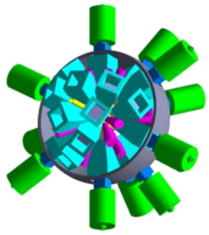
पीएलएफ में हाइब्रिड आईएनजीए के साथ नाभिकीय समावयवी

13

नाभिकीय समावयवी और अनुप्रयोग

आर. पालित
नाभिकीय एवं परमाणु भौतिकी विभाग, टाटा मूलभूत अनुसंधान संस्थान, मुंबई-400005, भारत



समावयवी स्पेक्ट्रमिकी के लिए हाइब्रिड आईएनजीए

सारांश

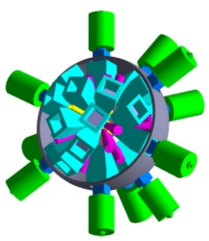
भापअ केंद्र-टीआईएफआर पेलेट्रॉन लीनॉक सुविधा (पीएलएफ) में नाभिकीय समावयवी के हाल के अन्वेषण का एक प्रेक्षण यहां प्रस्तुत किया गया है। नाभिकीय संरचना मॉडल की पूर्वानुमान शक्तियों के परीक्षण के लिए सममितीय अवस्थाओं के स्तर जीवनकाल और विद्युत चुम्बकीय क्षणों का माप महत्वपूर्ण है। N = 82 कवच अंतराल के पास समावयवी स्पेक्ट्रोमिकी के माप से चयनित परिणाम प्रस्तुत किए जाते हैं। इसके अलावा, ^{108}Ag में एक दीर्घकाल रहने वाले समावयवी के आसपास निम्न स्तर की स्थितियों के स्पेक्ट्रोमिकी माप के परिणामों की चर्चा निम्न स्तर की स्थितियों के माध्यम से प्रेरित समावयवी की कमी के संदर्भ में की जाती है। त्वरकों का उपयोग करके समावयवी स्पेक्ट्रमिकी में अनुसंधान के भविष्य की दिशा पर चर्चा की जाएगी।

Nuclear Isomers with Hybrid INGA at PLF

13

Nuclear Isomers and Applications

R. Palit
Department of Nuclear and Atomic Physics, Tata Institute of Fundamental Research, Mumbai-400005, INDIA



Hybrid INGA for Isomer Spectroscopy

ABSTRACT

An overview of the recent investigations of nuclear isomers at the BARC-TIFR Pelletron Linac Facility (PLF) is presented here. The measurements of level lifetimes and electromagnetic moments of the isomeric states are crucial for testing the predictive powers of nuclear structure models. Selected results from measurement of isomer spectroscopy near N=82 shell gap are presented. In addition, the results of spectroscopic measurements of low-lying states around a long-lived isomer in ^{108}Ag are discussed in the context of induced isomer depletion through the low-lying states. The future direction of research in isomer spectroscopy using the accelerators will be discussed.

KEYWORDS: *Nuclear Isomers, Lifetime measurements and electromagnetic moments*

**Author for Correspondence: R. Palit*
E-mail: rpalit@tifr.res.in

Introduction

Nuclear isomers were discovered by German Chemist Otto Hahn in 1921. The discovery of nuclear isomers by Hahn marked the birth of the field of nuclear structure. Isomers have fundamental importance in nuclear structure physics [1]. An isomer is a metastable state of a nucleus with a lifetime greater than 1 ns, caused by the hindrance of the decay process back to lower excited states. There are three main reasons for this hindrance. The first is the difference in the structural wave functions between the initial and final states. The other two reasons are the small decay energy and the significant change in angular momentum. Isomers can be classified based on the hindrance mechanisms affecting their decays. In spherical regions, they are categorized as spin and seniority isomers. In deformed regions, they are classified as shape, K, and fission isomers [1,2]. Nuclear isomers are produced within the same nucleus (N, Z) due to the different arrangement of nucleons. Isomers are crucial in basic nuclear structure studies, nuclear astrophysics, and energy storage in isomeric states. These isomeric states play an important role in testing the predictions of shell and collective models for nuclear structure. Using discrete gamma-ray spectroscopy, the excited levels of nuclei can be studied through different nuclear reactions. Nuclear moments are very sensitive probes that help us understand the detailed composition of the nuclear wave function.

This article will discuss the available experimental facilities for studying nuclear isomers at PLF and the selected results from isomer spectroscopy. We will also describe the scope of future research on this topic at PLF.

Experimental Facilities for Studying Isomers

Two experimental setups are used to investigate nuclear isomers. The first is for gamma-ray spectroscopy using a hybrid array of Compton-suppressed clover HPGe detectors coupled with $LaBr_3$(Ce) scintillator detectors. The other is for the time differential perturbed angular distribution (TDPAD) measurement. Brief descriptions of the setups and experimental results are given below.

Hybrid INGA for isomer spectroscopy

The gamma detector array at BARC-TIFR, PLF in TIFR can accommodate 24 Compton-suppressed HPGe clover detectors and 18 $LaBr_3$(Ce)/$CeBr_3$(Ce) detectors for fast timing measurements [3,4]. The Digital Data Acquisition system has been upgraded recently to a root-based multi-threaded software named TIFR Digital Data Acquisition Software for Nuclear Structure Studies (TIDES)" developed at TIFR to control and acquire data from PIXIE16 DGF from XIA for the hybrid configuration of 100 MHz for clovers coupled with 250 MHz or 500 MHz digitizers for different type of ancillary detectors with slow and fast signals. This hybrid spectrometer can perform lifetime measurements of excited nuclear states in the 50 ps to 2 microsec range to extract information on nuclear structure and isomers.

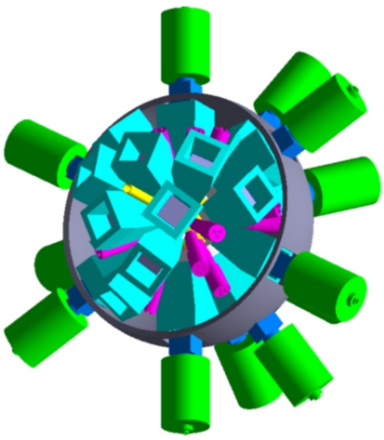


Fig.1: Schematic diagram of the hybrid INGA at PLF.

TDPAD setup at PLF and g-factor measurements

The g-factors of isomeric states were measured using the TDPAD method at the PLF facility. A split-coil superconducting magnet from American Magnetics, Inc. (AMI), capable of generating up to 7 T magnetic fields with 0.1% stability and 0.5% uniformity over a 1 cm diameter spherical volume, was used for magnetic moment measurements. The experiment employed a pulsed beam with 1 ns pulse width and 800 ns separation between pulses. Delayed γ-rays from the isomers were detected by four HPGe detectors positioned at $\pm 45^{o}$ and $\pm 135^{o}$ relative to the beam, 11 cm from the target. The detectors had a time resolution of ~5 ns (FWHM) for the 1173- and 1332-keV γ-rays from a ^{60}Co source. A time-to-amplitude converter (TAC) was started by the HPGe detector's time signal and stopped by the RF signal. Data were collected in LIST mode for energy and time signals from the four detectors, and two-dimensional energy vs. time spectra were constructed. Time difference spectra for γ-rays decaying from isomeric states were generated, and normalized counts N(θ, t) were used to create spin rotation spectra.

Selected Results

Several experiments have been conducted to study isomer spectroscopy across the nuclear landscape. This article highlights some physics results from these experiments related to testing nuclear shell model predictions and the depletion of long-lived isomers.

Our research focuses on nuclei near the N = 82 shell gap, gaining significant experimental and theoretical attention. In the Z > 50 transitional nuclei around A ≈ 135, for N < 82, a rich

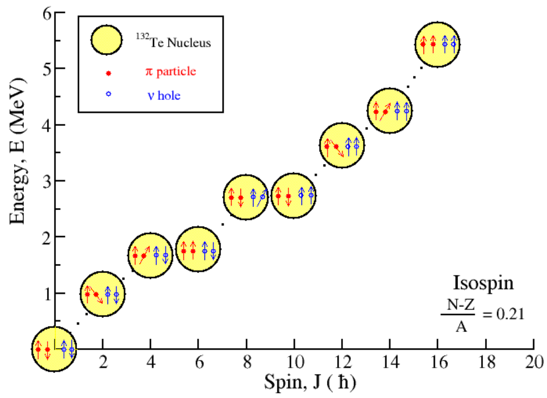


Fig.2: A schematic picture showing the alignment of the two proton particles in $g_{7/2}$ orbital and two neutron holes in $h_{11/2}$ orbital as a function of Spin(J) and Energy(E) in ^{132}Te (see Ref. [5]).

and complex level structure emerges due to the interplay of single-particle and collective excitation modes.

One crucial question is: How do we understand the competition of neutrons and protons in forming the high-spin states near the doubly magic ^{132}Sn? With the two proton particles and two neutron holes, the ^{132}Te is an interesting isotope near the doubly magic nucleus ^{132}Sn for studying the competition of protons and neutrons in forming sequences of high-spin states. Our experimental study provides new information on the *nn, pp* and *pn* interactions used in the shell model calculations to describe the level scheme of ^{132}Te. The states till 6^+ arise mainly due to the alignment of proton particles in the $g_{7/2}$ orbital, and the 8^+ and 10^+ states are due to the alignment of neutron holes in the $h_{11/2}$ orbital. In the present work, higher spin states above the 10^+ isomer have been observed, and these states arise because of the simultaneous alignment of protons and neutrons. The prompt-delayed coincident data from INGA complements the fragment-gated gamma spectroscopy data from EXOGAM-VAMOS++ and makes a firm assignment of the placement of various transitions in the level scheme of ^{132}Te with long-lived isomers [5]. Large-scale shell model calculations using the existing jj55pna interaction can predict the low-spin states, but deficiencies remain in the high-spin states. A similar study has been conducted for ^{66}Cu using a multi-nucleon transfer reaction [6].

The study of isomers in transitional nuclei around the A ≈ 135 region, which can be studied using low-energy stable beam accelerators, is particularly interesting due to the nuclear structure's evolution from spherical to deformed shapes as it moves away from the shell gap. These transitional nuclei between spherical and deformed regions present a significant challenge to nuclear models, particularly in studying high-spin structures. Experimental studies of nuclei near closed shells are ideal for testing evolving shell model predictions based on effective interactions, as well as projected shell model calculations. With recent advances in large-scale shell model (LSSM) calculations near A ≈ 130, it is now possible to study both transitional and closed-shell nuclei using the same effective interactions. The occupation of high-j orbitals by protons and neutrons leads to various structural phenomena, such as magnetic and chiral rotations, wobbling motion, and high-spin isomers. Many high-spin isomers with simple multi-quasiparticle configurations have been reported in this region, especially in nuclei near the N = 82 shell closure.

Lanthanum isotopes contain numerous low- and high-spin isomers, offering insights into nuclear structure changes as they approach the N = 82 shell gap. Experiments at the Pelletron Linac Facility (PLF) at TIFR, Mumbai, have investigated these isomers, while RCNP, Osaka University, has studied ^{135}La and ^{136}La using a Nitrogen-17 radioactive beam. The Z = 57 lanthanum isotopes are enriched with many low- and high-spin isomers. These isomers provide useful insight into the evolution of the nuclear structure of the lanthanum isotopes as we move toward the N = 82 shell closure. Recently, a longitudinal wobbling band has been found in ^{133}La, feeding the $11/2^-$ isomeric state in ^{133}La [9, 18]. The measurement of the nuclear moment of the $11/2^-$ isomeric state is needed to understand the structure of ^{133}La. The $11/2^-$ isomeric state at 535 keV in ^{133}La was studied using the reaction ^{126}Te(^{11}B, 4n)^{133}La at 52 MeV, with results reported by Laskar *et al*. The ^{126}Te target created a non-zero electric field gradient (EFG), causing the ^{133}La nuclei to experience both magnetic dipole and electric quadrupole interactions. The lifetime of the $11/2^-$ isomer was measured as 68.01 ± 0.41 ns, consistent with previous values. The spin-rotation spectrum indicated a strong damping due to perturbations, with extracted values of ω_L = 111.4 ± 6.7 Mrad/s and ω_Q = 8.0 ± 1.0 Mrad/s. For these, the g-factor was determined to be 1.16 ± 0.07, close to the value estimated for pure magnetic interaction (1.19 ± 0.06). The spectroscopic quadrupole moment was found to be 1.71 ± 0.34 b.

The level energy of the $11/2^-$ isomers in odd mass La nuclei increases, and the half lifetime decreases monotonically from ^{125}La to ^{139}La. The $11/2^-$ level is largely $h_{11/2}$ proton-dependent configuration. The results from LSSM calculations for the spectroscopic quadrupole moments and g-factors of these states in odd-A La isotopes are presented in Table 2 of Ref [6]. The quadrupole moment of ^{139}La (N = 82) was found to be relatively small. However, the quadrupole moment increases gradually as the neutron number decreases, indicating increased quadrupole collectivity. The LSSM quadrupole moment of ^{133}La was obtained as 1.25 b compared to the experimental value of 1.71 ± 0.34 b. On the other hand,

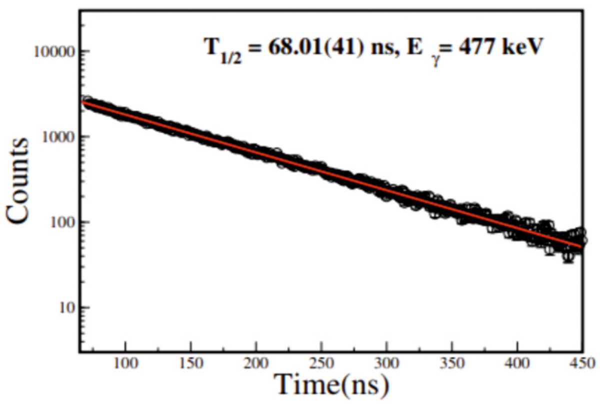


Fig.3: Decay curve for the 477 keV gamma-ray emitted from $11/2^-$ isomer in ^{133}La (adopted from Ref.[7]).

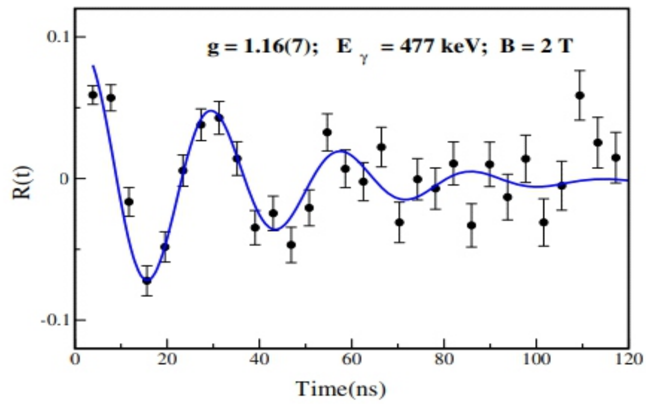


Fig.4: Spin rotation spectrum at B_{ext} = 2 T for the $11/2^-$ isomeric state of ^{133}La (Ref 7).

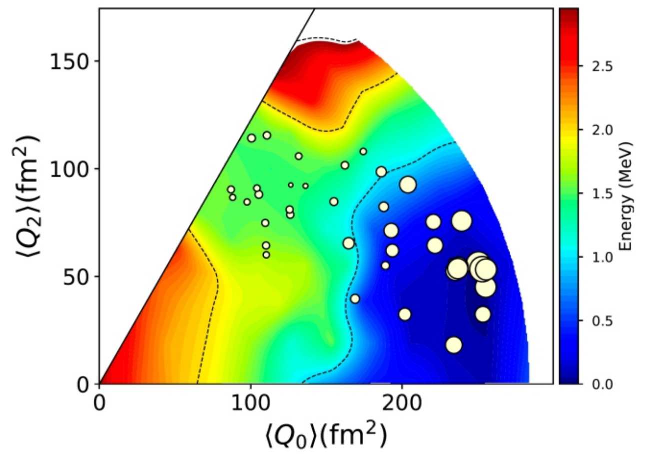


Fig.5: The T-plot for the 11/2$^-$ state in ^{133}La. The locations of the circles indicate the intrinsic shape of the MCSM basis states. (Ref 7].

the g-factors of the isotopes instead show a constancy indicative of a proton $h_{11/2}$ configuration-based structure. To discuss the intrinsic shape of the 11/2$^-$ state of ^{133}La in terms of the shell-model framework, Laskar *et al.* [7] presented the energy surface and the T-plot of the Monte Carlo shell model (MCSM) calculations. The published figure is reproduced in Fig.5. The contour lines represent the energy surface obtained by the quadrupole-constrained Hartree-Fock method utilizing the same shell-model Hamiltonian. The prolate minimum with modest triaxiality at Q_0 = 260 fm^2 is retrieved from the potential energy surfaces, corresponding to the deformation parameter β = 0.16. The LSSM provides the β value of 0.19, assuming K = 1/2. In another study, the *g* factor of an isomeric state at 2738 keV in ^{135}La was measured using the TDPAD technique. The measured g-factor of the high spin isomer, along with the LSSM calculations, was used to assign the configuration of the isomer in particular and then describe the level scheme of ^{135}La [8].

The nuclear isomers have the potential to provide material with the highest energy storage capacity with controlled release of its energy on demand. Spectroscopic measurement of the excited states around these isomers has become a topic of immense importance due to its crucial role in estimating the depletion pathway of the isomer and the concerned rate. The ^{108}Ag nucleus has been a subject of investigation for the study of isomer depletion due to the presence of a long-lived isomer with $T_{1/2}$ = 438 years at low spin and high production of this isomer through (n, gamma) cross-section using stable ^{107}Ag isotope. We have recently identified three possible transitions at energies below 500 keV from the isomer to the higher excited levels, whose subsequent decay can branch to the ground state in ^{108}Ag [9]. Our measurement will help improve the cross-section estimation for induced isomer depletion via these states. Recent developments on isomer depletion related to energy storage are described in Ref. [11].

Conclusion and Future Scope

Selected results from isomer spectroscopy carried out at PLF have been discussed. Prompt-delayed spectroscopy was carried out to develop the level schemes of neutron-rich ^{66}Cu and ^{132}Te isotopes. In the case of odd-A La isotopes, the g-factor of the isomeric states is discussed. These experimental results provide an excellent testing ground for the predictions of the modern shell model calculations. The deviations of the shell model predictions from the experimental data suggest the scope for improving the shell model calculations. A new configuration of high-efficiency gamma-ray detectors coupled with different ancillary systems, namely $LaBr_3$(Ce)/$CeBr_3$(Ce) detectors, active BGO collimators and CsI(Tl)/Si detectors, is proposed at PLF [10]. It aims to exploit the broad types of accelerated ions and beam pulsing systems available at the accelerator facility. Our main objectives are to investigate the coupling of single particles with collective vibrational modes, exotic modes of nuclei, rare decay modes of nuclei, nuclear isomers, reaction dynamics and applications of isomers in applied research.

Acknowledgements

The author would like to acknowledge the INGA collaborators for the success of the experiments. The author acknowledges the contributions of Dr Md. S. R. Laskar, Dr. S. Biswas, Dr J. Sethi, Dr. P. Singh and Prof. S.N. Mishra are acknowledged. The author thanks Prof. N Simuzu and Prof. Y. Utsuno for the calculations on the La isotopes. This work was partially funded by the Department of Atomic Energy, Government of India (Project Identification No. RTI 4002) and the Department of Science and Technology, Government of India (No. IR/S2/PF-03/2003-II). The author also thanks the Pelletron LINAC Facility staff for providing excellent beams during all experimental campaigns.

References

[1] P.M. Walker, G. Dracoulis, Nature 399, 6731 (1999).

[2] R. Palit et al., EPJST 233, 933 (2024).

[3] R. Palit et al., Nucl. Instr. Meth. Phys. Res. A 680, 90 (2012).

[4] Md S R Laskar et al., Phys.Rev. C 104, L011301 (2021).

[5] S. Biswas et al., Phys.Rev. C 93, 034324 (2016).

[6] P. Singh et al., Eur. Phys. J. A 53, 69 (2017).

[7] Md S R Laskar et al., Phys. Rev. C 101, 034315 (2020).

[8] Md S R Laskar et al., Phys. Rev. C 99, 014308 (2019).

[9] J. Sethi et al. J.Phys.(London) G43, 015103 (2016).

[10] B. Das et al., Nucl. Instr. Meth. Phys. Res. A 1060, 169030 (2024).

[11] J.J. Carroll et al., EPJST 233, 1151 (2024).