleus which is bound, the protons and neutrons occupy the same shell model orbitals. Because of this, the effects of shell gaps become very strong and determine rapid shape changes with N, Z, and spin. As a matter of fact, the even-even nuclei which could be studied until now have already revealed a rich variety of such phenomena. In ^{72}Kr there is a shape coexistence strongly manifesting itself in the lowest excited states [1]. The $N=Z=38$ and 40 nuclei (^{76}Sr and ^{80}Zr) have the largest ground-state deformation known [2,3]. The next even-even nucleus investigated, ^{84}Mo [4,5], appears much less deformed, indicating a rather rapid transition towards the spherical ^{100}Sn.

Undoubtedly, the strongest motivation for studying the $N=Z$ nuclei is given by the possibility of evidencing effects of the neutron-proton ($n-p$) pairing interaction. We expect $n-p$ pairing both with isospin $T=1$ and $T=0$, which will compete with the "usual" $T=1$ like nucleon pairing. The pairing between like nucleons is extremely important in nuclei and has been extensively studied. In the $N\neq Z$ nuclei it strongly overweight the effects of the $n-p$ pairing, due to the much larger number of like pairs. In the $N=Z$ nuclei the $n-p$ pairing should be relatively enhanced, and it is likely that only here will it be possible to observe its effects on the nuclear properties.

It is much discussed in the literature how one can recognize the effects of the $n-p$ pairing. Although in principle even the simplest properties, such as, e.g., in the even-even nuclei, the energy of the first excited 2^+ state $[E(2_1^+)]$, the ratio $E(4_1^+)/E(2_1^+)$, etc., should be modified, it is difficult, at present, to recognize unambiguously their signature. Nevertheless, extending our knowledge on the $N=Z$ nuclei in the higher mass region may be rather valuable, as a better systematic of their properties may reveal differences with respect to the behavior of other nuclei. In this respect one should note that, unlike in the heavier mass regions, the transition from the well deformed ^{76}Sr and ^{80}Zr nuclei to the spherical (doubly magic) ^{100}Sn is the only one which may be sizably influenced by the $n-p$ pairing effects. This systematic approach is especially interesting if one can get information on the higher spin states.

Since the $n-p$ pairing (especially the $T=0$ one) is more robust against rotation, it has been suggested that one of its possible signatures might be a delay in the rotational frequency where the Coriolis force begins to break the nucleon-nucleon correlations (particle alignment). Such effects have been reported so far in ^{72}Kr [1,6] and ^{76}Sr, ^{80}Zr [6], and therefore it is important to investigate heavier nuclei in this respect. One should emphasize, however, that the discussion of the $n-p$ pairing question has to be placed in the more complicated context of the complex interplay of pairing correlations, deformations, and angular momentum.

Going towards the highest masses (above $A=70$), the $N=Z$ nuclei become, nevertheless, increasingly difficult to investigate. With the available (stable) target-projectile combinations they are populated with extremely small cross sections compared to the huge background created by other reaction channels. Due to the low yield, the spectroscopic experimental information that could be obtained for the heaviest $N=Z$ nuclei investigated so far is rather rudimentary and consists mainly of a few yrast levels observed through their γ-ray decay. Even so, it is nevertheless valuable for getting a first insight into the nuclear structure evolution towards the very exotic ^{100}Sn nucleus. At present, the heaviest $N=Z$ even-even nucleus for which some experimental information on the excited states exists is ^{84}Mo [4,5].

The purpose of this Rapid Communication is to present

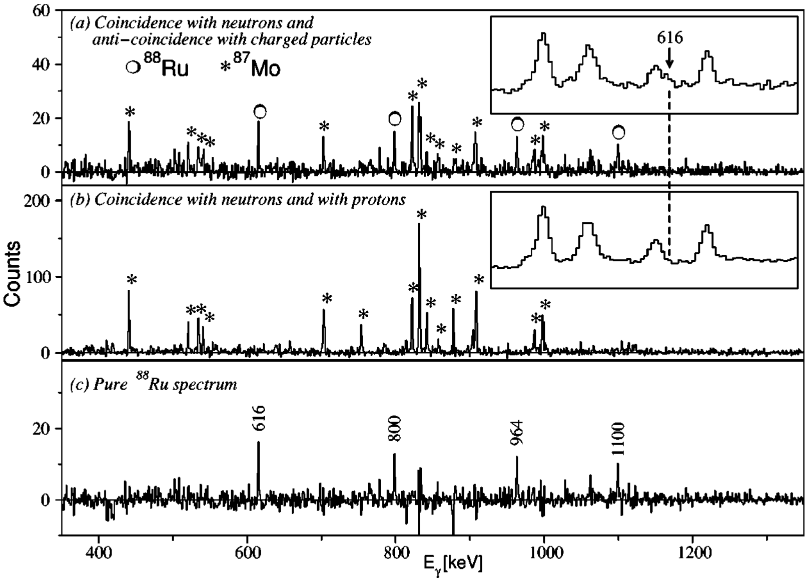

FIG. 1. Sum of gates on the 616, 800, and 964 keV lines in γ-γ matrices (a) in coincidence with one or more neutrons and anticoincidence with charged particles, and (b) in coincidence with any numbers of neutrons and protons. The spectrum in (c) is the difference between the upper two, normalized according to the measured proton detection efficiency. The insets show pieces of the matrix projection relevant for the situation of the 616 keV line, as discussed in the text.

the first experimental evidence on the structure of the next unknown $N=Z$ even-even nucleus, ^{88}Ru. The results will be compared to some theoretical predictions and discussed in the context of the evolution of the nuclear structure in this region.

We have used the reaction ^{58}Ni$+^{32}$S with a ^{32}S^{8+} beam of 105 MeV of about 6 particle nA delivered by the Legnaro XTU Tandem accelerator. The target consisted of a 1.1 mg/cm^2 ^{58}Ni layer evaporated on a 10 mg/cm^2 Au foil. The incident energy was chosen so as to favor the two particle evaporation channels.

The γ rays were detected with the GASP array [7] in its standard configuration with 40 Compton-suppressed HPGe detectors and the BGO inner ball. Given the expected very low cross section of the evaporation channel leading to ^{88}Ru, six elements, out of the 80 of the inner ball, placed on the most forward ring were replaced with the n-Ring detector [8]. The n-Ring consists of six BC501A liquid scintillator filled detectors for neutron-γ discrimination. The ISIS silicon ball [9], consisting of 40 $\Delta E - E$ telescopes having a geometry similar to that of GASP was also used with the aim of suppressing the strong charged particle channels through anticoincidence setup. The trigger condition required at least two Ge and three BGO detectors firing in coincidence. A total number of 10^9 events have been recorded in a six day experiment.

In the off-line processing of the data, we paid special attention to having clean neutron identification by setting two selection conditions, one on the time-of-flight–zero crossover (ZCO) time distribution, and the other on the energy-ZCO distribution. As a result, the γ rays coming from nuclei formed without evaporation of neutrons were reduced by a factor of more than 10^4 when the coincidence with neutrons was requested. The experimental values of the particle detection efficiencies were $\sim$56% for detecting one proton, 36% for one α particle, and 3.1% for one neutron.

The data were sorted into different γ-γ matrices in coincidence with charged particles and neutrons. Gamma-ray transitions from the $2n$ channel (^{88}Ru) are expected to be best observed in a γ-γ matrix sorted in coincidence with the neutrons and in anticoincidence with the ISIS silicon ball. The projection spectrum of this γ-γ matrix has been searched carefully for unknown lines not present in projection spectra from other matrices generated in coincidence with charged particles. In this way a line with the energy of 616 keV has been identified as candidate transition for ^{88}Ru. Gating on this 616 keV transition, three other lines at 800, 964, and 1100 keV were then found. These four lines are in coincidence with each other and can be seen in Fig. 1(a), where a sum of gates is shown.

In order to firmly assign these lines to ^{88}Ru, we must show that they are coincident with neutrons, but not with charged particles. They fulfill indeed this requirement and have been assigned to the yrast sequence of ^{88}Ru on the basis of the following arguments. The strongest neutron channels populated in the reaction are ^{87}Mo($2pn$) [10] and ^{88}Tc(pn) [11]. ^{87}Tc($p2n$) [11], ^{85}Mo(αn), and ^{84}Nb(αpn) [12] were also observed, but much weaker. Except for ^{85}Mo (which was also studied for the first time in this experiment and will be presented in a forthcoming paper) all mentioned nuclei are in coincidence with protons. Of course γ rays from each of these nuclei are intensified when a coincidence with protons is required, compared to the case when anticoincidence with the ISIS ball is set. Figure 1(b) shows the same sum of γ-ray gates as Fig. 1(a), but for a γ-γ matrix coincident with neutrons and with protons. Clearly none of the four lines mentioned above is in coincidence with protons. The same result is obtained with respect to the α particles. Consequently, the conclusion that these lines are in coincidence only with neutrons holds firmly.

In both Figs. 1(a) and 1(b) one observes ^{87}Mo transitions (strongly enhanced in the coincidence with protons, as discussed above). Due to the fact that the efficiency of the charged particle detector is not 100% one can explain their presence in Fig. 1(a) *if* there are ^{87}Mo transitions close in energy to some of our lines. In the paper of Winter *et al.* [10] there are no such lines reported. On the other hand, in Ref. [13] a more complex level scheme for ^{87}Mo is obtained and indeed there is a transition of 800 keV overlapping with ours. From gates on different matrices we confirm the existence of the 800 keV transition in ^{87}Mo; furthermore we have found another γ ray of 614.5 keV (close to our 616 keV line, see Fig. 1) which is in coincidence with other transitions of ^{87}Mo. These two transitions (which we placed in a more complete level scheme of ^{87}Mo) explain the presence of ^{87}Mo lines in Fig. 1(a). In order to obtain a cleaner ^{88}Ru spectrum, the spectrum from Fig. 1(b) (which contains contribution mainly from the $2pn$ channel) has been normalized to the one in Fig. 1(a) according to the measured efficiency for the detection of protons, and then subtracted from it. The resulting spectrum, shown in Fig. 1(c) contains only our four transitions, and this clearly demonstrates that they are coincident only with neutrons. We emphasize that the 616 and 800 keV lines are not mutually coincident in the charged particle-coincident matrices.

A direct evaluation of the neutron multiplicity of the lines of interest was not possible since in spectra not coincident with neutrons these weak lines were overwhelmed by much stronger contaminating lines. We have searched for γ rays from the known nuclei that can be formed with evaporation of only one particle. There are no lines belonging to ^{89}Tc (the $1p$ channel) [14] and the coincidence between the first two transitions of ^{86}Mo (the 1α channel) [15] was seen only at a level of 150 counts which corresponds to about 10^{-5} of the total reaction yield. One can therefore safely conclude that the channels with only one evaporated particle are practically not populated. Consequently, the lines we saw in coincidence only with neutrons must come from a nucleus produced by evaporation of *at least two neutrons*. From cross section calculations with the codes CASCADE and HIVAP it results that channels with evaporation of three neutrons are practically not produced at the incident energy of our experiment. Therefore, one may conclude that our four lines from Fig. 1(c) must come from the $2n$ channel.

The intensities of all the reaction channels were deduced from the coincidence spectra of the two lowest transitions corrected for efficiency. By normalizing their sum to the total fusion cross section calculated with CASCADE we get for the $2n$ channel an estimated cross section in the range 5–10 μb ($\sim 4\times 10^{-5}$ from the fusion cross section) which is in reasonable agreement with both the calculated value and the systematics of the cross section of the $2n$ channel in the reactions producing $N=Z$ nuclei.

Finally, we performed a careful search for possible known contaminants. We found traces of oxygen in the target but it manifested only in channels with charged particles and did not interfere with our lines. Similar γ-γ coincidence relationships were not found in any other known nucleus.

As a final conclusion, we assign the cascade of transitions with the energies of 616.2, 799.8, 964.3, and 1100.5 keV (with an uncertainty of ± 0.5 keV) to the yrast sequence of ^{88}Ru. Since the intensities of these lines are too small, we could not make estimations on their multipolarity based on angular distribution or directional correlation orientation (DCO) ratio information. However, we make the reasonable assumption that they represent the cascade of electric quadrupole transitions from the ground-state band up to the 8^+ state.

Using this result, we can deduce several features of the structure of ^{88}Ru based on the obtained spectroscopic information. Based on the energy of the 2^+ state and the semi-empirical relationship proposed by Grodzins [16] we estimate a quadrupole deformation $\varepsilon_2=0.23$ (in first order, $\beta_2=0.24$) which shows that ^{88}Ru is weakly deformed. The ratio $R_{4/2}=E(4^+)/E(2^+)$ is 2.3, which is characteristic of transitional nuclei not too far from the vibrational limit; due to this, the actual static deformation may be smaller than that extracted with the Grodzins formula. Of course, there is no experimental indication about the sign of the deformation. One may compare the estimated ε_2 value to various theoretical predictions. First macroscopic-microscopic Nilsson-Strutinsky potential energy surface calculations for the neutron-deficient Ru isotopes [17] predicted for ^{88}Ru a spherical shape and softness to quadrupole and γ deformation. The early macroscopic-microscopic calculations of Möller and Nix based on a Yukawa-plus-exponential potential [18] predicted an almost spherical shape for this nucleus, whereas more recent ones [19] give a ground-state deformation of $\varepsilon_2=0.05$. The calculations of Nazarewicz *et al.* [20] based on a deformed Woods-Saxon potential show, at $N=44$, deformed gaps in the single particle diagram for the values of ε_2 about -0.34, -0.12, and $+0.21$; the experimental value fits better with the prolate deformation predicted by these calculations. Prolate deformation of $\varepsilon_2=0.11$ is also predicted by the relativistic mean field calculations [21].

Finally, we can also compare our result with the predictions of the recent calculations of Goodman [22] with isospin generalized BCS equations and with the HFB theory. These calculations predict values for ε_2 around 0.18, in good agreement with the experimental estimation. The predictions correspond to either γ-soft oblate or γ-soft prolate shapes, depending very sensitively on different choices for the single particle energies used. Thus, the selection of the right solution of these approaches, which take fully into account the different types of both like-nucleon and neutron-proton pairing interactions, requires the knowledge of the sign of the deformation, which for such nuclei is difficult to be determined experimentally.

It is also interesting to consider ^{88}Ru in the context of different systematics of the ground-state quasibands in the 80 to 90 mass region. These are summarized in Fig. 2. The upper part shows the evolution along the $Z=44$ isotopic chain. ^{88}Ru is the first isotope which shows a rather regular collective band up to the 8^+ state. The middle part of the figure shows the known $N=44$ isotones. ^{88}Ru continues smoothly the tendency of decreasing collectivity after passing the ^{84}Zr nucleus. The lowest part of Fig. 2 shows the evolution along the $N=Z$ line; after reaching a maximum of collectivity at ^{76}Sr and ^{80}Zr (which, according to the experimental data and the theories presented above, have large quadrupole deformations, $\varepsilon_2\approx 0.4$) ^{88}Ru continues the trend of decreasing collectivity already observed at ^{84}Mo.

It is of particular importance to consider the behavior of

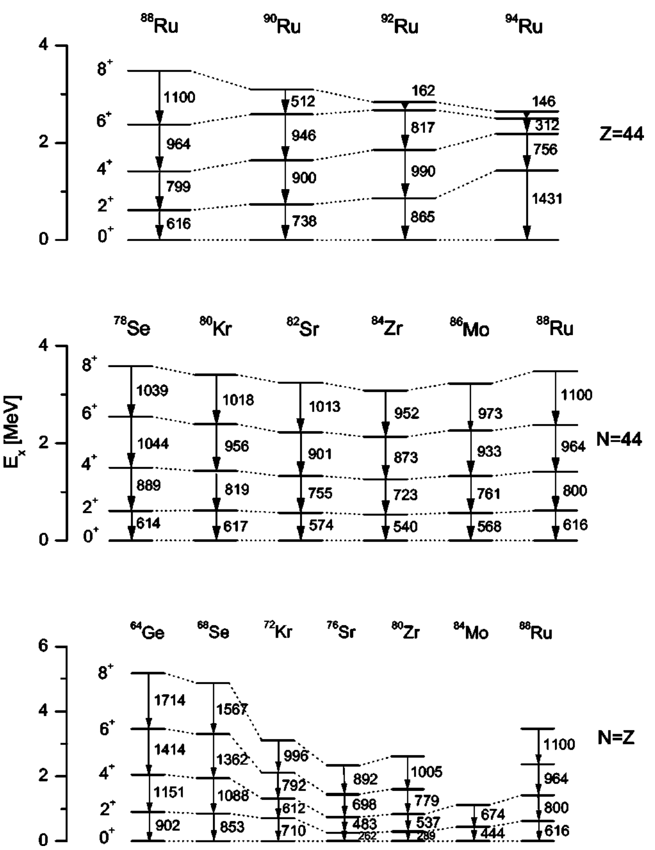

FIG. 2. ^{88}Ru in systematics. The yrast band of even-even nuclei along the Ru isotope chain (upper part), the $N=44$ isotones (middle part), and the $N=Z$ line (lower part). The data on the yrast level sequences have been taken from the NNDC database, except for ^{76}Sr, ^{80}Zr [6], and ^{68}Se [24].

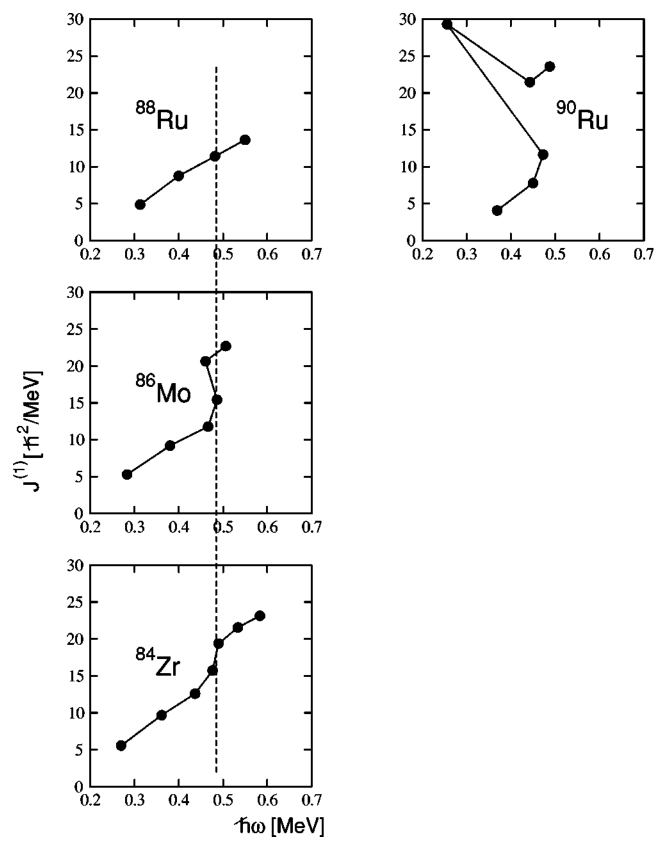

FIG. 3. Variation of the kinematic moment of inertia with spin (rotational frequency) in ^{88}Ru and its closest neighbors in the $Z=44$ and $N=44$ chains.

the yrast sequence at the higher spins. Nuclei in the mass 80–90 region are known to present a backbending of this sequence which takes place generally at the 8^+ state, at a value of the rotational frequency of $\hbar\omega \approx 0.48$ MeV, which is due to the alignment of a pair of $g_{9/2}$ protons. The plot of the kinematic moment of inertia versus the rotational frequency is shown in Fig. 3 for ^{88}Ru and its closest neighbors along the $N=44$ and $Z=44$ lines. It is striking in this figure that only in ^{88}Ru is there no sign of irregularity around $\hbar\omega \approx 0.5$ MeV. Based only on the existig data, shown in Fig. 3, one cannot exclude that the next state in the ground-state band of ^{88}Ru brings a sharp backbending, but even so its occurence at the 10^+ state in this mass region would be unusual. On the other hand, ^{88}Ru seems to continue a trend already observed in other lighter $N=Z$ nuclei, since in ^{72}Kr [1,6], ^{76}Sr, and ^{80}Zr [6] no sign of sudden alignment has been observed up to even higher frequencies. Such a delay in the crossing frequency has been proposed as a possible signature of the presence of collective $T=0$ neutron-proton pairing correlations, which are more resistant to the rotation than the $T=1$ like-nucleon pairing [22,23]. Nevertheless, as pointed out in [1], a delayed crossing may also result from intricate shape changes of the nucleus, therefore it is rather premature to draw conslusions about the role of the np-pairing effects.

In conclusion, we have presented the first experimental evidence on the yrast band of the heaviest $N=Z$ nucleus studied until now, which is ^{88}Ru. Based on these data, one can estimate that this is a weakly deformed transitional nucleus ($\varepsilon_2 \approx 0.2$). Its yrast band does not show the expected proton alignment at spin 8 (or rotational frequency around 0.5 MeV). This feature seems now to appear systematically in the $N=Z$ nuclei, but careful theoretical investigations and additional experimental measurements are needed to confirm it, and eventually relate it to the influence of the collective neutron-proton pairing interactions.

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