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Gamma Spectroscopy along $N \sim Z$ towards ^{100}Sn

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Abstract: A wide range of research topics in different fields of physics can be addressed by study of the self-conjugate $N=Z$ nuclei, such as the np pairing, isospin symmetry, the rp-process and the properties of the electroweak interaction. This contribution focuses on the spectroscopy of $N \sim Z$ nuclei towards ^{100}Sn. The latest results on the isomeric decay spectroscopy of $N \sim Z$ nuclei below ^{100}Sn, such as the $N=Z+2$ nuclides ^{94}Pd and ^{96}Ag, the $N=Z$ nuclide ^{96}Cd and so on are highlighted. New opportunities in in-beam γ spectrscopy of $N \sim Z$ nuclei towards ^{100}Sn, like ^{90}Rh and ^{92}Pd, with radioactive ion beams are discussed.

Key words: self-conjugate nuclei; np interaction; isospin symmetry; high spin isomer; knockout reaction

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1 Introduction

Nuclei with equal or almost equal number of neutrons and protons are of particular, multidisciplinary interest. They form a fascinating laboratory for the study of a wide range of areas in physics, such as nuclear structure, astrophysics and weak interaction[1].

The pairing effects of two fermions was first recognized in superconductors where two electrons with opposite spin projections build a Cooper pair. Similar pairing of alike fermions in the atomic nucleus, nn and pp "Cooper pairs" in time-reversed orbits gives rise to nuclear superfluidity, which is a well known phenomenon having a significant impact on the microscopic structure as well as on the collective properties of the nucleus[2−3] Moreover, the existence of two fermionic fluids, of neutrons and protons, gives rise to an additional quantum degree of freedom——the isospin T in nucleus. As a consequence four combinations of nucleon pairs can be formed, the $T=1$ isovector triplet: pairs of nn, pp and np with opposite spin projections, and the $T=0$ isoscalar singlet: np pair with aligned spin. There is clear evidence in $N \sim Z$ nuclei for the existence of isovector np pair condensate with the strength required by the isospin invariance of the strong nuclear force, *i.e.*, similar to the normal $T=1$ nn and pp pairs. Manifestation of the isoscalar np Cooper pairs of aligned, nonzero total angular momentum is considered most favorable in the vicinity of self-conjugate $N=Z$ nuclei, see, *e.g.*, Refs. [4-5]. In medium mass $N=Z$ nuclei, the existence of T=0 pairing has been searched for by studying the absence of Coriolis antipairing effects at high angular momentum in rotational bands[4−6]. The proton-neutron isoscalar pairing correlations were found to play an important role in the structure of heavier $N=Z$ nuclei ^{92}Pd and ^{96}Cd[7−8]. However, so far no clear signature of the isoscalar pairing condensate has been identified to date. A recent overview on this topic was given in Ref. [9].

The charge independence assumption of nuclear force leads to an exchange symmetry between neutrons and protons, yielding an elegant and simple symmetry. *i.e.* isospin symmetry[10], one of the cornerstone concepts in nuclear struture. Isospin symmetry breaking, generally due to the isospin-non-conserving (INC) forces, such as Coulomb force, is expected to become more pronounced with the increase of nucleus mass. INC forces manifest in energy differences between excited isobaric analog states (IAS) around the $N=Z$ line.

As the valence protons and neutrons occupy the same orbitals, nuclear structure effects are reinforced by the simultaneous occurrence for neutron and protons. For example in the $A=60 \sim 80$ region along the $N \sim Z$ line, nuclear shapes change rapidly with both nucleon number and angular momentum due to cohenrent action of protons and neutrons[11].

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The studies of $N\sim Z$ nuclei also have important implications for other areas of physics Above ^{56}Ni, the $N\sim Z$ nuclei are at the proton drip line and on the path of astrophysical rapid-proton-capture process in type-I X-ray bursts[12], which is predicted to end at α-decaying Te isotopes above ^{100}Sn[13].

Precise measurements of the β decay between nuclear analog states of $J^{\pi}=0^{+}$ and isospin $T=1$, provide demanding and fundamental tests of the properties of the electroweak interaction In these β decays the self-conjugate nuclei are involved as either parents or daughters. Collectively, these transitions sensitively probe the conservation of the vector weak current, set tight limits on the presence of scalar currents, and provide the most precise value for $V_{\rm ud}$, the up-down quark-mixing element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. This latter result has become a key in the most demanding available test of the unitarity of the CKM matrix, a property which is fundamental to the electroweak standard model. See Ref. [14] and Hardy's paper in this conference for an updated overview on this topic.

In this contribution we will focus on the γ spectroscopy of $N\sim Z$ nuclei below ^{100}Sn. The latest progress in isomeric decay spectroscopy will be presented first, then new opportunities in in-beam γ spectrscopy with RI beams will be discussed.

2 Isomeric decay spectroscopy of $N\sim Z$ nuclei below ^{100}Sn

The $N\sim Z$ nuclei just below ^{100}Sn are of particular interest in contemporary nuclear structure studies. This region is remarkable for an abundance of isomeric states, especially the occurrence of high-spin isomers, due to very strong interactions between fully aligned proton and neutron in $g_{9/2}$ shell and the seniority coupling scheme. The strength of pn interactions in the $\pi\nu g_{9/2}$ orbits manifests itself best in the strongly binding $T=0(g_{9/2})^2 9^+$ TBME which is comparable to the $T=1$ pairing[15]. The study of these isomers provides an ideal testing ground for the shell model theory and neutron-proton interactions around the $N=Z$ line. The experimental and theoretical results concerning these isomers were reviewed recently in Ref. [16] and are presented in Fig. 1, where their decay modes are displayed.

In the Rare Isotope Spectroscopic investigation (RISING) at GSI stopped beam campaign[17], our collaboration focused on the study of high-spin isomers around the $N=Z$ line below ^{100}Sn. In the $N=Z+2$ nuclide ^{94}Pd[18], a new high-spin isomeric state with a half-life of 197(22) ns was discovered and tentatively assigned as a (19^{-}) state with dominant configuration $(\pi p_{1/2}^{-1}g_{9/2}^{-3})_{11}\otimes(\nu g_{9/2}^{-2})_{8}$ by the shell model calculations, revealing the importance of including the well-bound $f_{5/2}$ and $p_{3/2}$ orbits for understanding the decay properties of high-spin isomers in the vicinity of ^{100}Sn. In another $N=Z+2$ nuclide ^{96}Ag[19], three new high-spin isomers with spin parity of (19^{+}), (15^{+}) and (13^{-}) were discovered. The (19^{+}) isomer was identified as the second known core-excited isomer in the ^{100}Sn region.

A β-decaying isomer in ^{96}Cd, mainly to the (15^{+}) isomeric state in ^{96}Ag[8], was identified as the long predicted 16^{+} E6 "spin-gap" isomer by shell model calculations on the level structure and GT strengths. This is the second highest spin (the 21^{+} isomeric state in ^{94}Ag being the highest[16]) observed for a state preceding β decay. The shell model calculations show that the isoscalar component of the neutron-proton interaction is essential to explain the origin of the 16^{+} isomer in ^{96}Cd. This result provides important evidence for the strong influence of the isoscalar neutron-proton interaction not only at low-spins as in the case of ^{92}Pd[2], but also at high-spin in the region around ^{100}Sn. These findings have stimulated much theoretical efforts. The role of $\pi\nu g_{9/2}$ pairs with maximum spin 9^{+} in the $N=Z$ nuclei ^{96}Cd, ^{94}Ag and ^{92}Pd has been investigated with respect to the controlling 9^{+}-TBME[20−22]. The content of the various pn-pairs in the three nuclei with increasing spin was discussed, however, no evidence for a pn-9^{+} condensate was found. Also the contribution of spin-aligned $J=9$ pairs to the structure of low lying states of these nuclei is found strongly dependent on the model space and it decreases considerably from the simple $(0g_{9/2})$ space to the more complete $(1p_{3/2}0f_{5/2}1p_{1/2}0g_{9/2})$ space[23−24].

Very recently the properties of the spin gap isomers in $N\sim Z$ nuclei below ^{100}Sn were further studied with much higher radioactive ion beam intensity in two experiments of the EURICA campaign at RIBF RIKEN. Some preliminary results on ^{98}In, ^{96}Cd and ^{94}Ag from these two experiments were presented at this conference, by R. Gernhäuser and P. J. Davies, respectively. In both experiments evidence for a new γ-decaying high-spin isomer was observed in ^{96}Cd. The β-delayed proton decay branch of the 16^{+} isomer in ^{96}Cd was also reported.

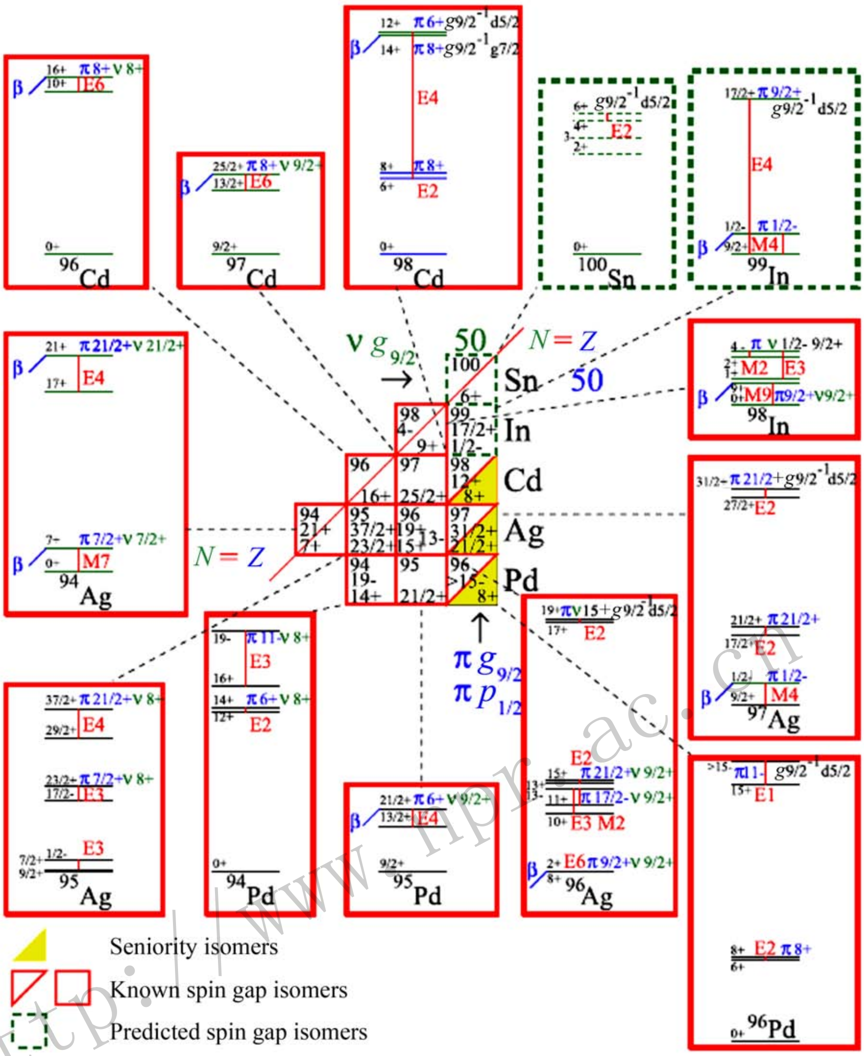

Fig. 1 (color online) High-spin isomers observed and predicted below ^{100}Sn (adapted from Ref. [16]).

3 In beam γ spectroscopy towards ^{100}Sn

Along the $N = Z$ line γ-spectroscopy have been performed up to ^{86}Tc[25] for o-o nuclei and to ^{92}Pd[7] for e-e nuclei. Fusion-evaporation cross-sections are too low for stuying the o-o $N = Z$ nuclei with $A \geqslant 90$, knockout reaction of RI beam is becoming feasible as the radioactive ion beam intensity being upgraded continuously at RIBF RIKEN and at NSCL MSU. For example, excited states of ^{90}Rh can be populated via -2n knockout reaction of ^{92}Rh unstable beam, as shown in Fig. 2.

The structure of ^{90}Rh is of particular interest as it lies in a transitional position between deformed and spherical nuclei along the $N = Z$ line. The $N = Z$ nuclei with mass $A = 60$ to 88 are deformed[25−26] as shown in Fig. 5 of Ref. [25], whereas the properties of heavier ones like ^{92}Pd, ^{94}Ag and ^{96}Cd can be described by the spherical shell model. By establishing the $T = 1$ level sequence of ^{90}Rh and comparing with that of the $T = T_z = 1$ isobar ^{90}Ru which is known,

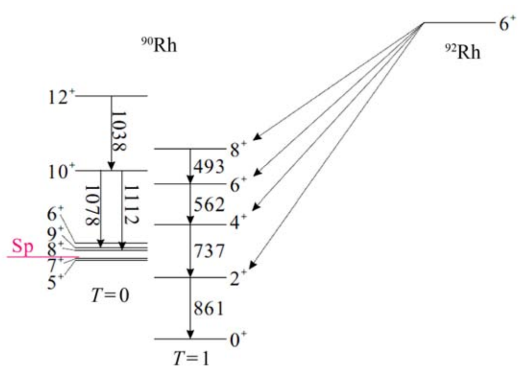

Fig. 2 (color online) A schematic diagram to show the population of excited states of ^{90}Rh in -2n knockout of ^{92}Rh. The excited states are calculated from shell model in $g_{9/2}$ space[27].

energy differences between excited IASs (generically termed Coulomb energy differences, or CEDs) can be obtained for the first time for A=90, pushing the study of the isospin-symmetry breaking to the heaviest isobaric multiplets.

Taking the advantage of relatively long-lived high-spin isomeric radioactive ion beams, high-spin states in $N \sim Z$ nuclei can also be populated in the region just below ^{100}Sn. For example, high spin states as high as $I^{\pi} \sim 16^{+}$ in ^{92}Pd can be populated via knockout reaction of the 14^{+} isomer ($t_{1/2} \sim 0.5$ μs) in ^{94}Pd, which has a quite high isomeric ratio of ~ 0.3 in fragmentation reactions[18,28].

To characterize the magicity of the self-conjugate ^{100}Sn and single particle states in neighboring nuclei, in-beam γ spectroscopy via neutron knockout reactions using the MINOS device[29] coupled to the DALI2 γ spectrometer has been proposed at RIBF[30]. Gamma detector array with much better energy resolution than DALI2 will be necessary for γ spectroscopy of $N \sim Z$ nuclei below ^{100}Sn, like ^{90}Rh, ^{92}Pd, ^{94}Ag and ^{96}Cd. Advanced γ Ge detector array like GRETINA or AGATA with tracking ability, or $LaBr_3$(Ce) array will be desirable, with the latter having the ability to measure the transition probabilities of excited states in very exotic nuclei.

In summary, the $N = Z$ self-conjugate nuclei provide a unique platform to address a variety of physics topics of different areas. The doubly magic ^{100}Sn being the heaviest self-conjugate nucleus experimentally accessible to date, the study of $N \sim Z$ nuclei below ^{100}Sn represents the very frontier of radioactive ion beam physics. Interesting results related to the isoscalar correlations between np pair are emerging from the latest experimental investigations below ^{100}Sn. Decay spectroscopy of isomeric states in this region are highlighted in this contribution. With the progress in the development of radioactive ion beams and gamma-ray detector arrays of higher energy resolution, in-beam γ spectroscopy of ^{100}Sn and $N \sim Z$ nuclei below will become feasible in the near future, and will provide the opportunity to probe the structure of these exotic nuclei in more details.

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