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Review

Ion traps in nuclear physics—Recent results and achievements

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ABSTRACT

Ion traps offer a way to determine nuclear binding energies through atomic mass measurements with a high accuracy and they are routinely used to provide isotopically or even isomerically pure beams of short-living ions for post-trap decay spectroscopy experiments. In this review, different ion-trapping techniques and progresses in recent nuclear physics experiments employing low-energy ion traps are discussed. The main focus in this review is on the benefit of recent high accuracy mass measurements to solve some key problems in physics related to nuclear structure, nuclear astrophysics as well as neutrinos. Also, several cases of decay spectroscopy experiments utilizing trap-purified ion samples are summarized.

Contents

1. Introduction 260
2. Ion trap techniques 261
    2.1. Radiofrequency cooler–bunchers 261
    2.2. Paul traps 261
    2.3. Penning traps 262
        2.3.1. Mass doublet technique 263
        2.3.2. The time-of-flight ion-cyclotron resonance technique 264
    2.4. Phase-imaging cyclotron resonance technique 266
    2.5. Gas-filled Penning trap for beam purification 266
    2.6. High-resolution Penning trap cleaning techniques 267
    2.7. Multi-reflection time-of-flight separators 268
    2.8. Summary of ion-trap facilities in the world 268
3. Overview of recent mass measurements employing ion traps 268
    3.1. Comparison with theoretical mass models 269
    3.2. Two-nucleon binding energies and shell gaps 273
        3.2.1. Neutron-rich Ca isotopes. A new shell closure? 275
        3.2.2. Neutron-rich Kr and Zr isotopes. Deformation around $N = 60$ 275
        3.2.3. Neutron-rich radium and francium isotopes 276
        3.2.4. Evolution of the two-neutron shell closure at $N = 50$ 276
        3.2.5. Two-neutron shell gaps and theoretical comparison 277
4. Isobaric mass doublets and isospin multiplets 277
    4.1. Superallowed and $T = 1/2$ mirror beta decays 278

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4.1.1. Superallowed β decays 278
4.1.2. Mirror decays 278
4.2. Isobaric multiplet mass equation 278
5. Trap-assisted spectroscopy 279
5.1. In-trap spectroscopy 279
5.1.1. Penning trap spectroscopy 279
5.1.2. Paul and Penning trap spectroscopy for beta-neutrino correlation measurements 280
5.1.3. Paul trap spectroscopy for beta-delayed neutrons 280
5.1.4. Electron beam ion trap for gamma- and X-ray spectroscopy 281
5.2. Post-trap decay spectroscopy 281
5.2.1. Conventional decay spectroscopy of trap-purified isotope sources 281
5.2.2. Nuclear structure studies 282
5.2.3. Total absorption gamma-ray spectroscopy 282
5.2.4. Delayed neutron spectroscopy at JYFLTRAP 283
5.3. Double beta decay studies of relevance for neutrino physics 286
6. Conclusion and outlook 287
Acknowledgments 288
References 288

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1. Introduction

Progress of ion manipulation technologies in ion traps has opened exciting opportunities for solving fundamental questions in atomic and nuclear physics. Calculation of electron binding energies in atoms using the well-known theory of QED (Quantum Electrodynamics) can be performed with accuracies of the order of a few eV for almost any atom. To be sensitive in this level in atomic mass itself, a relative mass uncertainty of the order of 10^{-10} or better is required. Experimentally this precision is already reached for stable isotope masses [1–3].

The calculation of the nuclear binding, however, has to rely on less accurately quantifiable strong interaction derived from the theory of QCD (Quantum Chromodynamics). The mass M of a neutral atom can be expressed as

$$M = N \times m_{\mathrm{n}} + Z \times m_{\mathrm{p}} + Z \times m_{\mathrm{e}} - \left(B_{\mathrm{atom}} + B_{\mathrm{nucleus}}\right)/c^2, \tag{1}$$

where N and Z are the neutron and proton numbers and m_{p}, m_{n} and m_{e} are free proton, neutron and electron masses, respectively. B_{atom} and B_{nucleus} are the total electron and nuclear binding energies, respectively. At best, the total mass (or binding energy, see Section 3.1) of an atom can presently be calculated to an accuracy of the order of a few 100 keV which corresponds to a relative mass uncertainty $\Delta m/m$ of the order of 10^{-6} only, which is several orders of magnitude less precise than for atomic binding energies. Therefore in nuclear physics, in general, the required experimental accuracies are currently less stringent than in atomic physics. This is particularly true when comparing experimental data with theoretical model predictions for absolute masses and the effects of global correlations on masses.

However, the first- and second-order differentials of masses can serve as sensitive indicators of local behavior of collective or single particle structures with changing proton and/or neutron numbers. In fact, the measurement accuracy required for those observables is of the order of 10 keV or better, and is comparable to that routinely available in spectroscopy of nuclear excited states. This opens up interesting perspectives for studying the binding energy systematics for the excited states as well. The observables, for example, include nucleon or nucleon pair binding energies, Q-values for radioactive decays, isomer masses, pairing gaps and shell gaps. Some examples of differentials and their typically required accuracies are given in Table 1 together with related key physics topics.

In this review, we wish to introduce the newest developments in ion trapping techniques for nuclear physics. The emphasis in the review is on the use of Penning-trap technique for high-precision mass measurements as well as in their use as high-resolution mass separators to produce high-purity isotopic or isomeric sources for decay spectroscopy of exotic nuclei. It will be shown that these techniques have opened up unique possibilities for high-precision measurements of rare isotopes of practically all chemical elements down to half-lives of few ms and production rates on the order of few ions per hour.

Then, we move on to present an update of recent progresses of direct mass measurements of neutron-rich nuclei covering a wide range of the chart of nuclei between mass numbers $A = 10$ and $A = 250$. The mass data will mainly be discussed in the framework of mass differentials, such as nucleon and nucleon-pair binding energies, pairing gaps and shell gaps. A comparison with some selected theoretical models will be discussed. In addition, a special class of high-precision measurements of isobaric mass doublets and isotopic mass multiplets will be presented. Finally, a novel technique of trap-assisted decay spectroscopy is introduced with applications on beta, gamma, conversion electron and β delayed neutron studies.