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Nuclear Physics A 958 (2017) 187–201

NUCLEAR PHYSICS A

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Cluster decay half-lives of trans-lead nuclei based on a finite-range nucleon–nucleon interaction

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Received 17 October 2016; received in revised form 28 November 2016; accepted 4 December 2016

Available online 8 December 2016

Abstract

Nuclear cluster radioactivity is investigated using microscopic potentials in the framework of the Wentzel–Kramers–Brillouin approximation of quantum tunneling by considering the Bohr–Sommerfeld quantization condition. The microscopic cluster–daughter potential is numerically constructed in the well-established double-folding model. A realistic M3Y-Paris NN interaction with the finite-range exchange part as well as the ordinary zero-range exchange NN force is considered in the present work. The influence of nuclear deformations on the cluster decay half-lives is investigated. Based on the available experimental data, the cluster preformation factors are extracted from the calculated and the measured half lives of cluster radioactivity. Some useful predictions of cluster emission half-lives are made for emissions of known clusters from possible candidates, which may guide future experiments.

Keywords: Cluster decay; Double-folding model; Finite range exchange NN interaction

1. Introduction

Cluster radioactivity is the spontaneous emission of clusters heavier than alpha particles [1–5]. This rare phenomenon was first predicted theoretically by Sandulescu, Poenaru and Greiner in 1980 [6]. In 1984, Rose and Jones from Oxford University reported their experiment on ^{14}C

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http://dx.doi.org/10.1016/j.nuclphysa.2016.12.002
0375-9474/

radioactivity of ^{223}Ra [7]. Several experiments are carried out by different experimental groups at Berkeley, Dubna, Orsay and Milano to investigate such peculiar rare decay mode of heavy nuclei. Intense experimental research has led to the detection of spontaneous emission of clusters including ^{14}C, ^{20}O, ^{22,24,25,26}Ne, ^{23}F, ^{28,30}Mg, and ^{32,34}Si [8–14]. The feature in the observed decays of the cluster emitters is that heavier nuclei will emit heavier fragments in such a way that daughter nuclei are usually the doubly magic or nearly doubly magic (i.e. ^{208}Pb or closely neighboring nuclei). Poenaru et al., [15,16] predicted quite heavier clusters ($Z_c > 28$) from parents with $Z > 110$ and daughter around ^{208}Pb, implying the possibility of another decay mechanism of superheavy nuclei (SHN).

Cluster decay which represents an intermediate process between α decay and spontaneous fission, could be understood theoretically from two different formalisms. One is based on the adiabatic "fission"-like theory [17–23] similar to superasymmetric fission, where the decay process goes through a sequence of geometrical shapes and the cluster is considered to be formed gradually during the adiabatic rearrangements of parent nuclei. The other is the nonadiabatic treatment similar to α-decay approach [2–4,24–28], where the cluster is treated to be preformed in the decaying nucleus with a certain preformation probability and penetrates the Coulomb barrier.

Extensive theoretical studies have been performed on both the cluster decay and α-decay from heavy and superheavy nuclei within various theoretical models. Wang et al. [29] recently performed systematic calculations on the α-decay energies (Q_α) and α-decay half-lives of superheavy nuclei with $Z \geq 100$ using 20 mass models and 18 empirical formulas, respectively. It is found that the WS4 [30] mass model is the most accurate one to reproduce the experimental Q_α values of SHN. Among 18 formulas used to calculate the α-decay half-lives, the SemFIS2 [31] formula is the best one to predict α-decay half-lives. In addition, the UNIV2 [31] formula with fewest parameters and the Viola–Seaborg–Sobiczewski (VSS) [32,33], Sobiczewski–Parkhomenko (SP) [34,35], and Ni–Ren–Dong–Xu (NRDX) [36] formulas with fewer parameters work well in the prediction on the α-decay half-lives of SHN. Various theoretical approaches have been used to describe the cluster emission such as the generalized density dependent cluster model [2,3,28], the generalized liquid drop model [19], the combined shell and cluster models [26,37], and the preformed cluster model [38]. Poenaru et al. [17,39–41] have calculated half-lives for several cluster decay modes of some heavy nuclei in the trans-lead region using analytical super-asymmetric fission model (ASAFM). Santhosh et al. [20,21] have calculated half-lives for experimentally observed cluster decay modes of several heavy nuclei in the trans-lead and trans-tin region by using Coulomb proximity potential model (CPPM).

In the present work, we focus on the investigation the cluster decay process in the framework of the density-dependent cluster model, where the cluster is treated to be preformed in the decaying nucleus with a certain preformation probability. The microscopic cluster–daughter potential is numerically constructed in the double-folding model using the density distributions of the cluster and the core nucleus. We will use the Michigan-three-Yukawa (M3Y) NN interaction supplemented with a zero-range exchange contribution. The effect of different degrees of deformation and orientation on the cluster decay process is clarified. Moreover, the main effect of antisymmetrization under exchange of nucleons between cluster and daughter nuclei has been included in the double-folding model through the finite range exchange part of the NN interaction. This is a novel development in the calculations of cluster decay. Based on the available experimental data, the cluster preformation factors are extracted from the calculated and the measured half lives of cluster radioactivity. Moreover, the results provide a useful method for