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NUCLEAR PHYSICS A
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Systematic of critical temperature of nuclear pairing transition

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Received 16 January 2018; received in revised form 7 April 2018; accepted 3 May 2018

Abstract

The critical temperature of nuclear pairing transition has been determined for 440 nuclei between ^{10}Be and ^{253}Cf within a microscopic model. The shell effect and mass number dependence of the critical temperature have been studied. The relation between the pairing gaps of neutrons and protons at zero temperature, and the critical temperature have been investigated. The critical temperatures have been compared with the constant temperatures extracted from the experimental nuclear level densities within a phenomenological model. The comparison shows that our theoretical calculations are consistent with the experimental evidences of pairing transition in nuclei.

Keywords: Nuclear pairing interaction; BCS model; Phenomenological model; Critical temperature

1. Introduction

One of the interesting phenomena which was revealed about nuclear structure in the systematic studies on nuclear masses is the nucleon pairing effect. The pairing interaction between nucleons can be extracted from the odd–even staggering (OES) of nuclear masses in the ground

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https://doi.org/10.1016/j.nuclphysa.2018.05.001
0375-9474/© 2018 Published by Elsevier B.V.

state. At higher energies, thermal effects can break down the nucleon pairs and give rise to a phase transition between paired and unpaired states at the so called critical temperature (T_c). After the phase transition, the nuclear system reverts to a non-interacting Fermi gas, which can be described well by the semi-empirical model of the Back Shifted Fermi Gas (BSFG). Some studies demonstrate that in an energy region below the neutron threshold, the Constant Temperature (CT) model describes well the existing experimental nuclear level densities. An extensive study on physics and systematics of the parameters of these level density models can be found in Ref. [1], and the references therein. The constant temperature behavior of nuclear level densities, turns out that due to a phase transition the energy goes into breaking the nucleon pairs, so the temperature remains constant [2,3]. Both of CT and BSFG are simple semi-empirical models which don't consider the nuclear interactions directly. The occurrence of a pairing transition in nuclei has been extensively studied experimentally [2–4], and discussed theoretically using the BCS (superconducting) model. In this microscopic model the nuclear system is assumed to have a BCS Hamiltonian, which describes a system of paired fermions. The critical temperature of the pairing transition in nuclei, which is the subject of this study, is one of the quantities that can be extracted by solving the BCS model equations. The BCS model predicts a relation between the critical temperature and the pairing gap at zero temperature (Δ_0) [5,6]:

$$T_c = \frac{\Delta_0}{\pi e^{-\gamma}} = 0.567\Delta_0, \tag{1}$$

where $\gamma = 0.5772$ is the Euler's constant. The relationship between T_c and Δ_0 in nuclei, has been investigated in several studies [7,8]. Using accurate values of the ground-state pairing gaps is of particular importance in the BCS calculations. In this paper, we first present a new set of neutrons and protons pairing gaps at zero temperature, which are extracted by using the nuclear masses published in AME2016 [9]. In Sec. 3 the BCS equations are outlined and systematic calculations on the critical temperature in the BCS model are performed for 440 nuclei. In Sec. 4, the constant temperature model is briefly reviewed. Then, the critical temperatures are compared with the constant temperatures and the results are discussed. Finally, the main conclusions are drawn in Sec. 5.

2. Ground-state pairing gap

A reliable method to determine neutrons and protons pairing gaps, is to derive them indirectly from experimental odd–even mass differences. For this purpose, several different formulas are available. The formulas differ depending on consideration of any other contributions to the OES, apart from the pairing effect, in the calculations. The empirical pairing gaps have recently been discussed in Refs. [10,11]. Finite-difference formulas for the pairing gaps have been derived from Taylor series expansions of masses in the neighborhood of the mass of interest. Several different finite-difference formulas and their properties have been discussed in Ref. [12]. We have used the fourth-order expressions from this work in order to obtain the neutrons and protons pairing gaps (Δ_n, Δ_p), at zero temperature [12]:

$$\begin{aligned}\Delta_n^{even-even} = -\frac{1}{8}[&M(Z,N+2) - 4M(Z,N+1) + 6M(Z,N) \\ &-4M(Z,N-1) + M(Z,N-2)],\end{aligned} \tag{2}$$

$$\begin{aligned}\Delta_n^{odd-neutron} = \frac{1}{8}[&M(Z,N+2) - 4M(Z,N+1) + 6M(Z,N) \\ &-4M(Z,N-1) + M(Z,N-2)],\end{aligned} \tag{3}$$

Please cite this article in press as: R. Razavi et al., Systematic of critical temperature of nuclear pairing transition, Nucl. Phys. A (2018), https://doi.org/10.1016/j.nuclphysa.2018.05.001