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Alpha decay as a probe for the structure of neutron-deficient nuclei

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ABSTRACT

The advent of radioactive ion beam facilities and new detector technologies have opened up new possibilities to investigate the radioactive decays of highly unstable nuclei, in particular the proton emission, α decay and heavy cluster decays from neutron-deficient (or proton-rich) nuclei around the proton drip line. It turns out that these decay measurements can serve as a unique probe for studying the structure of the nuclei involved. On the theoretical side, the development in nuclear many-body theories and supercomputing facilities have also made it possible to simulate the nuclear clusterization and decays from a microscopic and consistent perspective. In this article we would like to review the current status of these structure and decay studies in heavy nuclei, regarding both experimental and theoretical opportunities. We then discuss in detail the recent progress in our understanding of the nuclear α formation probabilities in heavy nuclei and their indication on the underlying nuclear structure.

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1. Introduction

There has been a long history of studies on the α radioactivity which was first described by Ernest Rutherford in 1899. The structure of the particle was identified by 1907 as ^{4}He (He^{2+} ion) with two protons and two neutrons, which, with the binding energy 7.1 MeV per nucleon, is the most stable configuration below ^{12}C. The greatest challenge then was to understand how the α particle could leave the less stable mother nucleus without any external disturbance. The decay process was successfully interpreted by Gamow [1] and Gurney and Condon [2,3] as a quantum tunneling effect, which required to accept the probabilistic interpretation of Quantum Mechanics. The extent to which this was revolutionary can perhaps best be gauged by noticing the multitude of models that have been put forward as an alternative to the probabilistic interpretation. Besides its pioneering role in nuclear physics and in the development of quantum theory, the tunneling effect is also realized to be responsible for the thermonuclear reactions and stellar evolution. Processes like nuclear fusion, proton and α captures can also be explained as an inverse tunneling [4]. The tunneling was accepted as a general physical phenomenon around mid-20th century and also becomes relevant at the nanoscale with important applications such as the tunnel diode, scanning tunneling microscopy and quantum computing as well as chemical and biological evolutions. Without tunneling there would be no star, no life, let alone nuclear physics or quantum mechanics.

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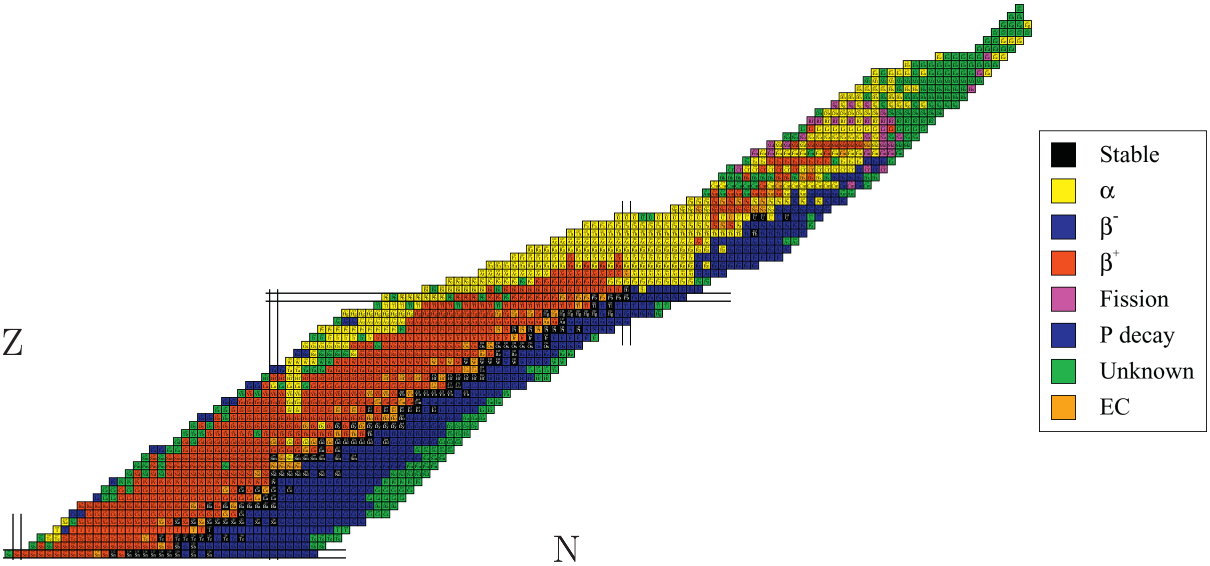

Fig. 1. Dominant ground-state decay modes for nuclei with proton number $Z \geq 50$. EC and P stand for electron capture and proton radioactivity, respectively. The horizontal and vertical lines correspond to the proton shell closures $Z = 50$, 82 and neutron shell-closures $N = 50$, 82 and 126, respectively. The shell structure in the superheavy nuclei is not known hitherto.

α decay has been among the most important decay modes of atomic nuclei for more than a century. The decay occurs most often in massive nuclei that have large proton to neutron ratios, where it can reduce the ratio of protons to neutrons in the parent nucleus, bringing it to a more stable configuration in the daughter nucleus. Almost all observed proton-rich or neutron-deficient nuclei starting from mass number $A \sim 150$ have α radioactivities, as shown in Fig. 1. Various phenomenological and microscopic models have been developed to study the α-decay process, which can successfully reproduce available experimental α-decay half-lives. The spontaneous emission of charged fragments heavier than the α particle is known as cluster radioactivity. This process is more closely related to spontaneous fission, i.e., a disintegration of the heavy nucleus into two lighter ones [5–7]. For available superheavy elements or superheavy nuclei [8–10], fission and α decay are the dominant decay modes. The detection of emitted α particles has been the principal method of identifying superheavy nuclei as well as their excited states [11], which can be created in heavy ion fusion reactions.

Nuclear physics is undergoing a renaissance with the availability of intense radioactive beams. The new facilities have opened up new possibilities to investigate highly unstable nuclei as well as to probe existing formalisms trying to describe those nuclei. Recent investments in new or upgraded facilities such as FAIR at GSI, Darmstadt, HIE-ISOLDE at CERN, Geneva, SPIRAL2 at GANIL, Caen, FRIB at MSU and RIBF at RIKEN, in conjunction with new detector systems, in particular γ ray tracking devices like AGATA, will produce unprecedented data on exotic nuclei and nuclear matter in the decades to come. In this review we would like to discuss the recent developments and new opportunities in the study of the decay of heavy nuclei and our understanding of the so-called nuclear α formation probabilities and the underlying structure of the nuclei involved. We will concentrate in particular on the progress that has been made during the past decade and the current status of experimental and theoretical studies. Extensive reviews on the α clustering in light nuclei, which is a closely related topic, could be found, e.g., in Refs. [12–14].

2. The microscopic description of α decay

The Gamow theory explained nicely the α decay as the penetration (tunneling) through the Coulomb barrier. Although successful, one can assert that this is an effective theory, where one has to assume a preformed α particle inside the nucleus and concepts like “frequency of escape attempts” have to be introduced. This semiclassical picture collides with basic quantum mechanics, since even if the α particle existed in the mother nucleus, the Pauli principle would hinder any free motion of the particle inside the nucleus. Actually it has been realized in the early study of nuclear structure that the nucleus cannot be composed of α particles [15]. The α configuration is usually a very small component of the nuclear wave function. What is missing in Gamow’s picture is the probability that the α particle is formed at a certain distance around the nuclear surface. A proper calculation of the decay process needs to address first the formation of the α particle around the nuclear surface and, in a second step, the evaluation of the penetrability (the probability of tunneling) through the static Coulomb and centrifugal barriers at the region where the α particle was already formed. It is expected that the decays of the proton and other charged clusters heavier than α can be described by the same mechanism.

We understand now that the structure of the nucleus is best described by the nuclear shell model where its building blocks, neutrons and protons, are held together by an average potential (the so-called nuclear mean field) generated by

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