SPECTROSCOPY AT THE NEUTRON-RICH EDGE OF β-STABILITY VALLEY*

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New results obtained in spectroscopic studies of three-valence -particle nuclei ^{211}Po and ^{135}Te are presented. Yrast states above the α-decaying isomer in ^{211}Po have been located in the γ-ray studies of deep-inelastic products of 450 MeV ^{76}Ge + ^{208}Pb collision. Prompt γ-ray cascades in ^{135}Te fission product nucleus have been measured at GASP using a ^{252}Cf source. Coincidences across the 0.5 μs $19/2^-$ isomeric state in ^{135}Te displayed the γ-rays feeding the isomer. Similarities between the yrast structures in ^{211}Po and ^{135}Te nuclei are discussed.

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1. Introduction

Spectroscopic studies of nuclei on the neutron-rich side of the stability valley were until recently very much restricted due to their inaccessibility in standard fusion evaporation reactions. In a series of recent experiments we have shown that yrast states of neutron-rich nuclei can be studied very successfully in heavy-ion multinucleon transfer processes ($\sim$15% above Coulomb barrier), using γ-γ thick target technique [*e.g.* 1,2]. Among others, region

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around doubly magic ^{208}Pb nucleus became available for yrast spectroscopy. Also, recent investigations using large γ-ray detector arrays to study fission fragments from actinide sources have opened prospects for broad exploration of the yrast spectroscopy of neutron-rich species in the ^{132}Sn neighborhood [3,4].

There is special interest in studying the structure of few-valence-particle nuclei around doubly magic ^{132}Sn and ^{208}Pb, which can yield information about nucleon-nucleon interaction and effective charges in these important parts of the nuclidic chart. Blomqvist [5] has pointed out that there should be many points of resemblance between the spectroscopy of the ^{132}Sn region and the well studied nuclei around doubly-magic ^{208}Pb. The orbitals above and below the energy gaps in the two cases are similarly ordered, and every single particle state in the ^{132}Sn region has its counterpart around ^{208}Pb with the same radial quantum number n, and one unit larger angular momenta l and j.

In the following we shall report new spectroscopic results on the three-valence-particle nuclei ^{211}Po and ^{135}Te and compare both structures.

2. High spin states in ^{211}Po

The 25.2 s α-decaying state with I^{π}=25/2$^+$ at 1462 keV in ^{211}Po is one of the classic examples of yrast "spin-gap" isomers in nuclei. In this three-particle nucleus the $(\pi h^2_{9/2}\nu g_{9/2})25/2^+$ level lies below the $19/2^+$, $21/2^+$, and $23/2^+$ multiplet members because the $\pi h_{9/2}\nu g_{9/2}$ proton-neutron attraction is significantly stronger in the maximally aligned $J = 9$ coupling than in the states with $J = 8, 7, 6, 5$ or 4. The level structure of ^{211}Po is not accessible for study by heavy-ion induced fusion-evaporation reactions, and only lower spin levels up to the 1462 keV isomer have been located in ^{211}Bi β^- decay and in ^{208}Pb$(\alpha, n\gamma)^{211}$Po investigations [6].

In the present work we have investigated the yrast excitations of ^{211}Po above the 25.2 s isomer using few-nucleon transfer reactions occuring during ^{76}Ge+^{208}Pb heavy-ion collision [7]. The experiment was performed at the Legnaro linear accelerator ALPI using pulsed beam of 450 MeV ^{76}Ge ions on a target of 50 mg/cm^2 ^{208}Pb. The time spacing between beam bursts was 400 ns. Gamma-rays were detected with the GASP array, which consists of 40 Compton-suppressed Ge detectors and an inner BGO ball of 80 elements.

Known high spin γ-rays in the neutron-rich Pb, Bi, Po, At nuclei were clearly observed in the data and analysis of the product yield distribution indicated that also in ^{211}Po the higher spin states should be populated.

In the $N = 127$ ^{211}Po nucleus with two valence protons and one valence neutron, one may expect low-lying multiplets arising from coupling of the $\pi h^2_{9/2}$ and $\pi h_{9/2}i_{13/2}$ configurations to the $\nu g_{9/2}$ neutron, with highest spin members $25/2^+$ and $31/2^-$, respectively. Further, one could expect an isomeric $31/2^- \rightarrow 25/2^+$ E3 transition in ^{211}Po analogous to the ^{210}Po $11^- \rightarrow 8^+$ E3.

We searched for this ^{211}Po $31/2^- \rightarrow 25/2^+$ transition in the $\gamma\gamma$ prompt-delayed coincidence matrix from the ^{76}Ge + ^{208}Pb reaction by examining the cross coincidence relationship between complementary Po and Zn reaction products. Gates were set on prompt γ-rays in ^{72}Zn, ^{70}Zn, and ^{68}Zn, and delayed γ-rays de-exciting isomeric states with 10-500 ns half-lives in Po partner nuclei were displayed. These delayed transitions included known γ-rays from several Po isotopes as well as a prominent 673 keV γ-ray not known previously. The intensity pattern of prompt transitions from $^{68-72}$Zn isotopes observed in coincidence with the delayed 673 keV line indicated clearly that this γ-ray occurs in the ^{211}Po nucleus, and is thus very likely to be the $31/2^- \rightarrow 25/2^+$ transition. No gamma-rays appeared in prompt coincidence with the 673 keV γ-ray, but 316 and 357 keV γ-rays in cascade parallel to the 673 keV transition were subsequently found. The 316 keV γ-ray intensity was observed to be about 2.5 times lower than that of the 357 keV γ-ray; intensity balance requirements point towards M2 character for the 316 keV transition ($\alpha_{\rm tot}$ ~2.0), with M1 for the 357 keV transition ($\alpha_{\rm tot}$ ~0.3). These results locate an intermediate level at 1819 keV.

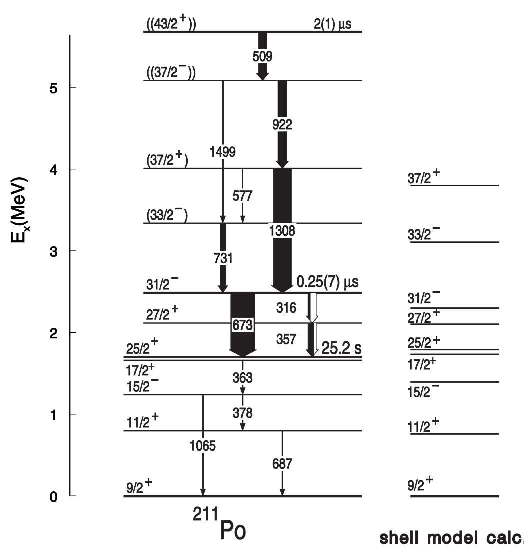

Fig. 1. Partial level scheme of the yrast level spectra established for ^{211}Po. Arrow widths denote the relative γ-ray intensities observed in prompt-delayed coincidence with the 673 keV transition. Results of the shell model calculations from Ref. [8] are also shown.

A gate on the delayed 673 keV γ-ray showed, in addition to γ-rays from the Zn reaction partners, a group of transitions with energies 1308, 922, 509, 731, and 1499 keV, which were thus identified as ^{211}Po γ-rays preceding the $31/2^-$ isomer. By detailed examination of the coincidence data, new states were located at 2866, 3443, 4365, and 4874 keV excitation energy, of which the highest is an isomer with $T_{1/2} = 2 \pm 1\mu$s. The partial level scheme of ^{211}Po is shown in Fig. 1. Analysis of the $T_{\gamma\gamma}$ time distributions between the 673 keV γ-ray and the strong transitions preceding that γ-ray (1308, 922, 509 keV) yielded the value $T_{1/2} = 0.25(7)$ μs for the $31/2^-$ state. Calculation of the B(E3) for the 673 keV transition, taking into account the 316 keV branching, gives B(E3; $31/2^- \to 25/2^+$) = $57(15)\times10^3$ e^{2}fm^6, or 22(6) W.u.

Warburton [8] has performed shell model calculations for ^{211}Po using modified Kuo-Herling nucleon-nucleon interactions, and the results agree rather well with the experimental level spectrum up to the $25/2^+$ isomer (Fig. 1). These calculations also predict higher lying $27/2^+$, $31/2^-$, $33/2^-$ and $37/2^+$ yrast states that should decay by γ-ray cascades feeding the $25/2^+$ isomeric state. The level at 1819 keV, almost certainly corresponds to the $(\pi h^2_{9/2}\nu i_{11/2})27/2^+$ calculated at about this energy. The $31/2^-$ yrast level is predicted at 498 keV above the $25/2^+$ isomer. The same calculations give only two yrast states above the $31/2^-$ isomer: a $33/2^-$ level at 2655 keV arising from the $\pi h_{9/2} i_{13/2} \times \nu i_{11/2}$ coupling, and a $37/2^+$ state at 3192 keV of $\pi \mathrm{h}_{9/2} i_{13/2} \times \nu j_{15/2}$ type. Both states should decay to the $31/2^-$ isomer by M1 and E3 transitions, respectively. The levels placed in this work at 2866 keV and 3443 keV, decaying to the $31/2^-$ isomer by 731 keV and 1308 keV transitions are probably these $33/2^-$ and $37/2^+$ excitations.

The two highest states located at 4365 and 4874 keV must involve excitation of the ^{208}Pb core.

The ^{211}Po nucleus was also recently studied in ^{9}Be and ^{7}Li induced incomplete fusion reactions by McGoram *et al.* [9] and their results fully confirmed our findings.

3. Yrast states of neutron-rich N=83 ^{135}Te nucleus

The occurrence of a 0.51 μs yrast isomer in the three valence particle nucleus ^{135}Te has long been known from fission fragment mass separator studies by Kawade *et al.* [10]. Its nature is similar to the I^π=$25/2^+$ α-decaying state in ^{211}Po. In ^{135}Te the $(\pi g^2_{7/2}\nu f_{7/2})19/2^-$ level lies below the $17/2^-$, state and only 50 keV above $15/2^-$ multiplet member because the $\pi g_{7/2}\nu f_{7/2}$ proton-neutron attraction is significantly stronger in the maximally aligned $J = 7$ coupling than in the states with lower J. The $19/2^-$ isomer decays by a 50 keV E2 transition followed by 325 and 1180 keV γ-rays through the $15/2^-$, $11/2^-$ levels to the $7/2^-$ ground state all of which are of mainly $\pi g^2_{7/2}\nu f_{7/2}$ character.

Recent investigation using multidetector Ge array Eurogam II to study fission product γ-rays from ^{248}Cm source has identified prompt and delayed γ-ray cascades from individual product nuclei in the ^{132}Sn neighborhood, including γ-rays feeding the $19/2^-$ isomer in ^{135}Te [11] New states in ^{135}Te at 2641, 3235, 4592, and 5642 keV were located and are shown in Fig. 2.

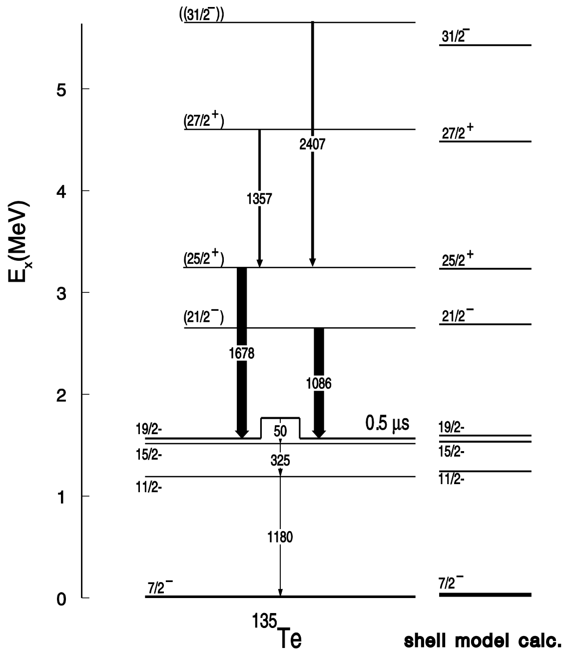

Fig. 2. Partial level scheme of the yrast level spectra for ^{135}Te. Arrow widths denote the relative γ-ray intensities observed in prompt-delayed coincidence with the 1180 keV transition. Results of the shell model calculations (see text) are also shown.

The shell model calculations with empirical interaction matrix elements, described in Ref. [11] support the interpretation of the 2641 and 3235 keV levels as $(\pi g^2_{7/2}\nu h_{9/2})21/2^-$ and $(\pi g_{7/2}h_{11/2}\nu f_{7/2})25/2^+$ states. This $25/2^+$ state is closely related to the $(\pi g_{7/2}h_{11/2})9^-$ state in ^{134}Te [4]. The level at 4592 keV may be either $(\pi g_{7/2}h_{11/2}\nu h_{9/2})27/2^+$ or $(\pi g^2_{7/2}\nu i_{13/2})25/2^+$, both of which are predicted around 4.6 MeV. The topmost level at 5642 keV could be a $(\pi g_{7/2}h_{11/2}\nu j_{13/2})31/2^-$ state predicted around that energy or a level of $(\pi g^2_{7/2}\nu f_{7/2}h^{-1}_{11/2})$ type directly related to the core-excited states identified in ^{134}Te at similar excitation energy [4].

Unfortunately, the Eurogam II $\gamma\gamma$ coincidence data were acquired with rather narrow TAC time ranges, not well suited for investigating delayed coincidence relationships across μs isomers.

We have performed another measurement at the GASP germanium array located at the Laboratori Nazionali di Legnaro. In that experiment we recorded γ-ray coincidence events from a sealed ^{252}Cf source delivering $\sim 10^4$ fissions/sec. The data were taken event-by-event with a trigger requiring prompt firing of at least two inner ball BGO detectors and two Ge detectors within an 200 ns time interval. An 800 ns wide time gate opened by a prompt event allowed detection of delayed γ-rays. During 3 weeks 2×10^9 γ-γ Ge coincidence events (with the inner ball fold treshold $F \geq 2$) were accumulated.

Very good prompt-delayed sorting conditions could be achieved for the ^{135}Te case by selecting prompt γ-rays in an 100-800 ns time interval preceding the 1180 and/or 325 keV γ-rays, which deexcite 0.5 μs isomer. The resulting spectrum of γ-rays preceding the 1180 keV transition, presented in Fig. 3, shows several low-energy Pd lines from cross coincidences and, the known (from the Eurogam measurement [11]) ^{135}Te transitions above the 0.5 μs isomer: 1086, 1678, 1357 and 2407 keV γ-rays. Those γ-rays, barely visible in the corresponding spectrum from the Eurogam data, now appear as very distinct lines. In addition, new 1917, 2468 and 2292 keV transitions preceding the $19/2^-$ 0.5 μs isomer could be identified.

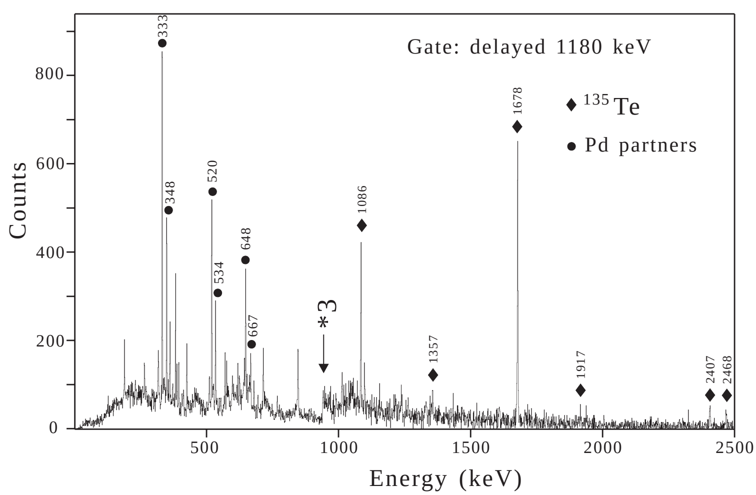

Fig. 3. Key γ-ray coincidence spectrum from the GASP measurement. It displays γ-rays preceding the 1180 keV ^{135}Te transition. Only strong cross-coincident lines from Pd parners are marked.

The present data essentialy confirm the ^{135}Te level scheme above the $19/2^-$ isomer established in the Eurogam study [11]. The new 1917, 2468 and 2292 keV weak transitions probably deexcite non-yrast states.

The shell model calculations for ^{135}Te were performed with the OXBASH code using modified Kuo-Herling nucleon-nucleon interactions [12] scaled from the Pb region with $A^{-1/3}$ factor and the results are shown in Fig. 2. The agreement with experimental level spectrum up to the $19/2^-$ isomer is very good. The calculations also predict higher lying $21/2^-$, $25/2^+$, $27/2^+$, and $31/2^-$ yrast states at energies close to the experimental levels at 2641, 3235, 4592, and 5642 keV, respectively, supporting the previous spin assignments.

4. Comparison of yrast structures in ^{211}Po and ^{135}Te

As mentioned earlier every single particle state in the doubly magic ^{132}Sn region has a corresponding single particle state around doubly magic ^{208}Pb with one unit larger angular momenta l and j. For example, the proton orbitals around ^{132}Sn: $\pi g_{7/2}$, $\pi d_{5/2}$, $\pi h_{11/2}$, correspond to the single particle $\pi h_{9/2}$, $\pi f_{7/2}$, and $\pi i_{13/2}$ states in the ^{208}Pb neighborhood, respectively. The neutron orbitals $\nu f_{7/2}$, $\nu h_{9/2}$, $\nu i_{13/2}$ have partners $\nu g_{9/2}$, $\nu i_{11/2}$, and $\nu j_{15/2}$, respectively.

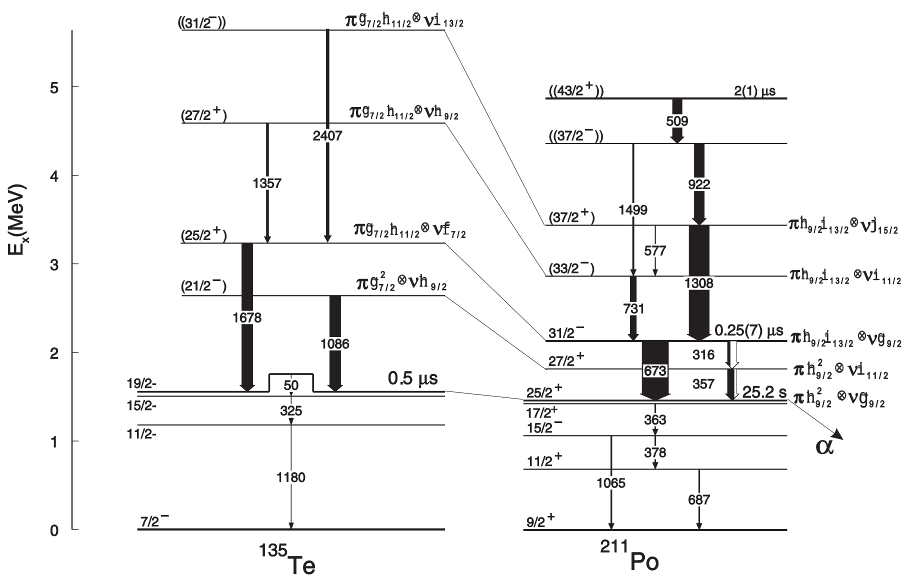

Fig. 4. Comparison of yrast structures above isomers in ^{211}Po and ^{135}Te three-particle-nuclei.

Taking into account these similarities one may expect a resemblance between level structures of the three-valence-particle nuclei ^{211}Po and ^{135}Te. The yrast levels above the isomers in ^{211}Po and ^{135}Te are shown in Fig. 4. Close inspection reveals striking similarity between high spin states in both cases. Each yrast level in ^{211}Po has its counterpart in ^{135}Te and, since three valence particles are involved, their are of opposite parity and the spins differ by 3 units. The ordering of corresponding states is the same and their relative spacings in energy and γ-ray decay patterns are very similar. We conclude that the resemblance of the single particle orbitals in the ^{132}Sn and ^{208}Pb neighborhoods determines also a similarity between much more complex shell model configurations in these regions.

5. Summary

Gamma-ray spectroscopic studies of hard-to-access neutron-rich nuclei in the doubly magic ^{208}Pb and ^{132}Sn regions have been performed using deep-inelastic heavy ion reaction ^{76}Ge+^{208}Pb and spontaneous fission of ^{252}Cf source. Yrast states above the 25 s α-decaying isomer in ^{211}Po and above the 0.5 μs $19/2^-$ isomer in ^{135}Te have been located. Level schemes of these three-valence-particle nuclei exhibit striking similarities, which may be traced back to the similarity between the shell structures in the two regions.

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