第 34 卷 第 3 期
2017 年 9 月

原 子 核 物 理 评 论
Nuclear Physics Review

Vol. 34, No. 3
Sep. , 2017

Article ID: 1007-4627(2017) 03-0332-06

Studies of in-beam Gamma Spectroscopy and Next-generation Gamma Detector Array at HKU

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Abstract: Exploring the evolution of shell closures and examining the magicity of extremely exotic nuclei are the main research interests of HKU (University of Hong Kong) experimental nuclear physics group. The group has employed in-beam gamma-ray spectroscopy technique to investigate the vanishing of N=20 magicity in ^{30}Ne ($N=20$) and the strong magicity in nuclei around ^{78}Ni (Z=28, N=50). The approved future's experiment on spectroscopy of ^{53,56}Ca, proposed by HKU, will give quantitative information for the "magic index" of N=34 and shell evolution toward N=40. The next goal is to investigate the structure of ^{100}Sn ($N=Z=$50), particularly the energy of the first 2^+ state, and the low-lying states in the neighboring nuclei. ^{100}Sn lies on the proton drip-line and on the astrophysical *rp*-process path. Characterizing the magicity of ^{100}Sn and the nature of single-particle states in its neighboring nuclei is therefore essential to the fundamental understanding of nuclear forces and nucleo-synthesis. To significantly increase the data statistics for our physics goals, HKU group has prepared the upgrade of gamma-ray spectrometer DALI2 with 30% more NaI(Tl) detectors integrated into a new array configuration. On the other hand, next significant insights into the structure of nuclei would require new gamma-ray detection array capable for higher precision gamma-ray spectroscopy. HKU group in collaboration with IMP and CIAE therefore proposes to construct a new-generation gamma-ray detection array based on the novel scintillator $LaBr_3$(Ce) to explore the new physics in nuclei far from the valley of stability. Utilizing the radioactive beams at the Chinese large-scale facilities such as the Heavy Ion Research Facility in Lanzhou (HIRFL) in IMP and the future's High Intensity heavy-ion Accelerator Facility (HIAF), this novel $LaBr_3$(Ce) array would lead to a significant boost to the frontiers of exotic-nuclei research, which will guide scientists towards the comprehensive and even beyond-traditional understanding of nuclear forces and nucleosynthesis.

Key words: structure of exotic nuclei; magic number; In-beam gamma spectroscopy; NaI(Tl) detector array; LaBr3 detector array

CLC number: O572.21$^+$2 **Document code:** A **DOI:** 10.11804/NuclPhysRev.34.03.332

1 Introduction

Nuclear physics encompasses the quest to understand the origin, structure and evolution of matters in the universe. The properties of atomic nuclei govern the creation and evolution of the chemical elements from deuterium to uranium through nuclear reactions in the stars and stellar explosions[1,2]. A complete understanding of the structure of atomic nucleus is essential to elucidate the nuclear astrophysical processes in the nucleonsynthesis.

Atomic nucleus is a many-body system composed of neutrons and protons. The current models predict the existence of approximately 7,000 different nuclei with all possible combination of protons and neutrons. So far, 3,000 different nuclei have been discovered, in which only 300 form stable nuclei and exist in nature, as displayed in the nuclear chart (Fig. 1). The wealth of nuclear interactions and their interplay in a nucleus (such as spin-orbit interactions, three-body forces, Isospin $T=0$ and $T=1$ pairing interactions) lead to very different nuclear structures in various regions of the nuclei chart, making it remarkable in the world of quantum physics.

The "magic number" is the most fundamental quantity governing the nuclear structure. The concept of nuclear magic number (2, 8, 20, 28, 50, 82 and 126) in nuclear structure was introduced by the discovery of particularly stable nuclei with specific proton (Z) and neutron numbers (N)[3,4]. By examining a large number of precise experimental data close to the β-stability, these magic numbers were then recognized

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Received date: 10 Dec. 2016; **Revised date:** 25 Apr. 2017

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as a consequence of underlying nuclear shell structure given by a mean field potential plus a strong spin-orbit interaction[3, 4] as the discovery of the 1963 Physics Nobel Prize. Along this direction, a vast amount of nuclear data was then interpreted simultaneously. Therefore, nuclear magic numbers are regarded as cornerstones to the studies of nuclear physics. However, the magic numbers marking the complete filling of a nuclear shell are well established for stable nuclei, but are not universal over the nuclear chart.

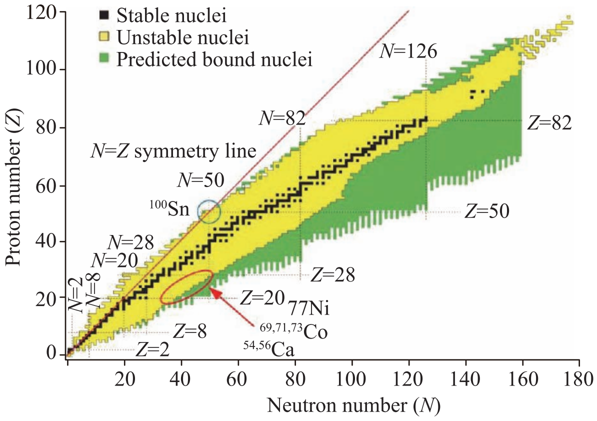

Fig. 1 (color online) Nuclear chart. The horizontal and vertical axes represent N and Z, respectively.

The recent experimental works exploiting radioactive ion beams revealed that the nuclear shell structure sometimes changes drastically towards the exotic nuclei (with unbalanced N/Z ratios), giving rise to the emergence of “new” magic numbers while the “classical” may vanish. Well-known examples are the weakening or even disappearance of shell closures occurs in neutron-rich nuclei at N=8[5], the new N=16 magic number for ^{24}O[6−8], and the neutron N=20 shell gap quenching in ^{34,36,38}Mg[9]. And the more recent work in heavier nuclei demonstrates the weakening of the N=28 shell closure in ^{42}Si[10−12] and the new magic number N=32 in ^{52}Ca[13] and N=34 in ^{54}Ca[14]. These surprising discoveries challenge our understanding in the fundamental nuclear interactions and reveal the novel aspects of nuclear forces such as tensor and three-body forces[15,16] which play dominant role in nuclei.

Verifying conventional/new magic nuclei and evolutions of shell closure far from the β-stability are thus the main subjects in modern nuclear physics to advance the knowledge of fundamental forces and benchmark theories describing nuclear structure. In particular, “doubly magic” nuclei are of importance as they provide a reasonable scheme for nuclear shell models to truncate their configuration space by assuming an inactive doubly magic core. This truncation makes it feasible to calculate properties of complex nuclei in the vicinity of doubly magic cores. Besides advancing the nuclear structure models, a better understanding and predictability of nuclear forces are also crucial to understand how the properties of the nucleon-nucleon forces impact the abundance curve and the synthesis of heavy elements in the universe[1, 2].

2 Physics goals

The research interest of HKU group is to explore the evolution of shell closures and examine the magicity of extremely exotic nuclei with classical magic numbers in heavier mass regions. Our group has employed in-beam gamma-ray spectroscopy technique with direct reactions to investigate ^{30}Ne (N = 20) and the nuclei around ^{78}Ni (Z=28, N=50). Our ^{30}Ne result clearly indicates the vanishing of N = 20 magicity with large intruder *pf* configuration; while in ^{77}Ni spectrum, the observed ∼ 2.5 MeV gamma transition coupled with low-lying states implies the core-excited states which suggests the relatively strong magicity at Z = 28 and N = 50 (papers in preparation). The ^{69,71,73}Co (Z = 27) spectrum in analysis will provide information about the development of deformation in the mass region southeast of ^{68}Ni and investigate the shell evolution between N=40 and N=50 on the less-proton side of Z=28. Also, the ^{97,99}Kr (Z = 36) spectrum in analysis can also shed light on the nuclear deformation mechanism. On the other hand, the approved future’s experiment on spectroscopy of ^{53,54,56}Ca, proposed by our group, will give us the spectroscopic factor to quantify the probability of the ground state being a closed shell (“magic index”) at N=34 and the systematics study of the first 2^+ state for shell evolution toward N = 40. All these experimental data will serve stringent constraints to establish reliable theories for understanding of nuclear forces.

Our next goal is to investigate the structure of ^{100}Sn (N=Z=50), particularly the energy of the first 2^+ state, and the low-lying states in the neighboring nuclei (^{101}Sn, ^{99}Cd, ^{99,100}In) via in-beam gamma spectroscopy technique using RIKEN facility. ^{100}Sn, the heaviest existing self-conjugated nucleus, has long been an interesting topic because of its unique nucleon number. Both neutron and proton number N = Z =50 are magic numbers in the valley of stability. It is therefore expected that ^{100}Sn behaves as a doubly magic nucleus. Experimental information on ^{100}Sn is however scarce due to its extremely low production cross section. Only recently, the decay properties of the ^{100}Sn ground state have been studied in detail[17], but no excited state of ^{100}Sn has been identified so far. This nucleus serves as a launching point for nuclear shell models to probe the A = 100 nuclei around proton drip line. In addition, the identical proton and neutron numbers make ^{100}Sn an ideal case to study the proton-neutron interaction with both isospin channels, T = 0 and 1, in details, which has been suggested to play an important role in the nuclear structure of lighter N = Z nuclei[18,19]. Located on the path of rapid proton capture process (rp-processes) and at the proton drip-line, ^{100}Sn is also considered as a key nucleus in nuclear astrophysics. In order to describe the nucleo-synthesis in thermos-nuclear explosions, and in particular, to determine the highest mass number that can be produced in the rp-process, nuclear structure information on $A\sim$100 nuclei is required.

One of the first observables, together with mass and half-life, that gives indication on the structure information of the even-even nuclei is the energy of the first 2^+ excited state ($E_{\rm x}(2^+)$). We therefore aim at measuring the location of the first 2^+ excited state of ^{100}Sn to infer the magicity of Z=50 and N=50 simultaneously. Several theoretical predictions for the energy of the first 2^+ state are summarized in Fig. 2. All calculations predict a high energy, between 3.7 and 5.2 MeV, similar to the double magic ^{132}Sn nucleus and significantly higher than for the tin isotopes between N=50 and 82. However significant differences between the different calculations can be observed in $E_{\rm x}(2^+)$ as well as the general excitation spectrum of ^{100}Sn. According to large-scale shell model calculations, the $E_{\rm x}(2^+)$ in ^{100}Sn lies somewhere between 3 and 5.2 MeV[20,21]. On the other hand, $E_{\rm x}(2^+)$ of 3.7 and 5.2 MeV are predicted using the relativistic quasiparticle random-phase approximation formalism based on Hartree-Fock[22] or relativistic Hartree-Bogoliubov mean field[23]. An experimental determination of the value of $E_{\rm x}(2^+)$ is therefore essential in clarifying the underlying driving forces.

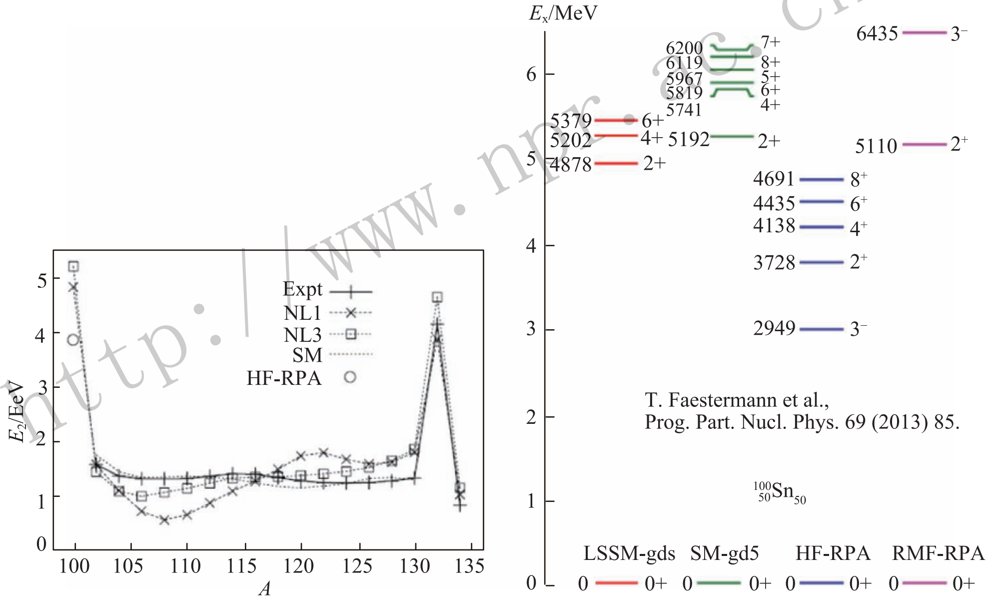

Fig. 2 (color online) (a) Excitation energy of the first 2^+state along the Sn isotopic chain calculated[23]. Also plotted are shell-model predictions (dashed line), HF-RPA calculations[22] and experimental values (crosses). (b) Predicted excitation spectra for ^{100}Sn. (see text)

In addition to the excitation energy of the first 2^+ state, the location and occupation of single-particle and hole orbits give valuable information on the magicity of a nucleus. These single-particle orbitals can be probed by studying the neighboring odd-even nuclei. In the case of ^{100}Sn, we are particularly interested in the low-lying excitations of ^{99}In and ^{101}Sn. These nuclei should be described as a single proton hole (^{99}In) or single neutron particle (^{101}Sn) outside the presumably doubly magic core ^{100}Sn. Excited state spectroscopy of these nuclei will probe the single-particle orbitals, and give information on the rigidity of the core ^{100}Sn by comparison with theoretical predictions and extrapolations (Fig. 3(a)). We therefore aim at the identification of all low-lying single-particle and hole levels outside of ^{100}Sn.

Along the Sn isotopic chain, it has recently been discovered that the ground state of ^{101}Sn ($Z=50, N=51$) has spin and parity $7/2^{+}$[24]. This is in contrast to the heavier Sn isotopes where the ground state is known to be $5/2^+$. Furthermore this inversion of the $5/2^+$ and $7/2^+$ states in ^{101}Sn was not expected from

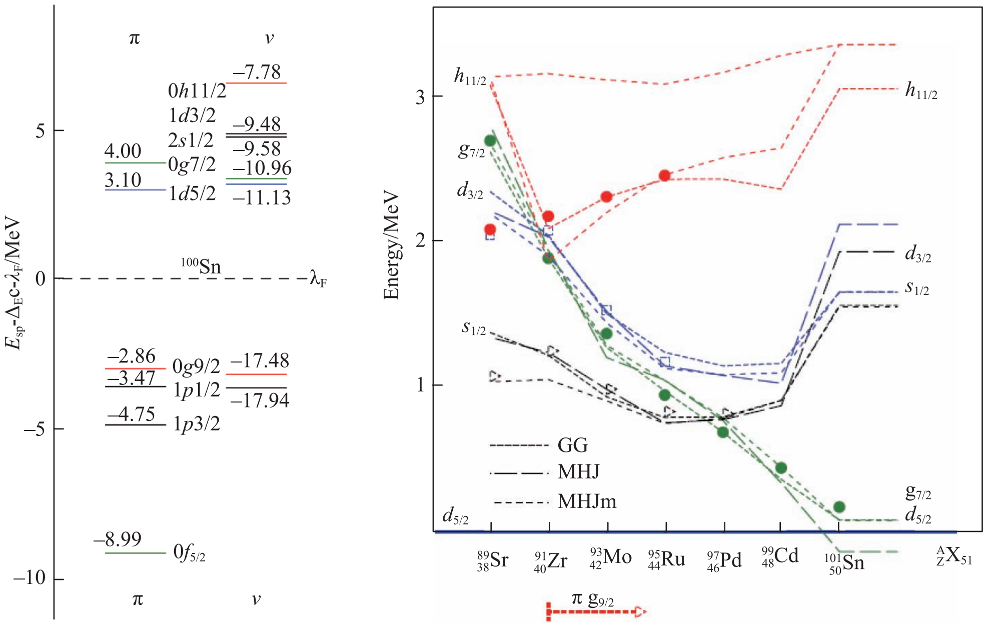

Fig. 3 (color online) (a) Single particle/hole energies for ^{100}Sn. Levels are labeled by their energies $E_{\rm sp}$ and shown relative to the middle of the gap $\lambda_{\rm F}$, which accounts for Coulomb shift $\Delta E_{\rm c}$ between protons and neutrons[21]. (b) Neutron single particle orbitals relative to the $d_{5/2}$ level for N=51 isotones[21](see text).

earlier shell-model calculations. The measurement of an excited state in ^{101}Sn (J=5/2$^+$ at 172 keV)[24] suggests an inversion of the $d_{5/2}$ and $g_{7/2}$ single-neutron levels at N = 51[25]. However spin assignments in ^{101}Sn are only tentative and no other excited state has been identified so far. The evolution of neutron single-particle orbitals as a function of proton number is shown in Fig. 3 (b). Phenomenological (labeled GG) as well as realistic G-matrix based predict a rise in energy of the $3s_{1/2}$ and $2d_{3/2}$ with respect to the $2d_{5/2}$ orbital as the magic proton number $Z = 50$ is approached. This behavior is so far experimentally not confirmed as single-particle like states in ^{99}Cd and ^{101}Sn remain unknown. ^{99}Cd has been extensively studied through fusion evaporation reactions, and a number of high spin states are established. Single-particle like states, however, are unknown, and therefore more experimental information on the $N = 51$ nuclei close to ^{100}Sn is highly desired.

3 Experimental technique

While fuller fundamental understanding of nuclear forces and nucleosynthesis would be achieved (*eg.* around ^{100}Sn region) via in-beam gamma spectroscopy technique using the DALI2 NaI(Tl)-based gamma-ray spectrometer[26] at RIKEN, the next significant new insights into the structure of nuclei would then require new gamma-ray detection array capable for higher precision gamma-ray spectroscopy.

Gamma-ray spectroscopy study at relativistic beam energies with the current state-of-the-art detection array is hampered by either the lack of either the energy resolution of the currently available NaI(Tl) based or the efficiency of the high-purity Ge based gamma-ray spectrometers, as shown in Table 1. Recently, with the rapid development of scintillation detector technology, new material LaBr$_3$(Ce) has entered the market that greatly surpass traditional scintillators in terms of energy resolution (2% FWHM at 1 MeV), time response (<500 ps), and efficiency as well as detection rate capability. The high efficiency is essential to construct the level schemes with multiple γ-decays from γ-γ coincidence detection. Due to its highly reduced price compared to Ge material, LaBr$_3$(Ce) is an excellent choice to build a spectrometer. A 4π LaBr$_3$(Ce)-based gamma-ray spectrometer will open a very broad field of nuclear structure studies, so far inaccessible. It also allows scientists to fully exploit and utilize beams of exotic nuclei for research ranging from basic nuclear structure studies over nuclear astrophysics to applied nuclear physics.

Table 1 Comparison of the characteristics of different detectors.

Crystal type	Intristic energy res/ (1 MeV, %)	Time res./ns
NaI(Tl)	7	5
CsI(Na)	8	Poor
HPGe	0.2	~10
LaBr$_3$(Ce)	2	0.2

The HKU group is currently in collaboration with the Nuclear Structure Group at the Institute of Modern Physics (IMP) of CAS and the China Institute of Atomic Energy (CIAE) for the design and construction of this novel $\mathrm{LaBr_3(Ce)}$-based gamma-ray spectrometer. We propose to construct a new-generation gamma-ray detection array based on the novel scintillator $\mathrm{LaBr_3(Ce)}$ to explore the new physics in nuclei far from the valley of stability. This whole array at the first-phase consists of 100 $\mathrm{LaBr_3(Ce)}$ crystals, providing exceptionally high energy resolution (3%) and full-energy peak efficiency (15%) for 1 MeV gamma-rays as well as excellent timing resolution (300 ps). The full-energy peak efficiency is the GEANT4 simulation result based on the detector size and the configuration of 100 crystals. This state-of-the-art array would be the world's only large-scale $\mathrm{LaBr_3(Ce)}$ array with superior gamma-timing-energy resolution, significantly enhancing the gamma-ray detection ability in the measurements of exotic nuclei. Utilizing the radioactive beams at the Chinese large-scale facilities such as the Heavy Ion Research Facility in Lanzhou (HIRFL) in Institute of Modern Physics and the future's High Intensity heavy-ion Accelerator Facility (HIAF), this novel $\mathrm{LaBr_3(Ce)}$ array would lead to a significant boost to the frontiers of exotic-nuclei research, which will guide scientists towards the comprehensive and even beyond-traditional understanding of nuclear forces and nucleosynthesis.

4 Summary and outlook

Currently, other countries such as US and Japan have to continue their development of HPGe array started years ago and have very limited resources for the recently achievable novel $\mathrm{LaBr_3(Ce)}$ crystals. By carrying out this proposed project, China therefore would take a lead worldwide in the application of $\mathrm{LaBr_3(Ce)}$-based detector technology, opening a very broad field of nuclear structure studies which so far is inaccessible. In addition, the proposed novel $\mathrm{LaBr_3(Ce)}$ array will have broad applications on nuclear medicine, such as gamma imaging etc. This proposed LaBr3 would sufficiently promote China international impact and influence on nuclear physics research.

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香港大学在束伽玛谱学研究与新一代伽玛探测器阵列

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摘要： 探索原子核的壳层演化，验证奇特核的幻数结构是香港大学核物理研究的重要方向。目前，科研团队利用在束伽玛谱学技术已经研究了^{30}Ne 的 $N=20$ 幻数消失和 ^{78}Ni ($Z=28$，$N=50$) 附近原子核的双幻数结构，而即将开展的^{53,56}Ca 在束伽玛谱学实验会对新幻数 $N=34$ 的定量研究，以及到 $N=40$ 核的壳层演化提供重要的数据。下一步的研究目标是探索^{100}Sn ($N=Z=50$) 的奇特结构，特别是研究它的第一个 2^+ 激发态与其邻近原子核的低激发态性质。^{100}Sn 处于质子滴线以及核天体快质子俘获路径上，因此，它的幻数结构及其临近原子核单粒子性能研究将会极大增强对核力和核合成机制的认识。为了进一步提高物理实验统计，香港大学在数量上增加了 30% NaI(Tl) 晶体从而全面升级了 DALI2 伽玛探测阵列。此外，为了探索远离稳定线核区的新物理，开展更高精度在束伽玛谱学实验，香港大学与中国科学院近代物理研究所、中国原子能科学研究院计划合作研制基于溴化镧晶体的新一代伽玛探测器阵列。这套阵列主要在兰州重离子加速器 (HIRFL) 和将来建成的强流重离子加速器 (HIAF) 等大科学装置上开展实验, 从而在奇特核研究方面取得大量重要的成果，促进科研人员全面认识、理解核力以及天体核合成过程。

关键词： 奇特核结构；幻数；在束伽玛谱学；碘化钠探测阵列；溴化镧探测阵列

收稿日期： 2016-12-10； **修改日期：** 2017-04-25

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