Evaluation Activities at JCPRG

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Abstract

Nuclear structure and reaction theory always plays a very important role to study nuclear physics. In this report, we introduce briefly some evaluation activities in JCPRG in 2014. These theoretical calculations can help us to evaluate some nuclear data from experiments and also provide us with a good prediction for some required nuclear data.

1 Introduction

The JCPRG's central task is to compile the data obtained in Japan on charged-particle and photo-induced nuclear reactions [1]. As the member of the International Network of Nuclear Reaction Data Centres (NRDCs), JCPRG has contributed about 10 percent of the data on charged-particle nuclear reactions in the database. On the other hand, some members of JCPRG are also doing some theoretical calculations for studying nuclear reaction and structure. By using different nuclear models, we can get useful information on the nuclear reaction and structure. Now, to develop further the theory-based approaches for the evaluation of nuclear reaction data has became one important objective in JCPRG.

In this report, our activities on the evaluation of the nuclear data are presented. First, we will show a systematic study on electric dipole (E1) modes of even-even nuclei obtained from the canonical-basis time-dependent Hartree-Fock-Bogoliubov theory (Cb-TDHFB). Then, we will show some results on the continuum discretized coupled channel (CDCC) analysis to the integrated elastic and inelastic scattering cross sections for ^{6,7}Li. Next, nuclear scattering problems in the complex scaling method are discussed. Finally, 2-alpha correlation of the ground state of ^{12}C is studied in a container picture.

2 Systematic investigation of low-energy electric dipole modes of even-even nuclei

We systematically investigate the electric dipole (E1) modes of even-even nuclei using the canonical basis time-dependent Hartree-Fock-Bogoliubov theory (Cb-TDHFB). The Cb-TDHFB can describe the nuclear dynamics in the three-dimensional Cartesian coordinate space dealing with nuclear superfluidity [2]. Therefore we can carry out systematic investigation without any restriction for mass number, open shell structure and deformation. The linear response calculation with the Cb-TDHFB for E1 and quadrupole excitation reproduces the strength function obtained by the quasi-particle random phase approximation which is a small amplitude limit of full TDHFB. Actually the photoabsorption reaction cross section of ^{172}Yb is well reproduced by the Cb-TDHFB calculation [3].

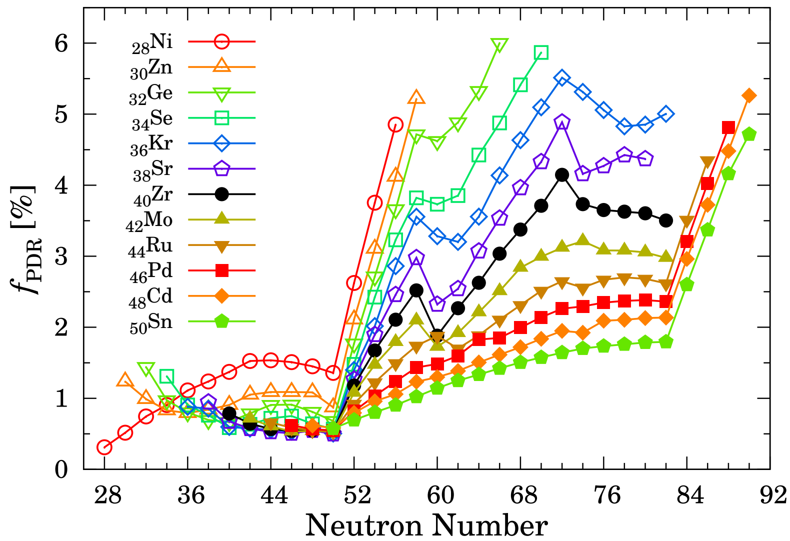

Figure 1: Neutron number dependence of the low-lying E1 modes in total E1 strength which is taken from Refs. [4, 5].

To understand the structure of unstable nuclei and the contribution of them to the nucleosynthesis related with neutron-rich region, we investigate especially the systematics of low-lying E1 mode which is often called Pygmy dipole resonance (PDR). Figure 1 shows the neutron number dependence of the low-lying E1 strength, which is evaluated as the ratio in the energy weighted total E1 strength. There are kinks of the ration which are reflected in shell structure at N=50 and 82, and also the kinks at N=60 and 70 corresponding to the shape transition region [4, 5]. This work shows that the shell effects for PDR of heavy nucleus remain also around N=82 corresponding to f-orbits occupation, and the change of chemical potential due to the deformation induces the PDR suppression (N=60) and enhancement (N=70). In our future work, we will construct the theoretical database for medical, astrophysics and nuclear engineering from these systematic calculation and simulations.

3 Analysis of ^{6,7}Li + n reactions using CDCC method

We have studied applicability of the continuum discretized coupled channel (CDCC) method for neutron scattering on lithium isotope [6–8]. In this fiscal year, we extended the CDCC [9] analysis to the integrated elastic and inelastic scattering cross sections for ^{6,7}Li at incident neutron energies below 10 MeV by using optical model potential (OMP) [10, 11] and above 10 MeV by using JLM [12]. Energy dependence of the normalization factors, for the OMP cluster-folding potential is introduced and determined from measured integrated elastic cross sections, respectively, at incident neutron energies below 10 MeV. We adjust the normalization constants for the OMP, because the agreement of the calculated cross sections data at very low incident energies of the neutron is insufficient without any adjustments. The energy dependent normalization constants, real part λ_v and imaginary part λ_w, of the OMP and JLM are determined explicitly from integrated elastic cross section data, respectively. Comparing the results of calculations and experimental data, we discuss that the present CDCC calculations, which reproduce the experimental data observed in incident energies higher than 10 MeV with the single folding potential of the JLM and in lower energies with introducing the normalization factors for the cluster folding potential of the OMP.

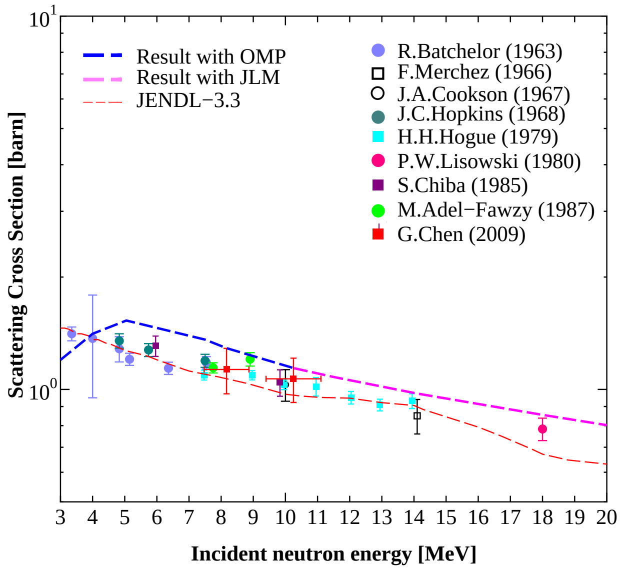

Figure 2: The integrated elastic scattering cross sections of ^{6}Li, in comparison with the evaluated data and experimental data.

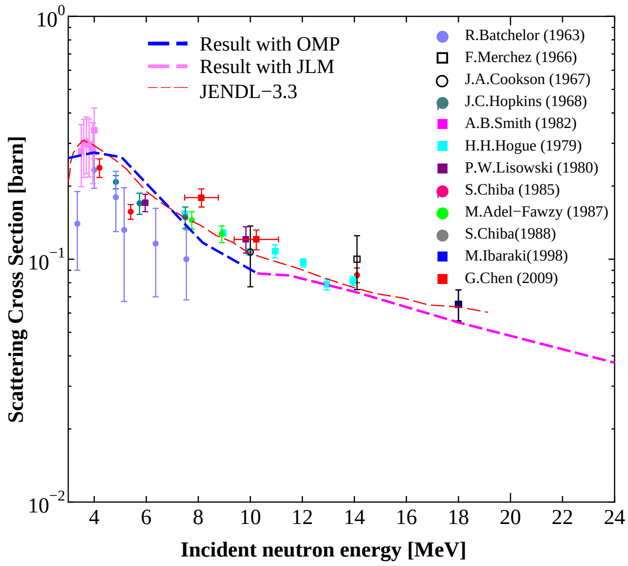

Figure 3: The integrated inelastic scattering cross sections for the 2.186-MeV state of ^{6}Li, in comparison with the evaluated data and experimental data.

For example, the integrated elastic cross sections for ^{6}Li agree with the evaluated data (JENDL-3.3) and other measurements within the experimental uncertainties, as shown in Fig. 2. In Fig. 3, the integrated inelastic cross-section values for the 2.186-MeV state of ^{6}Li are almost in good agreement with the evaluation data of JENDL-3.3 and the experimental data.

4 Nuclear scattering problems in the complex scaling method

Our long standing problem is to understand the scattering phenomena together with nuclear structure problems. For this purpose, the complex scaling method is very promising, because it has the following advantages: 1) We can obtain resonant states by solving a eigen-value problem with an L^2 basis functions in the same way as a bound-state problem. 2) The discretized continuum states are also obtained as complex energy solutions on the rotated branch cuts separately from isolated resonances. 3) Not only two-body but also many-body resonances can easily be obtained. In 2013, we had developed results of the following two problems:

i) Decomposition of scattering phase shifts and reaction cross sections using the complex scaling method [13]. In this work, we have shown a new method to calculate the scattering phase shift using complex scaled eigen-value solutions. This method provides us with a useful decomposition of the phase shift into resonance and background terms. We presented the applications for several two-body systems: (a) a schematic model with the Gyarmati potential, which produces many resonances, (b) the α+α system, which has a Coulomb barrier potential in addition to an attractive nuclear interaction, and (c) the α+n system, which has no barrier potential. Using different kinds of potentials, we discuss the reliability of this method to investigate the resonance structure in the phase shifts and cross sections.

ii) Analysis of Three Body Resonances in the Complex Scaled Orthogonal Condition Model [14]. Although the resonance structures of α+α+n have been studied experimentally and theoretically, it is still necessary to have more accurate and comprehensive understandings of the structure and decay of the low-lying excited states in ^{9}Be. To perform calculations of an α+α+n system, we investigate five resonant states of α+α subsystem by utilizing different potential parameters and basis functions. In addition, two resonance states of α+n subsystem are computed.

These studies have shown that the CSM provides us with a useful way for evaluations of nuclear data through analyses of the observed scattering data using resonance solutions of the CSM. On the basis of these results, it is planned to carry out an analysis of the photodisintegration cross sections of ^{9}Be in which some discrepancies are observed in the experimental data.

5 Study of the ground state of ^{12}C in the container picture

Recently, we proposed a container picture for the description of the cluster structures in light nuclei, which has been very successful for the description of the inversion-doublet band states of ^{20}Ne [15] and the hoyle state of ^{12}C. To develop the container picture on the firmer ground, we construct the 2-alpha+alpha THSR (Tohsaki-Horiuchi-Schuck-Röpke) wave function [16], in which the 2-alpha correlation can be included in a natural way. Thus, we can get the single optimum THSR wave function by variation calculations and then explore whether the compact ground state of ^{12}C can be described well by this extended THSR wave function.

In the container picture, the 2-alpha+alpha THSR wave function can be written as follows,

$$\Phi(\boldsymbol{\beta}_1, \boldsymbol{\beta}_2) \propto \phi_G \mathcal{A}\{\exp[-\sum_{i=1}^{2}(\frac{r_{ix}^2}{B_{ix}^2} + \frac{r_{iy}^2}{B_{iy}^2} + \frac{r_{iz}^2}{B_{iz}^2})]\phi(\alpha_1)\phi(\alpha_2)\phi(\alpha_3)\}, \tag{1}$$

Where $B_{1k}^2 = b^2 + \beta_{1k}^2$, $B_{2k}^2 = \frac{3}{4}b^2 + \beta_{2k}^2$, and $\boldsymbol{\beta}_i \equiv (\beta_{ix}, \beta_{iy}, \beta_{iz})$. b is the size parameter of the harmonic-oscillator wave function. $\phi(\alpha_i)$ represents the ith-α-cluster intrinsic wave function and $\boldsymbol{X}_i$ is its corresponding center-of-mass coordinate. $\boldsymbol{r}_1 = \boldsymbol{X}_2 - \boldsymbol{X}_1$, $\boldsymbol{r}_2 = \boldsymbol{X}_3 - (\boldsymbol{X}_1 + \boldsymbol{X}_2)/2$. ϕ_G is the center-of-mass wave function of ^{12}C, which can be expressed as, $\exp(-6X_G^2/b^2)$. If we make the replacement, $\boldsymbol{\beta}_1 \to \sqrt{2}\boldsymbol{\beta}_0$ and $\boldsymbol{\beta}_2 \to \sqrt{3/2}\boldsymbol{\beta}_0$ in Eq. (1), this 2-alpha+alpha THSR wave function becomes the 3-alpha THSR wave function with single $\boldsymbol{\beta}_0$ parameter used by Funaki et al. in Ref [17].

First, we find that the single extended two-$\boldsymbol{\beta}$ THSR wave function for the ground state of ^{12}C is very close to the full solution results of the 3-alpha cluster models [18, 19], e.g., the calculated squared overlaps between $\hat{\Phi}_{\rm GCM}(\boldsymbol{\beta}_1, \boldsymbol{\beta}_2)$ and the single normalized 2-alpha+alpha THSR wave functions corresponding to their minimum energies are as high as 98%. Thus, the container picture is proved to be also very successful for describing this compact three-body cluster structure of the ground state with normal density. Furthermore, the squared overlap between the single 3-alpha THSR wave function and the THSR-GCM wave function for the ground state is about 93%, by introducing the 2-alpha correlation, the corresponding squared overlap increases to 98%. This provides a strong support for the existence of the 2-alpha correlation in the ground state of ^{12}C. See details in Ref. [20].

Compared with the traditional microscopic RGM (resonating group method)/GCM(generator coordinate method) wave function for ^{12}C, the THSR wave function is very simple and flexible. Next, this extended THSR wave function can be used for the evaluation of nuclear structure data related with ^{12}C, e.g., the recently observed 0_3^+ and 0_4^+ states from experiments [21].

6 Summary

In summary, firstly, we show the systematic study for electric dipole (E1) modes of even-even nuclei obtained with Cb-TDHFB. Based on the Cb-TDHFB theory, the evaluation database for medical, astrophysics and nuclear engineering can be built from the systematic calculation and simulations in the future. Secondly, it is shown that the integrated inelastic and elastic cross-section values for the 2.186-MeV state of ^{6}Li by CDCC are in good agreement with the experimental data. Thirdly, we discuss the complex scaled orthogonal condition model, which is a useful way for evaluations of nuclear data through analyses of the observed scattering data. Last, it is shown that the ground state of ^{12}C has been described very well in a container picture, thus, the related excited states information of ^{12}C are promising to be evaluated in this theoretical framework in the future.

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