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Direct mass measurements of the heaviest elements with Penning traps

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Abstract

Penning-trap mass spectrometry (PTMS) is a mature technique to provide atomic masses with highest precision. Applied to radionuclides it enables us to investigate their nuclear structure via binding energies and derived quantities such as nucleon separation energies. Recent progress in slowing down radioactive ion beams in buffer gas cells in combination with advanced ion-manipulation techniques has opened the door to access even the elements above fermium by PTMS. Such elements are produced in complete fusion–evaporation reactions of heavy ions with lead, bismuth, and actinide targets at very low rates. Pioneering high-precision mass measurements of nobelium and lawrencium isotopes have been performed with SHIPTRAP at the GSI Darmstadt, Germany. These have illustrated that direct mass measurements provide reliable anchor points to pin down decay chains and that they allow mapping nuclear shell effects, the reason for the very existence of the heaviest elements. Thus, accurate masses contribute to our understanding of these exotic nuclei with extreme proton numbers. In this article experimental challenges in mass measurements of the heaviest elements with Penning traps are discussed. Some illustrative examples of the nuclear structure features displayed based on the presently known masses are given.

Keywords: Superheavy nuclei; Atomic mass; Penning trap; Mass spectrometry

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1. Introduction

Superheavy element (SHE)[1] research is a topic attracting interest from atomic physics, chemistry, and nuclear physics. This originates from the extraordinary atomic and nuclear properties of these exotic systems. On the one hand their nuclei owe their existence to nuclear shell effects that stabilize them against spontaneous fission due to strong Coulomb repulsion, on the other hand large relativistic effects influence their atomic structure and chemical behavior significantly. Precision measurements of their atomic properties by laser spectroscopy are reviewed in a separate contribution to this special issue [1]. Another technique for precision measurements that has been pioneered in atomic physics is Penning-trap mass spectrometry (PTMS) [2,3]. PTMS has meanwhile become a well-established tool for nuclear structure studies [2–4]. The mass of an atom provides information on all interactions between its constituents and thus also reflects the characteristics of the strong interaction. The absolute binding energy is readily obtained from direct mass measurements without any knowledge of the nuclear level scheme of the investigated nuclide. Thus, high-precision mass measurements allow us to study the nuclear structure evolution in radionuclides far off stability, where little is known, and they often provide first indicators of new structure effects.

Information on the nuclear structure of the heaviest elements has previously been obtained mainly from decay spectroscopy that is discussed in different contributions to this special issue [5,6]. Recently, the first direct mass measurements in the region above fermium have been performed using the Penning-trap mass spectrometer SHIPTRAP at the GSI Darmstadt, Germany [7–9]. These have opened the door to extend PTMS to the heaviest elements. Binding energies and their differences that are obtained from accurate mass values provide sensitive indicators of global trends in the nuclear shell structure. For example, the location of shell closures is displayed by nucleon separation energies. Furthermore, specific features of the nuclear interaction such as nucleon pairing can be investigated by masses. Mass differences of nuclides moreover determine the energy available for nuclear decays and allow us to determine energetically possible decay modes.

In the region of the heaviest elements direct mass measurements can also provide reliable anchor points to pin down α-decay chains originating from superheavy elements. This would be of particular interest if PTMS could be extended to the more neutron-rich superheavy nuclides that have been first produced in so-called hot-fusion reactions by collaborations working at Dubna, Russia [10]. Even though a significant part of the reported data has been independently confirmed by experiments performed at LBNL Berkeley [11] and at GSI Darmstadt [12–15], the assignment of their atomic number Z and atomic mass A relies largely on cross bombardments and α-decay systematics. A direct measurement of either the mass number A or the atomic number Z is still desirable. In a direct (high-precision) mass measurement the A/Q-ratio of a nuclide can be determined so that in combination with the observation of the corresponding α decay an ambiguous identification of new elements would become possible.

The paper is organized as follows. In Section 2 the basics of PTMS are briefly introduced. In Section 3 selected experimental results are presented and compared with representative theoretical models. Section 4 discusses future perspectives based on new developments and next-generation accelerators.

[1] In this paper elements with atomic number $Z > 103$, the transactinides in the Periodic Table, are called superheavy elements. From a nuclear physics point of view the distinction is usually made based on the fission barrier, which in a description based on a liquid drop model vanishes at $Z \approx 104$–106 depending on the parametrization.