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Nuclear structure at the limits: Continued exploration with Gammasphere

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More than a decade after the large γ-ray detector arrays came into operation, their impact is as large as ever. A few examples from Gammasphere are discussed here. They illustrate that the arrays make substantial contributions, not only in areas where they were expected to do so such as studies of nuclei at high angular momentum, but also in other domains such as nucleosynthesis, for example.

1. Introduction

Construction of the Gammasphere array [1] was completed in 1995. Over the past ten years, the array has been used both to address the scientific issues for which it had originally been designed, and to study other pressing nuclear physics questions for which its use was not envisioned at the time the instrument was proposed. The same can, of course, also be said of Gammasphere's European competitor arrays Euroball and Gasp [2]. Through a number of examples, this presentation aimed to demonstrate that substantial progress in our understanding of the nucleus has been achieved. Because of their detection sensitivity, there is little doubt that the large γ-ray arrays will also continue to impact our field for the foreseeable future.

2. Nuclei at High Angular Momentum

The discovery of superdeformation in the ^{152}Dy nucleus [3] played an important role in making the scientific case for the construction of large detector arrays of Compton-suppressed spectrometers with high efficiency, good energy resolution and high resolving power [4]. The signal of a superdeformed band is indeed so weak that detection systems of earlier generations were unable to address essential properties such as the excitation energy and quantum numbers of the superdeformed states or the nature of the excitations in the second well. As shown in Ref. [5], the excitation energy, spin, and parity of the yrast superdeformed band in ^{152}Dy have now been firmly established with Gammasphere through the measured properties of a number of high-energy (∼ 4 MeV) single-step transitions connecting directly the superdeformed levels with the yrast states. Furthermore, while most excited superdeformed bands can be understood in terms of quasi-particle excitations where intruder orbitals play an important role [6], evidence is now also available for an excited superdeformed band in ^{152}Dy associated with a collective octupole vibration [7].

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Recently, the large arrays have also enabled further exploration of the nuclear deformation space and first evidence has appeared for triaxial shapes. Data from Euroball and Gammasphere on ^{163}Lu provide evidence for this new collective excitation through the discovery of three strongly deformed bands with remarkably similar rotational properties. In this case, the two excited bands are understood as one-phonon and two-phonon wobbling excitations built on the lowest-lying triaxial superdeformed band [8]. All the properties of the bands, and in particular their in- and out-of-band deexcitation patterns, are in good agreement with particle-rotor calculations for wobbling excitations. However, many open questions remain. For example, the extent of the region where wobbling occurs is at present poorly known. Also, a number of cases have been proposed in Hf nuclei with mass A $\sim$ 175 [9], but the experimental evidence is ambiguous [10]. Triaxiality has also been invoked to account for the so-called chiral doublet bands seen in the A $\sim$ 135 region. Partner bands built on the $\pi h_{11/2}\nu h_{11/2}$ two-quasiparticle configuration have been identified in a number of odd-odd Cs, La, Pm and Pr nuclei [11]. Aplanar solutions of 3D tilted axis cranking calculations for triaxial shapes define left- and right-handed chiral systems out of the three angular momenta provided by the valence particles and the core rotation [12]. This mode leads to spontaneous chiral symmetry breaking and to the doublet bands seen experimentally. This essentially geometrical picture has recently received further confirmation through the discovery of chiral bands built on a three quasi-particle configuration in ^{135}Nd [13].

3. Nuclei at the edges of Stability

Over the last few years, the study of nuclear properties has increasingly focussed on nuclei at the very edge of stability, be it along the proton drip line, at the highest Z values or on the neutron-rich side of the valley of stability, in order to address the challenge of developing our knowledge of the nuclei we know well to describe the whole nuclear landscape. Investigations of these nuclei often require the use of the large γ-ray detector arrays in combination with other detection systems, new techniques and reaction modes.

Not so long ago, proton emitters were investigated with the aim of understanding the process itself. More recently, proton radioactivity has become a powerful spectroscopic tool providing insight into structural properties beyond the proton drip line. For example, studies at Gammasphere uncovered rotational bands feeding the ground state and the isomeric state in the proton emitter ^{141}Ho [14] using the recoil-decay tagging method. The data give direct evidence that ^{141}Ho is deformed, provide the value of the quadrupole deformation, and indicate that the nucleus could be triaxial in its ground state. The latter property had not been considered in descriptions of proton emission and has been the subject of much theoretical debate ever since. Experimental studies continue with the recent investigation at Gammasphere of level structures based on proton emitting states in the $^{145-147}$Tm isotopes aiming at mapping the evolution of deformation at the drip line along this isotopic chain [15].

Nucleosynthesis processes such as the rapid proton and rapid neutron capture processes (the *rp*- and *r*-processes) involve exotic nuclei. Reaction rates are in most cases rather poorly known and new data are in much demand. This is clearly a domain where radioactive beam facilities contribute substantially and are expected to continue to do so as they become more powerful. Perhaps surprisingly, it is also an area of research where large detector arrays such as Gammasphere can play a role. For example, understanding the processes which create and destroy ^{22}Na is important for diagnosing classical nova outbursts. Conventional ^{22}Na(p,γ) studies are complicated by the need to employ radioactive targets. In contrast, the particle-unbound states of interest can be formed through the fusion reaction ^{12}C(^{12}C,n)^{23}Mg, and Gammasphere was used to investigate their radiative decay branches [16]. Detailed spectroscopy was possible and the ^{22}Na(p,γ) reaction rate was reevaluated. New hydrodynamical calculations incorporating the upper and lower limits on the new rate indicate a reduction in the yield of ^{22}Na with respect to previous estimates, implying a reduction in the maximum detectability distance for ^{22}Na γ rays from novae by space missions such as INTEGRAL, for example.

The structure of neutron-rich nuclei has recently become the focus of much theoretical and experimental effort. Central to the on-going investigations is the expectation that substantial modifications can occur to the intrinsic shell structure of nuclei with a sizable neutron excess. Alterations to the energy spacings of the orbitals and/or to their ordering can have a considerable impact on global nuclear properties such as the nuclear shape or the type of excitations characterizing the low-energy level spectra. While studies of neutron-rich nuclei are mostly carried out at radioactive beam facilities, opportunities remain for investigations with large detector arrays at stable beam accelerators. The case of the neutron-rich Ti isotopes, just above doubly-magic ^{48}Ca is an example. As shown in Ref. [17], yrast spectroscopy of hard-to-reach neutron-rich nuclei populated in heavy-ion multi-nucleon transfer reactions (at energies 15-25% above Coulomb barrier), can be studied successfully in $\gamma-\gamma$ coincidence measurements with a thick target. The neutron-rich Ti isotopes were measured at Gammasphere with the ^{48}Ca + ^{208}Pb and ^{48}Ca + ^{238}U reactions at beam energies 25% above the Coulomb barrier [18,19]. The level structures of $^{54}_{22}\mathrm{Ti}_{32}$ and $^{56}_{22}\mathrm{Ti}_{34}$ were explored for the first time by combining β-decay measurements from fragmentation products with prompt γ-ray spectroscopy following deep inelastic reactions. Evidence for a sub-shell closure at $N = 32$ was found. Large-scale shell model calculations with the GXPF1 effective interaction, optimized for the description of pf shell nuclei [20], attribute the onset of a $N = 32$ gap in neutron-rich Ca, Ti and Cr nuclei to the combined actions of the $2p_{1/2} - 2p_{3/2}$ spin-orbit splitting and the weakening of the monopole interaction strength between $f_{7/2}$ protons and $f_{5/2}$ neutrons.

4. Conclusions

More than a decade after the large detector arrays came into operation, their impact on nuclear structure research is as large as ever. They continue to explore the (spin,energy) plane and its fascinating properties resulting often from the delicate balance between single-particle and collective degrees of freedom. Furthermore, the arrays are also put to good use in the exploration of the (N,Z) domain of exotic nuclei at the limits of stability. They have proven to be a powerful tool, not only for unravelling the properties of proton- and neutron-rich nuclei, but also for measurements of stellar reaction rates of importance in nucleosynthesis. Their role is likely to be unsurpassed until new, more powerfull instruments with tracking capability are fully developed.

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