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Excited states in $^{110}$I and core polarization effects of the $h_{11/2}$ proton and neutron orbitals

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Excited states in $^{110}$I have been identified for the first time using the $\alpha pn$ evaporation channel from the $^{58}$Ni+$^{58}$Ni reaction at a beam energy of 250 MeV. The experiment was carried out using GAMMASPHERE coupled to the MICROBALL charged-particle detector array and an array of 15 neutron detectors. Two collective structures were observed with the yrast band built on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration. Comparisons of the yrast-band energies with the excitation energies of the yrast states in even $^{52}$Te and in odd $^{52}$Te and $^{53}$I isotopes for $A \sim 110$ were analyzed, revealing different responses of the underlying cores to the valence $\pi h_{11/2}$ and $\nu h_{11/2}$ orbitals. It is concluded that the neutron $h_{11/2}$ valence orbital has a larger influence than that of the proton $h_{11/2}$ valence orbital.

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Excited states resulting from the coupling of unique-parity neutron and proton valence orbitals in odd-odd nuclei are of special interest for nuclear structure studies due to the relatively simple configuration space. These states in the neutron-deficient $A \sim 110$ region involve $\pi h_{11/2}$ and $\nu h_{11/2}$ orbitals which become yrast at moderate spins and excitation energies. In the current paper, excited states in $^{110}$I are presented for the first time with the yrast band identified as built on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration. The $^{110}$I nucleus is the most neutron deficient iodine isotope that is stable with respect to proton emission. The ground state was previously reported to proton decay in Ref. [1]. The ground state of the neighboring $^{109}$I nucleus was recently employed in recoil delayed tagging (RDT) studies of excited states in $^{109}$I (see Refs. [3,4]).

Nuclear structure in the $A \sim 110$ region is determined by the few valence nucleons outside the doubly magic $^{108}$Sn core. The number of valence particles is large enough to develop collective behavior, but single-particle aspects still play an important role. In the current paper, this issue is addressed through a comparative systematic study of yrast states in even $^{52}$Te isotopes, odd $^{52}$Te and $^{53}$I isotopes, and odd-odd $^{53}$I isotopes, employing recent results for $^{109}$Te (Ref. [5]), $^{111}$Te (Ref. [6]), $^{109}$I (Ref. [4]), $^{111}$I (Ref. [7]), and $^{113}$I (Ref. [8]).

Excited states in $^{110}$I were populated following the $^{58}$Ni($^{58}$Ni,$\alpha pn$) reaction at a beam energy of 250 MeV. The experimental setup consisted of the GAMMASPHERE array of 83 HPGe detectors [9] coupled with the MICROBALL array of 95 CsI(Tl) charged-particle detectors [10], and an array of 15 scintillators for neutron detection, which replaced the 15 front Ge detectors. Charged-particle and neutron gating turned out to be essential in the analysis of the weak channels populated in the experiment, for example, as for the odd $^{52}$Te isotopes (see Refs. [5,6]). More information concerning the optimum utilization of the neutron-detector array is presented in Ref. [5].

Two self-supporting $\sim 500$ $\mu g/cm^2$ stacked targets were used in the current experiment. Measured $\gamma$-ray energies were corrected off line for Doppler shifts; the Doppler correction procedure involved event-by-event reconstruction of the momentum vector of the residual nucleus based on reaction kinematics and measured charged-particle momentum vectors [10]. The average velocity of the recoiling nuclei was measured to be $\beta \sim 4.4\%$ in agreement with the value calculated based on reaction kinematics. In the $\alpha pn$ channel, an overall $\gamma$-ray energy resolution of 4.3 keV full width at half maximum (FWHM) at 0.5 MeV was achieved.

The 527-, 569-, 622-, 664-, 716-, and 742-keV transitions assigned to $^{110}$I were identified in the $\alpha pn$-gated $\gamma$-ray spectrum shown in the upper panel of Fig. 1. These transitions are not observed in the $2\alpha pn$-gated or in the $\alpha 2pn$-gated spectrum shown in the lower panels of Fig. 1. This suggests that these transitions originate from a nucleus having atomic
number \( Z = 53 \) and \( A = 110 \). The only alternative assignment for these transitions is to \( \text{apxn} \) channels with \( x \geq 2 \). This hypothesis can be ruled out, however, with quantitative analysis of the \( \text{ap}^2n \)-gated spectrum. The above transitions are observed in the \( \text{ap}^2n \) spectrum; however, their reduced intensities are consistent with those expected from instrumental effects. Such effects include scattering of a single neutron between two neutron detectors and imperfect \( \gamma \)-neutron separation. In addition, the assignment of these transitions to the \( \text{ap}^2n \) channel would be in disagreement with the recent RDT study on \( ^{109}\text{I} \) (Ref. [4]). Transitions identified in \( ^{109}\text{I} \) in Refs. [3,4] were not observed in the current data. This suggests that the reaction used in the current study does not populate the \( \text{apxn} \) channels with \( x \geq 2 \) with cross sections above the experimental sensitivity, and further confirms the proposed assignment of the 527-, 569-, 622-, 664-, 716-, and 742-keV transitions to \( ^{110}\text{I} \).

The main contaminants observed in the spectra shown in Fig. 1 are from \( ^{109}\text{Te} \) and \( ^{112}\text{I} \) populated in the \( \text{ap}2n \) and \( 3pn \) channels, respectively. Transitions of \( ^{109}\text{Te} \) are observed in the \( \text{ap}2n \) spectrum because of the ~80\% MICROBALL efficiency for proton detection that resulted in a ~20\% probability for missing one proton. Transitions of \( ^{112}\text{I} \) are observed in the \( \gamma \)-gated spectra due to the small probability of proton-\( \alpha \) misidentification. The same is true for the \( ^{109}\text{Te} \) transitions observed in the \( 2\text{ap}n \) gate.

For subsequent analysis, coincident \( \gamma \)-ray events were sorted into an \( \text{apxn} \) gate two-dimensional (2D) matrix and \( \text{ap} \) gate three-dimensional (3D) cube. In the \( \text{ap} \) gate data, the \( \text{ap} \) evaporation channel had an intensity of ~1\% compared to the intensity of the most intense \( \text{ap}2p \) evaporation channel that leads to \( ^{110}\text{Te} \); therefore most of the analysis was performed using the \( \text{apxn} \) gate matrix. The number of events in the matrix was 2.2 million. The most intense channel in the matrix was the \( \text{ap}2p \) channel that populates \( ^{109}\text{Te} \). The intensity of \( ^{110}\text{I} \) in the matrix was ~15\% compared to the intensity of \( ^{109}\text{Te} \). The \( \gamma \)-ray spectroscopy software package RADWARE [11] was used for the data analysis.

The level scheme deduced for \( ^{110}\text{I} \) is shown in Fig. 2. Two characteristic \( \gamma \)-ray sequences are observed, the first at low excitation energy with 569-, 639-, 716-, and 883-keV transitions (see upper panel of Fig. 3) and the second at higher excitation energy with 527-, 742-, 764-, and 968-keV transitions (see lower panel of Fig. 3).
transitions (see lower panel of Fig. 3). The first sequence can be interpreted as a collective rotational band built on the $p_g (7/2) d_{5/2}^n h_{11/2}$ configuration, which is expected to be favored at moderate spin due to the position of the proton and neutron Fermi levels. The second sequence, populated with significantly more intensity, is interpreted as a collective band built on the $p_h h_{11/2}^n h_{11/2}$ configuration, which is expected to be yrast at higher spin as in other odd-odd nuclei in the $A \sim 110$ region.

The current data lack sufficient statistics to confirm the proposed configuration/spin assignments with an angular correlation analysis. Additionally, it is not certain that the links to the ground state have been established in the current study, and the ground state spin and parity for $^{110}$I are not known. Some conclusions about spins and parities of the observed excited states can be drawn, however, from the energy systematics of the yrast bands in the odd-odd $^{53}$I isotopes shown in Fig. 4. With the $^{110}$I assignment proposed in Fig. 4, the energies of the odd-spin members of the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands relative to the (11+) bandhead energies smoothly decrease with decreasing neutron number. The energies of the even-spin members (unfavored signature) are increasing relative to the odd-spin members as the neutron number decreases, which explains why the even-spin members are not observed in $^{110}$I.

The influence of the unique parity $h_{11/2}$ neutron and proton orbitals on the collectivity of the transitional nuclei above the $Z = 50$ closed proton shell is of special interest. The transition from quadrupole vibrations to deformed rotors should be affected by these shape driving high-spin valence orbitals. Information on such possible effects as a function of the Fermi level might be obtained from comparisons of the level sequence (band) energies of the even core nuclei with those of the odd nuclei having an added neutron or proton to a valence orbital, and with those of the nuclei having both valence orbitals occupied. These comparisons over the neutron-deficient region $N = 56 - 62$ are presented in Fig. 5. The energy systematics of the yrast states in $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in odd-odd $^{53}$I isotopes are compared to the yrast states in even $^{52}$Te isotopes, $\nu h_{11/2}$ bands in odd $^{52}$Te isotopes, and $\pi h_{11/2}$ bands in odd $^{53}$I isotopes. All energies are plotted relative to the bandheads of the corresponding bands. The comparisons show several interesting features.

The energies of the yrast states in even $^{52}$Te isotopes decrease as the neutron number decreases. The energies of the states in the $\nu h_{11/2}$ bands in odd $^{53}$I isotopes are substantially reduced with respect to the core energies, and decrease as the neutron number decreases showing the same trend as the even $^{52}$Te cores. The energies of the states in the $\pi h_{11/2}$ bands in odd $^{53}$I isotopes are generally smaller than the corresponding energies of the even $^{52}$Te cores, but increase with decreasing neutron number. The response of an even-even core to the $h_{11/2}$ proton coupling is different therefore from the response to the $h_{11/2}$ neutron coupling, despite the fact that the position of the Fermi level favors the same low-$K$ orbital for both protons and neutrons.

The decreasing trend established for the energies in the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in odd-odd $^{53}$I isotopes follows more...
closely the trend for the $\nu h_{11/2}$ bands in the odd $^{52}$Te isotopes rather than that for the $\pi h_{11/2}$ bands in the odd $^{53}$I isotopes.

These unusual energy trends would suggest that any theoretical interpretation would not be simple. As the neutron number decreases and the neutron Fermi level approaches theoretical interpretation would not be simple. As the neutron isotopes rather than that for the

valence orbitals are indicated by these systematics, the lack though the different effects of the combinations of high-spin both of which would have increasing energy trends. Al-

stiffer and collective rotors should become less deformed, closely the trend for the $\nu h_{11/2}$ bands in the odd $^{52}$Te isotopes.

In conclusion, excited states were identified for the first time in neutron-deficient odd-odd $^{110}$I, taking advantage of the resolving power of the GAMMASPHERE array in con-
time in neutron-deficient odd-odd $^{110}$I, taking advantage of the theoretical investigation.

The systematics of yrast bands in odd-odd $^{53}$I isotopes were discussed in comparison to the systematics of the yrast bands in even $^{52}$Te and in odd $^{53}$Te and $^{54}$I isotopes. These comparisons were made relative to the different responses of the underlying core in the odd nuclei for the $\pi h_{11/2}$ or $\nu h_{11/2}$ orbital. The similarity between $\pi h_{11/2}\nu h_{11/2}$ bands in the light odd-odd $^{53}$I isotopes and the $\nu h_{11/2}$ bands in the related odd $^{52}$Te neighbors suggests that the influence of the neutron $h_{11/2}$ valence orbital is larger than that of the proton $h_{11/2}$ valence orbital.

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[10] D. G. Sarantites, P.-F. Hua, M. Devlin, L. G. Sobotka, J. El-