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Photodisintegration cross section of ^{9}Be up to $E_\gamma = 16$ MeV in the $\alpha + \alpha + n$ three-body model

Y Kikuchi[1], **M Odsuren**[2], **T Myo**[3,4] **and K Katō**[5]

[1] RIKEN Nishina Center, Wako 351-0198, Japan
[2] Nuclear Research Center, National University of Mongolia, Ulaanbaatar 210646, Mongolia
[3] General Education, Faculty of Engineering, Osaka Institute of Technology, Osaka 535-8585, Japan
[4] Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki 567-0047, Japan
[5] Nuclear Reaction Data Centre, Faculty of Science, Hokkaido University, Sapporo 060-0810, Japan

E-mail: `yuma.kikuchi@riken.jp`

Abstract. We investigate the photodisintegration cross section (PDXS) of ^{9}Be in low and higher energy regions by using the $\alpha + \alpha + n$ three-body model and the complex scaling method (CSM). The calculated photodisinegration cross section of well reproduces the recent experimental data, and shows that the transitions into the ^{8}Be$(2^+) + n$ states dominate the cross section in the energy region of $6 \le E_\gamma \le 16$ MeV.

1. Introduction

The photodisintegration cross section (PDXS) of ^{9}Be is very important in investigations of not only astrophysical reaction cross sections for fomation of heavior elements but also nuclear structures of an $\alpha+\alpha+n$ cluster system. As for the former, a very sharp peak corresponding to the $1/2^+$ state has been observed at the energy just above the ^{8}Be+n threshold and our recent investigation is also reported in this meeting by Odsuren[1]. About the second problem, it was reported that the observed dipole strength in ^{9}Be at the exciation energy of ~ 8 MeV exhausts 10% of Thomas-Reiche-Kuhn sum rule and almost all the cluster dipole sum rule [2].

In this talk, we discuss the PDXS due to the electromagnetic transitions into resonant and continuum states of ^{9}Be applying the complex scaling method (CSM) [3, 4] to an $\alpha + \alpha + n$ three-body model. The observed cross section below $E_\gamma \sim 6$ MeV are reproduced with several resonant states corresponding to the experimetal data on excited states of ^{9}Be. The broad bump with the peak position at 8 MeV is also well expained in our calculation, which shows the electric-dipole transition from the ground state of ^{9}Be to the ^{8}Be$(2^+) + n$ continuum state.[5]

2. Complex-scaled $\alpha + \alpha + n$ three-body model

We solve the Schrödinger equation for the $\alpha + \alpha + n$ three-body model using the orthogonality condition model [6]:

$$\hat{H}\Psi^{\nu}_{J^\pi} = E_\nu \Psi^{\nu}_{J^\pi}, \qquad \langle \Phi_{PF} | \Psi^{\nu}_{J^\pi} \rangle = 0, \tag{1}$$

where the second equation means the orthogonality condition for the solution $\Psi^{\nu}_{J^\pi}$ to be orthogonal to the Pauli forbidden states Φ_{PF} in the relative motion of α-α and α-n. The Hamiltonian for the relative motion of the $\alpha + \alpha + n$ three-body system is given as

$$\hat{H} = \sum_{i=1}^{3} t_i - T_{c.m.} + \sum_{i=1}^{2} V_{\alpha n}(\xi_i) + V_{\alpha\alpha} + V_{\alpha\alpha n}. \tag{2}$$

We employ the KKNN potential [7] for $V_{\alpha n}$, and the folding-type nuclear and Coulomb potentials for $V_{\alpha\alpha}$. Furthermore, we introduces the $\alpha+\alpha+n$ three-body potential $V_{\alpha\alpha n}$ of a single Gaussian form with the strength v_3 and the range paprameter μ so as to reproduce the binding energy of ^{9}Be and the energy positions of the observed peaks in the PDXS.

We solve the eigenvalue problem for the complex-scaled Schrödinger equation using the coupled rearrangement-channel Gaussian expansion method [8] where the spatial part of the wave function is expanded with the complex-range Gaussian basis functions.

The cross sections of ^{9}Be$(3/2^-) + \gamma \to \alpha + \alpha + n$ by the electro-magnetic dipole transitions σ_{EM1} are expressed as the following form:

$$\sigma^{\gamma}(E_\gamma) = \sigma_{E1}(E_\gamma) + \sigma_{M1}(E_\gamma), \quad \sigma_{EM1}(E_\gamma) = \frac{16\pi^3}{9}\left(\frac{E_\gamma}{\hbar c}\right)\frac{dB(EM1, E_\gamma)}{dE_\gamma}. \tag{3}$$

Using the energy eigenvalues and eigenstates of the complex-scaled Hamiltonian $\hat{H}^\theta$ and the extended completeness relation [9] in the CSM, the electro-magnetic dipole transition strength is calculated as

$$\frac{dB(EM1, E_\gamma)}{dE_\gamma} = -\frac{1}{\pi}\frac{1}{2J_{gs}+1} Im \left[\sum\!\!\!\!\!\!\int_{\nu} \langle \tilde{\Psi}_{gs}(\theta) || \hat{O}^{\theta}_{EM1} || \Psi^{\nu}(\theta) \rangle \frac{1}{E - E^{\theta}_{\nu}} \langle \tilde{\Psi}^{\nu}(\theta) || \hat{O}^{\theta}_{EM1} || \Psi_{gs}(\theta) \rangle \right], \tag{4}$$

where J_{gs} and $\Psi_{gs}(\theta)$ are the total spin and the wave function of the ground state, respectively, and $\hat{O}^{\theta}_{EM1}$ is an electro-magnetic dipole transition operator.

3. Cluster dipole resonance

We determine the strength $v_3 = 1.10$ MeV and the range parameter $\mu = 0.02$ fm^{-2} of the $\alpha+\alpha+n$ three-body potential so as to fit the binding energy, charge and matter radii of the ^{9}Be ground state. In Fig. 1, calculated PDXS is shown in comparison with experimantal data. Although the peak positions are fitted by adjusting the strength v_3 for each spin-parity state, the magnitudes and widths of the observed cross section are well reprodced simultaneously. We see that the lowest peak just above the ^{8}Be$(0^+)+n$ threshold energy ($E_\gamma = 1.6654$ MeV) comes from the $E1$ transition into the $1/2^+$ state, and the calculated cross section shows that the strength below the ^{8}Be$(0^+) + n$ threshold is negligibly small. We have no resonance solutions corresponding to the peak, and discussed that the origin of the peak is a virtual state [1]. The second and third peaks at $E_\gamma = 2.5$ and 3.0 MeV in the cross section come from the transitions into the resonances of $5/2^-$ and $5/2^+$ states, respectively. The $M1$ transition into the $1/2^-$ resonance has a sizable contribution to the cross section at around $E_\gamma = 2.7$ MeV. The transitions into the $3/2^-$ and $3/2^+$ states play minor roles in the PDXS below $E_\gamma = 6$ MeV. The energy level diagram is also shown in Fig. 2, where we show the levels which are obtained using $v_3 = 1.10$ MeV commonly for all the spin-parity states for reference.

From Fig. 1, we see that the calculated PDXS has a broad peak at $E_\gamma \sim 8$ MeV, similar to the experimental data. The calculation indicates that the peak is dominated by the $E1$ transitions into $3/2^+$ and $5/2^+$. In the recent measurement, it is reported that the energy integrated cross section for the enhanced dipole strength measured for $4 \le E_\gamma \le 16$ MeV is estimated to be

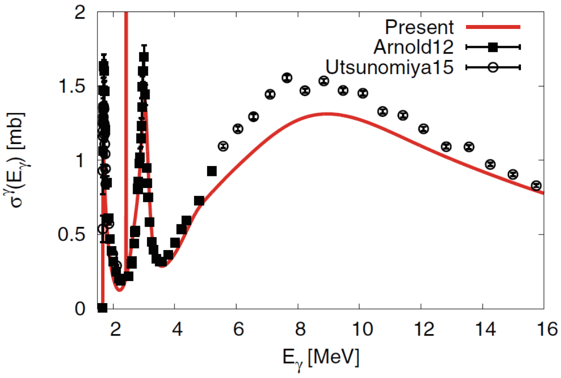

Figure 1. Calculated PDXS up to E_γ =16 MeV. The solid squares and open circles represent experimental data taken from Refs. [11, 2], respectively.

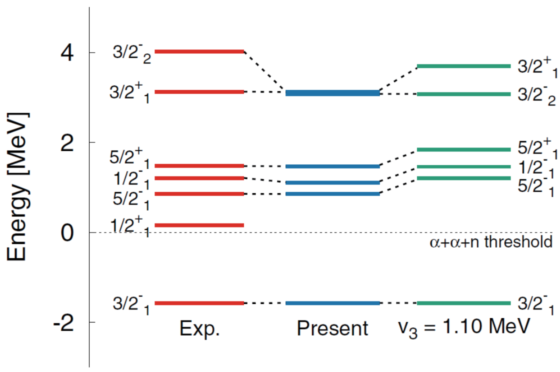

Figure 2. Comparison of the energy diagrams from the present calculation, experimetal data [10] and calculations using $v_3 = 1.10$ MeV for all the spin-parity states.

11.3 mb·MeV as a lower limit [2]. It is also suggested that this energy-integrated cross section exhausts 10% of the Thomas-Reiche-Kuhn (TRK) sum rule and almost all of the energy-weighted cluster dipole sum rule. We calculated the energy-integrated cross section by integrating σ_{E1} over the energy interval of $4 \leq E_\gamma \leq 16$ MeV. The calculated energy-integrated cross section is 12.1 mb·MeV for this energy interval, which is consistent with the experimental value (11.3 mb·MeV). On the other hand, we obtain the energy-integrated cross sections for $E_\gamma < 4$ MeV and $E_\gamma > 16$ MeV as 0.954 and 8.40 mb·MeV, respectively. It is seen that the energy-integrated cross section for $4 \leq E_\gamma \leq 16$ MeV is 56.5 % of the total amount in the present calculation.

We calculated the decomposition of the PDXS into different families of the nonresonant continuum states. The result shows that the cross sections at $E_\gamma \sim 8$ MeV are dominated by the contributions from the ^{8}Be$(2^+) + n$ continuum states, while the contribution from the ^{8}Be$(0^+) + n$ continuum solutions is negligible in the cross section [5]. This result is consistent with the previous study [12].

4. Conclusion

The photodisintegration of ^{9}Be in the energy region lower than E_γ =16 MeV was investigated by using the $\alpha + \alpha + n$ three-body model and the complex scaling method. It was shown that the dipole strength at $E_\gamma \sim 8$ MeV is understood to be caused by the single-neutron excitation from the ^{8}Be$(2^+) \otimes \nu p_{3/2}$ configuration in the ground state.

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