RECENT THEORETICAL ADVANCES REGARDING α-SPECTROSCOPY

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Abstract

We present an overview of a unified description of the structure and α-emission properties of even-even nuclei. The low-energy spectrum relevant for α-emission is described within the framework of the Coherent State Model (CSM). The treatment of the α-emission process is based on an α-daughter interaction containing a monopole component, calculated through a double folding procedure with a M3Y interaction plus a repulsive core simulating the Pauli principle, and a quadrupole-quadrupole (QQ) interaction. The decaying states are identified with the lowest narrow outgoing resonances obtained through the coupled channels method. The α-branching ratio to the first excited state is reproduced by means of the QQ strength. Simultaneously, a reasonable agreement is obtained for the α-branching ratios to the second and third excited states.

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1 Introduction

The field of α-spectroscopy in an extension of traditional nuclear spectroscopy, where the probe is no longer of electromagnetic, but of strong origin. Thus, in addition to the usual γ-ray analysis, one may investigate nuclear structure through α-emission. This work summarizes recent results regarding the fine structure of the α-decay spectrum in even-even nuclei. For a comprehensive study of the presented structure properties and α-transitions, as well as a review of the literature, see Refs. [1, 2]. For a systematics of experimental data regarding decay intensities and partial half-lives, consult Ref. [3]. The topic of α-decay in odd-mass nuclei is expanded upon in Ref. [4], for the case of favored α-transitions. Remarks concerning the even-odd staggering of the α-particle spectroscopic factor and its relation to α-clustering can be found in Ref. [5].

2 The CSM Model

The main idea behind this approach consists in treating the surface vibrations of a deformed even-even nucleus as a superposition of quadrupole phonons [6, 7]. Following this idea, the model was greatly expanded towards the treatment of three interacting collective bands [8, 9, 10], as well as in terms of the particle-core interaction in odd-mass nuclei [11].

In its simplest realization, the model is based on the assumption that the intrinsic state of an even-even nucleus having an arbitrary axial deformation is given by a coherent superposition of quadrupole phonons

$$|\psi_g\rangle = e^{d\left(b_{20}^\dagger - b_{20}\right)}|0\rangle \ , \tag{1}$$

where $\left(b_{2\mu}^\dagger, b_{2\mu}\right)$ are the phonon operators with projection $\mu = 0$ and d is the deformation parameter, proportional to the usual quadrupole deformation [8].

The ground band states are obtained by projecting out the angular momentum components of the intrinsic function

$$|\varphi_J^{(g)}\rangle = \mathcal{N}_J^{(g)} \hat{P}_{M0}^J |\psi_g\rangle \ , \tag{2}$$

by using the projection operator $\hat{P}_{M0}^J$ and normalizing with the factor $\mathcal{N}_J^{(g)}$. The corresponding energy levels E_J follow as the expectation values in this basis of the Hamiltonian

$$\hat{H} = A_1 b_2^\dagger \cdot b_2, \tag{3}$$

where A_1 is a strength factor and the dot designates a scalar product. The resulting level structure is harmonic for vanishing deformation, goes through a transitional regime as the deformation increases and then stabilizes into a rotational band. Detailed applications of this method to the study of even-even α-emitters and its extension to the odd-mass case can be consulted in Refs. [2, 4].

3 The coupled-channels method and applications

The general theory of resonant states is expanded upon in Refs. [12, 13]. Here, we will give a concise overview of the coupled-channels equation and its application to α-decay in the case of even-even nuclei.

The α-transition process can be represented as

$$P \to D(J) + \alpha(J) \ , \tag{4}$$

where, J is the spin/parity of the daughter nucleus and emitted α-particle, coupling to the 0 angular momentum of the parent nucleus.

The wave function that is under consideration has the form of a clustered α-daughter ansatz [13] with the total spin of the initial state

$$\Psi(b_2^\dagger, \mathbf{R}) = \sum_J \frac{f_J(R)}{R} \mathcal{Y}^{(J)}(b_2^\dagger, \hat{R}) \ . \tag{5}$$

The function $f_J(R)$ describes the α-daughter radial motion in the channel J. We introduce the core-angular harmonic

$$\mathcal{Y}^{(J)}(b_2^\dagger, \hat{R}) = \left[\varphi_J(b_2^\dagger) \otimes Y_J(\hat{R})\right]_0 \ , \tag{6}$$

where $\varphi_J(b_2^\dagger)$ designates the daughter internal wave function, with $b_2^\dagger$ the daughter degrees of freedom, while $Y_J(\hat{R})$ is the usual spherical harmonic that describes the relative angular motion of the α-daughter system. These core-angular harmonics are orthonormal.

The α-daughter dynamics is treated using a stationary Schrödinger equation, i.e.

$$H\Psi(b_2^\dagger, \mathbf{R}) = Q_\alpha \Psi(b_2^\dagger, \mathbf{R}) \ , \tag{7}$$

where Q_α is the Q-value of the decay process. Due to the fact that all measured decay widths are by many orders of magnitude smaller than the corresponding Q-values, the stationarity approximation is a very good assumption. Hence, an α-decaying state is identified with a narrow resonant solution that contains only outgoing components.

The Hamiltonian

$$H = -\frac{\hbar^2}{2\mu}\nabla_R^2 + H_D(b_2^\dagger) + V(b_2^\dagger, \mathbf{R}) \ , \tag{8}$$

contains the kinetic operator depending on the reduced mass, a term describing the dynamics of the daughter nucleus $H_D(b_2^\dagger)$ and the α-core interaction $V(b_2^\dagger, \mathbf{R})$, which is generally split into spherical and deformed parts. The spherical component follows from the matching of a harmonic oscillator with the double folding potential integrated from the M3Y nucleon-nucleon plus Coulomb force (see Ref. [13] for computational details, along with references contained therein), while for the deformed component it is enough to retain the QQ coupling.

This expansion of the interaction, together with the expansion of the wavefunction in the core-angular harmonic basis of Eq. (6), leads to a system of coupled differential equations for the radial functions

$$\frac{d^2 f_J(R)}{d\rho_J^2} = \sum_{J'} A_{JJ'}(R) f_{J'}(R) \ , \tag{9}$$

where ρ_J is the reduced radius. The coupling matrix $A_{JJ'}$ has off-diagonal components given by the matrix elements of the deformed part of the interaction. When evaluated in the CSM model, the QQ component of the interaction term present in Eq. (8) can be adjusted by a coupling strength dependent on the CSM deformation [2]. These matrix elements vanish at large distances, where the field is Coulombian, and there the asymptotic expression of the first resonance of this potential is an outgoing Coulomb-Hankel wave. One can show [13] that the partial decay widths that constitute the fine structure of the α-emission spectrum can be supplied by the asymptotic form of these functions

$$\begin{aligned} \Gamma &= \sum_J \Gamma_J = \sum_J \hbar v_J \lim_{R\to\infty} |f_J(R)|^2 \\ &= \sum_J \hbar v_J |N_J|^2 \ , \end{aligned} \tag{10}$$

in terms of the scattering amplitudes N_J and the center of mass velocity at infinity for each α-daughter channel J.

The goal is to give an accurate description of the decay intensities

$$\Upsilon_J = \log_{10} \frac{\Gamma_0}{\Gamma_J}, \tag{11}$$

which is easily checked by means of the so-called suppression factors

$$\log_{10} SF_J = \Upsilon_J^{\rm exp} - \Upsilon_J^{\rm theor}, \tag{12}$$

where the two values stand for experimental and theoretical quantities, respectively. Clearly, small suppression factors will indicate an accurate theory.

Solving the coupled channels system of Eq. (9) in a manner that reproduces the decay intensities to 2^+ states leads to a linear dependence of the QQ coupling strength, denoted by C, on the CSM deformation d. This dependence has different slopes around the neutron number $N = 126$. For heavy nuclei, where several transitions are observed in the decay spectra, this dependence can be used to predict their structure. For example, in the case of even-even actinides, one can obtain a simultaneous description of the transitions to 2^+ and 4^+ states up to a factor of 3, while the transitions to 6^+ states are usually described with an accuracy of about an order of magnitude.

In conclusion, the CSM model offers a unified approach to the study of vibrational, transitional and well-deformed nuclei. Inserting the parametrization of the deformation that describes the nuclear structure in the coupled channels equation supplies good estimates for the fine structure of the α-emission spectrum.

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