The search for resonances in ^{26}O exotic nucleus using the SSQM

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Introduction

The global scientific community has been increasingly interested in the so-called dripline nuclei in recent years, focusing on identifying the precise positions of particle stability boundaries. Understanding the characteristics of nuclei with extreme neutron-to-proton ratios poses a significant challenge for rare isotope experiments and theory. The nuclei along the driplines are also of importance since they should exhibit a distinctive nature known as a halo, as well as rare characteristics due to their enormous R.M.S. matter radii, low one and two nucleon separation energy, extended low-density tail and so on[1].

The neutron dripline, in particular, indicates the stability limitations of neutron-rich isotopes. To shed additional insight into the neutron dripline's anomalous behaviour in the oxygen area, it is worthwhile to explore the characteristics of exotic oxygen nuclei. The finding of halo nuclei near nuclear driplines is one of the most significant breakthroughs since the establishment of radioactive ion-beam facilities. Tanihata et al. (1985) were the first to confirm the 2n-halo structure in neutron-rich ^{11}Li [2]. Some theories and experiments have established two neutron halo nuclei are ^{6}He, ^{11}Li, ^{12,14}Be, ^{17,19}B, ^{18,20,22}C, ^{40,42,44}Mg, ^{62,72}Ca, and so on. Which reflects the unique nuclear structure of a dense stable core surrounded by a low-density envelope with a long extension [3]. According to findings from literature, ^{26}O is one of the most exotic neutron-rich nuclei in the oxygen area, meaning it is highly weakly bound in nature, with two neutron separation energies on the order of keV. In 2012, E. Lunderberg et al. revealed that the resonance energy for the ^{26}O ground state is 150^{+50}_{-150} keV and the cross section for populating the ^{26}O ground state is 1.8 ± 1.0 mb [4]. In 2013, the NSCL-MoNA group retrieved a half-life of approximately $4.5^{+1.1}_{-1.5}$ (Stat.) $\pm$ 3 (Syst.) ps, which corresponds to a lifetime of 6.5 ps. They also determined the ground state resonance energy, which is E=150^{+50}_{-150} keV [5, 6]. In 2015, Y. Kondo et al. determined the ground state of ^{26}O with a higher precision to be 18 ± 3 (Stat.) ± 4(Syst.) keV, and the 2^{+} state at $1.28^{+0.11}_{-0.08}$ MeV[7]. In 2016, K. Hagino and H. Sagawa revealed that the ground state energy of ^{26}O is E= 0.018 MeV [8]. In 2017, Y. Kondo et al. reported that the ground state of ^{26}O was barely unbound w.r.t. two neutron emission by $6 - 53$ keV in an intermediate energy reaction study [9]. Within the framework of the few-body cluster model, we have examined the ground and resonance states of ^{26}O (^{24}O + n + n) in the present work using an advanced theoretical approach. We use the HHE (hyperspherical harmonics expansion) approach to solve the three-body Schrödinger equation in relative coordinates for the ground state energy and wave functions, with standard GPT (Gogny-Pires-Tourreil) n-n and standard SBB (Sack-Biedenharn-Breit) core-n potentials. To ensure that the ^{25}O subsystem is simply unbound, the core-n potential parameters will be changed. Supersymmetric quantum mechanics (SSQM) is used to analyze resonant states near the binding threshold. We then used the ground state wave function to generate the one-parameter family of isospectral potentials. The parameter is set to generate a narrow and deep attractive well, followed by a positive barrier. This well-barrier combination successfully confines the particle, producing a sharp resonance. To find the correct resonance energy, we calculate the probability of finding the system with energy $E > 0$. Finally, the width of the resonance is calculated using the WKB approximation.

Method

A three-body ^{26}O exotic nuclear system is solved using the HHE Method. The much heavier nuclear core ^{24}O is designated as particle "i" whereas two orbiting valence neutrons are designated as particles "j" and "k" respectively. The Jacobi coordinates are defined as follows in the partition 'i' with i, j, k = 1, 2, 3

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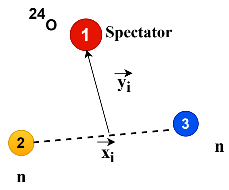

FIG. 1: Illustrative scheme of the choice of Jacobi coordinates.

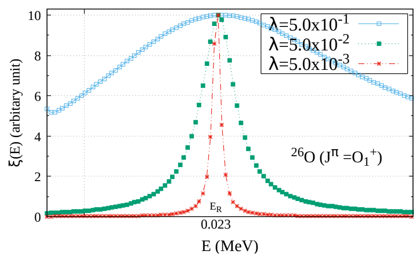

FIG. 2: Resonance profile of ^{26}O.

cyclic:

$$\vec{x_i} = a_i(\vec{b_j} - \vec{b_k}) \tag{1}$$

$$\vec{y_i} = \frac{1}{a_i}\left(\vec{b_i} - \frac{m_j\vec{b_j} + m_k\vec{b_k}}{m_j + m_k}\right) \tag{2}$$

$$\vec{R} = \frac{\left(m_i\vec{b_i} + m_j\vec{b_j} + m_k\vec{b_k}\right)}{M} \tag{3}$$

where a_i is const. ; $m_i, \vec{b_i}$ are the mass and position of the i^{th} particle and $M = m_i + m_j + m_k, \vec{R}$ is the centre of mass (CM) of the system. The hyperradius ρ, and the five angular variables $\Omega_i \to \{\phi_i, \theta_{x_i}, \phi_{x_i}, \theta_{y_i}, \phi_{y_i}\}$ constitute hyperspherical variables of the system. It should be noted that hyperangles Ωi are determined by the partition "i" chosen. The Schrödinger equation is rewritten in terms of hyperspherical variables (ρ, Ω_i):

$$\left[-\frac{\hbar^2}{2\mu}\{\frac{1}{\rho^5}\frac{\partial}{\partial\rho}(\rho^5\frac{\partial}{\partial\rho}) - \frac{\hat{\mathcal{K}}^2(\Omega_i)}{\rho^2}\right] + \left[V(\rho,\Omega_i) - E\right]\Psi(\rho,\Omega_i) = 0 \tag{4}$$

TABLE I: Comparison of the calculated results with experimental data and other reference works found in the literature for ^{26}O.

K_{Max}	S_{2n} (MeV)	$P_{lx=0}$ (fm^{-3})	$E_{lx=0}$(MeV)
16	0.004165	0.8845	-0.01549
20	0.013108	0.8853	-0.03121
24	0.018464	0.8861	-0.03875
∞	0.01896		
State	Observables	Present work	Others work
0^+	S_{2n} (MeV)	0.01896	0.018 [8]
	R_A (fm)	5.635	5.7 [10]
0_1^+	E_R(MeV)	0.023 MeV	$0.15^{+0.5}_{-0.15}$ [5], 0.006-0.053 [9], 0.14 [8],
	Γ(MeV)	0.013 MeV	-

Results and Discussions

In this study, we use a robust approach (very accurate and efficient) to investigate resonances in the ^{26}O exotic nucleus. This approach applies to any weakly bound few-body system, even if it lacks a bound state. FIG.1 depicts Jacobi coordinate selection for ^{26}O three-body systems. The computed probability of particle trapping within the enhanced well-barrier combination, shown as a function of energy E, is illustrated in FIG. 2 with a resonance peak at E$_R$ = 0.023 MeV. Solving the three-body Schrödinger equation to get a converged solution for weakly bound exotic systems is a challenging task. This method could be extremely beneficial for investigating weakly bound states, as well as bound states in the continuum and resonances. The results, as reported in Table 1, imply that ^{26}O could be a potential 2n-halo nucleus that is very weakly bound in nature.

Acknowledgments

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