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In-beam spectroscopy of heavy elements

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Abstract

Traditionally the experimental study of heavy and superheavy elements has belonged to the realm of decay spectroscopy and nuclear reactions. Only in the past twenty years or so has it become feasible to study nuclei with $Z = 96$ and beyond with in-beam spectroscopic techniques. Since the pioneering studies in the late 1990s, development of both instrumentation and experimental techniques has resulted in a significant lowering of the spectroscopic limit for in-beam measurements. Such measurements give access to a wide range of nuclear structure observables which in general are beyond the reach of other techniques. The current review aims to present the most recent developments and results in the field, building upon previous reviews with a similar theme.

Keywords: In-beam spectroscopy; Heavy elements; Superheavy elements; Nuclear structure; Isomeric states

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1. Introduction

The past two decades have witnessed steady progress in the development of in-beam spectroscopic techniques. The lowering of spectroscopic limits to unprecedented levels and the selectivity provided by modern techniques have allowed in-beam studies to be employed in a wider range of heavier nuclei, yielding a wealth of new experimental data. These data have been

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effectively applied to test modern nuclear structure theories, leading to the identification of deficiencies which are currently being addressed by the theoretical community and which are briefly discussed in the current manuscript. As is the case with many of the experimental and theoretical studies presented in this volume, the main theme behind in-beam spectroscopic studies is to further our understanding of the spherical superheavy island of stability. It is well-known that the different theoretical models give differing results concerning the properties of nuclei in and around the island of stability, and also on the location and extent of the island (for details see the theoretical reviews in this volume). At least in part, these differences in the predictions can be traced back to the ordering and energies of the underlying single-particle levels. An experimental determination of the structure and configurations of excited states in heavy nuclei can therefore have a direct impact on this discussion.

Historically, the experimental study of heavy elements has been approached through decay spectroscopy and a limited number of transfer reaction experiments. Such approaches generally only give information on a limited number of nuclear states, and are subject to the rather selective nature of the decay processes and reaction mechanisms. The field of decay spectroscopy has also benefited in recent years from technological developments and multi-detector systems, resulting in much more detailed spectroscopy and the possibility of putting level assignments on a firmer basis through determination of transition multipolarities. The current status of the field of decay spectroscopy is reviewed elsewhere in this volume. The application of in-beam techniques to heavy nuclei can give access to a range of experimental observables which complement beautifully the information from decay spectroscopic studies. It is now possible to make systematic studies of rotational bands and moments of inertia in a reasonably wide range of nuclei (spanning ranges in both N and Z), which in turn provide information on the development of deformation, collectivity and pairing. At higher spins, rotational alignment properties and blocking arguments can give insight into the particles active at the Fermi surface. In particular, the high-j orbitals which are most sensitive to rotational alignment effects through the Coriolis interaction are also those which effectively form the boundary to the island of stability. Here again, confrontation of theoretical models with experimental data on the location of the high-j states can impact the discussion of the properties of SuperHeavy Elements (SHE).

While most of the experiments discussed in the review were made using fusion-evaporation reactions, the use of transfer reactions, either of a few particles, or of a large number of particles in a deep-inelastic collision, is still a very powerful tool in the study of heavy nuclei. In-beam experiments generally rely on discrete-line spectroscopy, but another approach is to measure the total energy and multiplicity of gamma-rays emitted in the decay of particular nucleus. This “continuum” approach allows the fission barrier height to be determined, and provides information on the reaction mechanism.

The following article aims to review recent progress in in-beam spectroscopic studies of heavy nuclei. As the field was reviewed as recently as 2008 [1], emphasis is placed on developments since that time, even though some overlap is inevitable. Section 2 describes the current status of experimental apparatus and techniques, followed by sections dealing with even–even (Section 3) and odd-mass nuclei (Section 4), two-quasiparticle states (Section 5), discussion of the experimental findings and comparison with theory (Section 6) and finally ending with an evaluation of the perspectives for further progress in the field (Section 7).

The current status of experimental knowledge on nuclei from Cm to Db is summarised in Fig. 1, which shows the ground-state spin assignments along with the number of known excited states which are classified with a colour code. The figure is an updated version of that presented in

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