BRIEF REPORTS

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Systematics of yrast levels in odd Ru isotopes: Do they point to coexistence at low excitation?

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New spectroscopic strength information extracted through ^{102}Ru$(d,p)^{103}$Ru shows the $3/2^+$ ground state in ^{103}Ru to be poorly populated in both one-neutron transfer reactions, in contrast with former claims. In comparison with ^{101}Ru, particle and hole strengths are significantly reduced in ^{103}Ru and these facts are interpreted as signs of a poor overlap of the odd isotope with its even neighbors plus or minus one neutron. Very-low-lying $3/2^+$ levels, associated with small one-particle spectroscopic factors, are shown to exist in most odd-neutron nuclei in the region and may represent the lowest state of a coexisting configuration. [S0556-2813(98)06202-5]

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Within our systematic experimental research program of the $A\sim100$ nuclei [1,2] we came recently across some peculiar characteristics linking the ground states of even Ru isotopes with states of their odd neighbors. This prompted us to follow those characteristics along the region and this is the theme of the present Brief Report. The São Paulo Nuclear Spectroscopy Group has for more than one decade been involved with experimental nuclear structure research in which light ions (in particular deuterons, protons, and alphas for which the interaction parameters are well established) are employed as spectroscopic tools. Because of the good beam characteristics of the Pelletron accelerator and of the use of nuclear emulsions as detectors at the focal plane of an Enge spectrograph, in addition to the especially prepared thin and uniform targets, high quality data are usually obtained. In fact, the recent ^{102}Ru$(d,p)^{103}$Ru results of the São Paulo Group [1] extended the spectroscopic information up to 3.8 MeV of excitation and revealed 39 levels observed for the first time in this reaction. Figure 1 shows part of the proton spectrum obtained at $\theta_{\rm lab}=8°$, one of the ten angles at which the reaction was observed [1]. Above $E_{\rm exc}$=0.9 MeV much was gained in spectroscopic detail. In all, 79 states were detected, their excitation energies being in excellent agreement with the pertinent adopted values of the Nuclear Data compilation [3]. In particular, γ-ray results, for the 20 levels up to 2.00 MeV of excitation, for which a clear correspondence with states reached by one-neutron transfer may be established, agree with the (d,p) energies mostly within 1 keV, as may be appreciated comparing the energies presented in Fig. 1 with the adopted ones [3]. In this context, the value of $E_{\rm exc}=(3.3\pm0.7)$ keV determined for the lowest energy transition [1] means that in the (d,p) reaction, as well as in the formerly measured (d,t) one [2], the known $5/2^+$ first excited state is populated in a preferential manner. This finding supersedes the indetermination of previous studies [4] which could not decide if the ground state or the first excited state was reached in (d,p). In the emulsion detection technique no possibility of such a difference being due to an

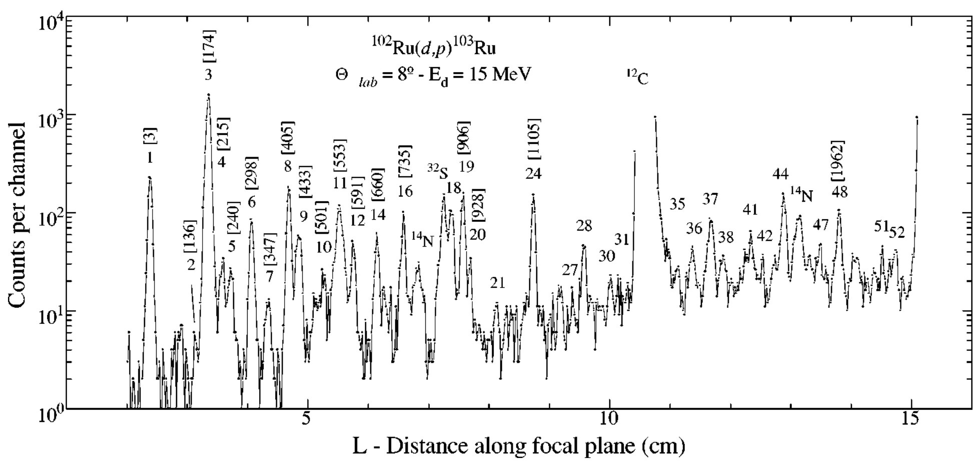

FIG. 1. Partial spectrum (up to ∼ 2.1 MeV) of protons emerging from the ^{102}Ru(d,p) reaction at $\theta_{\rm lab}=8°$. The ^{103}Ru levels which were identified in the reaction are sequentially numbered. The energies (in keV) of those levels which have been associated with γ-ray results are presented above, within square brackets.

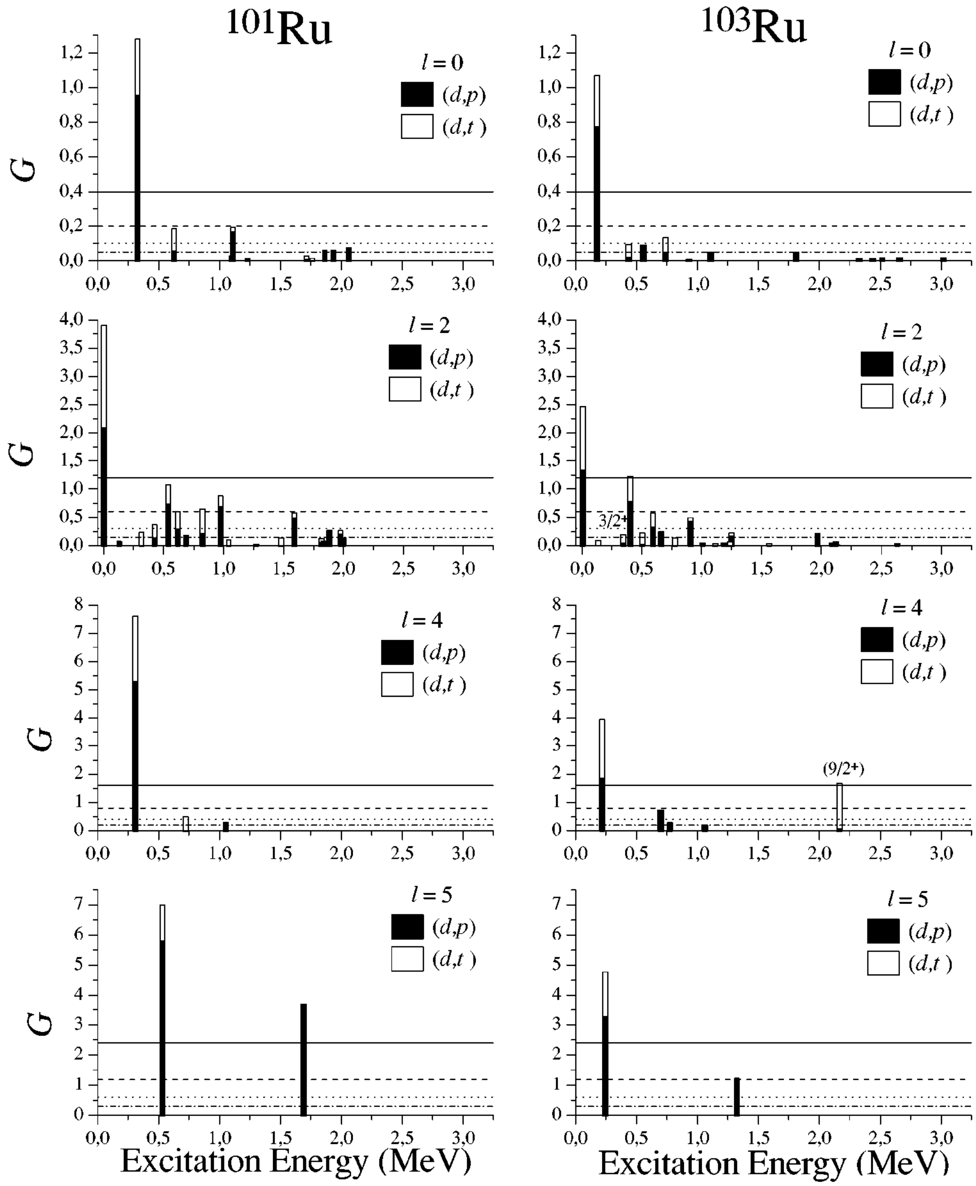

FIG. 2. Spectroscopic strengths, classified according to transferred l, in ^{101,103}Ru [1,2,5]. The symbol $G=G_{\mathrm{pick}}+G_{\mathrm{strip}}$ stands for the summed spectroscopic strengths, with $G_{\mathrm{pick}}=C^2S(d,t)$ and $G_{\mathrm{strip}}=C^2S'(d,p)$. Horizontal lines correspond to cuts at the 2.5%, 5%, 10% and 20% values of the total expected strength, for each l.

experimental zero or scale calibration error exists. In the chain of odd Ru isotopes, $A=101$ [2,5] and $A=103$ [1,2] are now known with similar spectroscopic detail. Figure 2 shows, in an additive and comparative manner, the spectroscopic strengths gathered through the ^{100,102}Ru(d,p) and ^{102,104}Ru(d,t) reactions studied by the São Paulo Group, as superposed solid and open bars, respectively. The information is classified according to transferred orbital angular momentum l, and horizontal lines serve to indicate where cuts, at predetermined fractions of the respective $(2j+1)$ limit of the valence shell, would lie. In the case of $l=2$, the cuts correspond, arbitrarily, to $j=5/2$, as do the strengths, if the level spin is not known. For the other l values, for unknown level spin, the spin of the valence shell model orbital was taken. This procedure may superestimate the valence strengths for $l=2,\ 4$, and 5. It is to be stressed that, as Fig. 2 shows, the detection limits of the experiments are, except for $l=5$, extremely low and mostly below 1%. An interesting feature put into evidence through Fig. 2 is that in both ^{101,103}Ru, for each l transferred, the levels situated lowest in excitation energy are the most intensely populated. For these states the summed strengths (hole plus particle) always exceed 60% of the limit of the corresponding spherical shell model orbital in ^{101}Ru, while in ^{103}Ru, although the yrast levels still preserve their predominantly quasiparticle character, the strengths are appreciably reduced. A global overview of the information shows that, for each l, in ^{101}Ru the total expected strength was almost all found, but in ^{103}Ru up to $\sim$ 3 MeV of excitation strength is certainly lacking. This loss of strength necessarily indicates that it is difficult to form the ^{103}Ru nucleus starting from either the ^{102}Ru or ^{104}Ru ground states. Other peculiarities are observed for ^{103}Ru. First, it is to be remembered that the first excited state and not the ground state is preferentially populated through $l=2$ transfer, starting both from ^{102}Ru and from ^{104}Ru, defining the lowest ^{103}Ru configuration to be of small similar-

TABLE I. Excitation energy and spectroscopic small intensity of the $3/2^+$ yrast state in ^{A}Ru isotopes.

A	E_{exc} (MeV)	$C^2S'(d,p)$	$C^2S(d,t)$
97	0.18922 [7]	low [8]	—
99	0.08968 [9]	—	0.037 [2]
101	0.12723 [10]	0.067 [5]	0.006 [2]
103	0 [3]	low [1]	low [2]
105	0 [11]	0.009 [6]	

ity with the ground states of the neighboring even isotopes. Second, the state at 2.2 MeV of excitation reached by $l=4$ is, through its excitation characteristics, most probably associated with the $1g_{9/2}$ orbital and, thus, an excitation of the $N=50$ core [1]. Both the high strength and the relatively low excitation energy of this state are rather unexpected.

The uncommon situation of a ground state being poorly populated in one-particle transfer reactions, as was evidenced for ^{103}Ru, merits a closer investigation, both from experimental and theoretical points of view. In fact, the next odd isotope of the ruthenium chain, ^{105}Ru, also displays the same behavior in ^{104}Ru(d,p) [6] and otherwise also very similar spectroscopic characteristics [7]. A survey of the experimental information, for the odd ruthenium isotopes and for the isotones of ^{101,103}Ru (always taken from the most recent Nuclear Data Sheets compilations), can be appreciated for the known yrast states with $J^{\pi}=1/2^+$ to $9/2^+$ and $J^{\pi}=7/2^-$ and $11/2^-$ in Figs. 3 and 4. It is seen that a yrast $3/2^+$ is known in most nuclei, appearing for the majority of them at excitation energies lower than 0.3 MeV, this value being exceeded only for ^{97}Zr and ^{109}Sn with known semimagic properties. Table I shows this yrast level to be consistently weakly populated in one-neutron transfer for all cited Ru isotopes, being thus similar to the ^{103,105}Ru ground states. Not many other odd nuclei were studied with similar spectroscopic detail in this mass region; in particular little transfer information is available for the isotones, lying 3–11 neutrons above the magic $N=50$ shell. The $3/2^+$ yrast is, however, known to have small spectroscopic factors also in ^{105}Pd [11] and ^{101}Mo [9]. Other regularities in the here high-

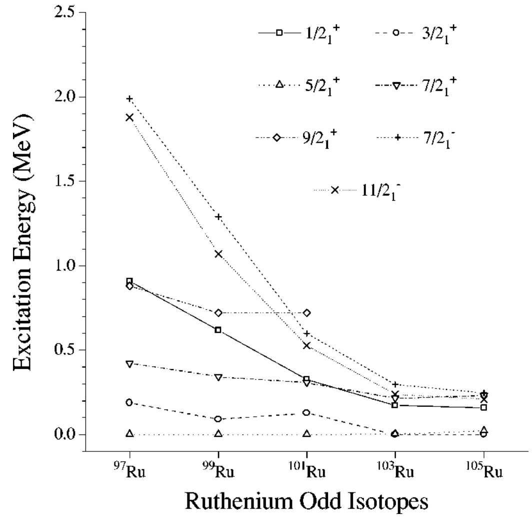

FIG. 3. Yrast states for Ru isotopes.

lighted isotopes and isotones are disclosed through Figs. 3 and 4: the yrast $7/2^+$ and $9/2^+$ levels, where known, and with the exception of ^{97}Zr and ^{107}Sn lie almost constant, respectively, 0.2–0.4 MeV and 0.7–0.9 MeV above the ground state, while the energy of the $11/2^-$ level, followed, where already detected, by a ''companion'' $7/2^-$ yrast, varies by a factor of 9, being lowest for ^{103,105}Ru. Transfer reactions show all these levels, as well as the $5/2_1^+$, to have an important quasiparticle character in Ru, in contrast to the lowest $3/2^+$ levels. However, it is to be stressed again that the yrast $5/2^+$, $7/2^+$, and $11/2^-$ have their strengths about halved, when going from $A=101$ to $A=103$. The yrast $1/2^+$ level lowers its energy in the Ru isotopes, between $N=53$ and $N=61$, by a factor of about 5, but never becomes a ground state, as it is for the lighter isotones (Sr, Zr, Mo) with $N=57$ and $N=59$. As far as studied, the yrast $1/2^+$ exhausts a rather constant fraction of about half of the expected $3s_{1/2}$ quasiparticle strength throughout the region.

It seems clear that in the $A\sim100$ region, in most odd neutron nuclei, a low-lying $3/2^+$ level exists which has, where measured, a small overlap with the neighboring 0^+

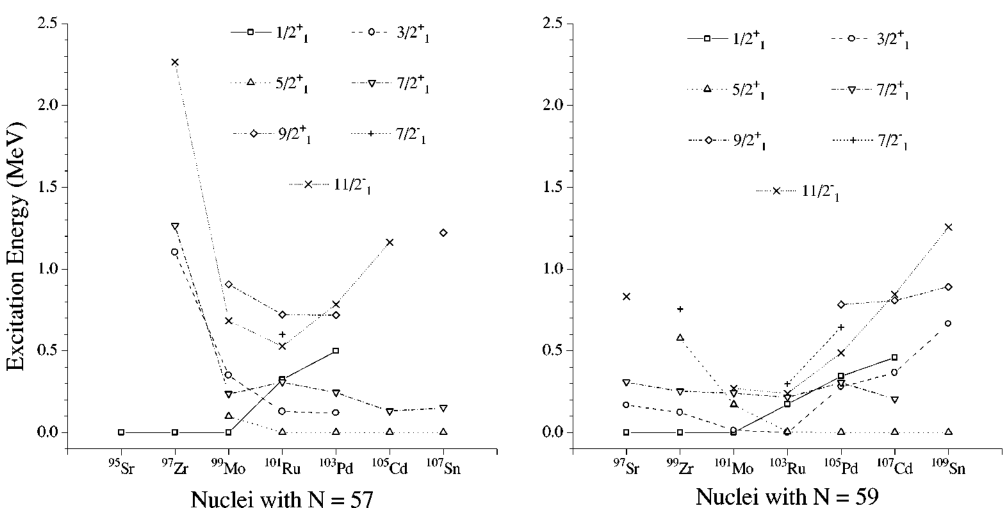

FIG. 4. Yrast states for ^{101,103}Ru isotones.

ground states plus one quasiparticle. Gamma-ray decay properties show it to be linked to other $(3/2^+, 5/2^+)$ levels which are poorly populated in transfer and also to the $1/2_1^+$ one, which in turn has, as already mentioned, an appreciable single-quasiparticle character. This singular $3/2^+$ state may represent the survival of $(2d_{5/2})^3$ characteristics, as interpreted in $^{93}Zr_{53}$ and $^{95}Mo_{53}$ by Talmi [12], as far from the $N=50$ shell as $^{105}Pd_{59}$, a fact which would be certainly surprising. Instead, it could indicate the presence in the odd neutron nuclei in this mass region of still more complex configurations at very low excitation. Both situations may be taken as characterizing a coexistence phenomenon in these nuclei, put also into evidence through a very consistent γ decay pattern, which always favors the feeding of either, one or the other, the yrast $5/2^+$ or the yrast $3/2^+$ states. A ''parent'' configuration for these coexisting states in the odd Ru isotopes is not easily traced in the even neighbors. The broken pair $(2d_{5/2})^2$ would be obviously absent in the even ground state, but it is also not evident in the rest of the spectra if available experimental information is taken into account; nor is there any other configuration which could provide the basis for a direct interpretation of the $3/2_1^+$ state in the odd neutron nuclei.

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