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ABSTRACT

The alpha cluster model is used in considering the ^{16}O nucleus as a bound state of four alpha particles. This problem is represented by integral equations which are exact effective two-particle equations. These equations have the form of two-particle Lippmann-Schwinger equations. The separable expressions are used in approximating the scattering amplitudes in the separable potential model to include also few and small non-separable rest parts of the interactions. The integral equations obtained are manageable and suitable for computations. Numerical calculations are carried out for the ^{16}O nucleus, with the structure of four bound alpha particles. The obtained binding energy of ^{16}O with that structure is 16.86 MeV which is in good agreement with the experimental value.

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I. INTRODUCTION

The three-body problem has been shown to be a powerul tool in studying the static properties of light nuclei. Faddeev [1] succeeded in introducing an exact solution of the three-body problem representing the three-body integral equations in a matrix form. The Faddeev equations [2),3)] form a well-behaved set of three-body equations involving the two-body T matrix rather than the potential. Separable expansion with separable two-body interactions has been shown [4),5)] to reduce the Faddeev equations to a set of coupled one-dimensional integral equations, and are found [6)-11)] to extract some of the properties of light nuclei.

Different approaches have been introduced [12)-14)] to study the N-particle problem. The first approach [12),13)] has been applied [15)] for scattering and bound-state problems of four-nucleon systems, while the second approach [14)] has been applied [16)] for different clustering structure in different light nuclei. The use of the three-body Faddeev equations for heavier than mass three nuclei needs big computation facilities. The Faddeev equations and its formalism with its extension to N-particle systems are exact equations but with the difficulty of the big volume of computations needed. Alt, Grassberger and Sandhas in their treatments [12),13),15),17)] of the N-particle problem, obtained integral equations which have the structure of multi-channel two-particle Lippmann-Schwinger equations, and are more practical than those of Faddeev.

In the present work, we are interested in studying the bound state of the ^{16}O nucleus. We use for the ^{16}O nucleus, the alpha cluster model, considering that the alpha particle is a structureless unit entity. Thus, the ^{16}O nucleus is considered as the bound state of four alpha particles. Then, presently, we are studying a four-body problem. We follow, in the present work, the formalism previously introduced by Alt, Grassberger and Sandhas for the three-nucleon system [17)], which is extended to the N-particle system [12),13)] and applied to the case of the four-nucleon system [15)]. In this formalism, the separable potential model approximation is used. With this approximation, the four-particle equations are reduced to effective two-particle equations. These equations become one-dimensional equations by using angular momentum decomposition. Also, it is allowed to take into account some of the non-separable rest kernels by calculating the Schmidt norms. These non-separable parts of the interaction were neglected earlier, and now they are considered by means of perturbation theory. The variational method of Wright and Scadron [18)] is applied in finding as few as possible terms of the separable approximations. The alpha particles in the alpha cluster model [19),20)] are treated as rigid entities without internal structure. Thus, the alpha particles are considered to interact with each other by a potential determined from the alpha-alpha scattering experiments. In the present work we use non-local separable alpha-alpha interactions obtained by fitting the S-wave alpha-alpha scattering length and effective range. Three forms of the non-local separable potentials are considered. For the different forms of the non-local separable potentials, we use the Yamaguchi [21)], the Gaussian and the Tabakin [22)] form potentials. The Yamaguchi potential is taken as purely attractive, while the Gaussian and the Tabakin potentials are considered to contain both attraction and repulsion. With these forms of the separable potentials, the four-body integral equations of four bound alpha particles in ^{16}O are reduced to exact effective two-body Lippmann-Schwinger equations. The integral equations obtained are manageable for computations and suitable for numerical calculations.

In Sec.II, we introduce the four-body integral equations for four bound alpha particles in ^{16}O. Numerical calculations and results are given in Sec.III. Sec.IV is devoted to discussion and conclusions.

II. FOUR-BODY INTEGRAL EQUATIONS

The present problem of the ^{16}O nucleus is considered with the alpha cluster model structure. In this model, the alpha particles are considered as rigid entities without any internal structure. Correspondingly, the alpha particles interact with each other by means of a potential determined from the alpha-alpha scattering experiments. The separable two-nucleon potentials show great simplicity in the analysis and calculations of the three-nucleon problem. In the present work we use non-local separable potentials for the alpha-alpha interactions. We also use the S-wave of the alpha-alpha interactions with the parameters adjusted to fit the scattering length and the effective range, which are measured experimentally with the Coulomb effects removed. The mass of the alpha particle is m_α . Then, a separable form for the alpha-alpha potentials is expressed as

$$V_{\alpha\alpha}(p,p') = -(\hbar^2/m_\alpha)\ (1/2\pi^2)\ f(p(\ f(p') \quad . \qquad (1)$$

With this form for the non-local separable alpha-alpha potential expressed by Eq.(1), the two-body alpha-alpha binding energy $\hbar^2K^2/m_\alpha$ is obtained from the relation

$$1 = \frac{2}{\pi}\int_0^\infty dp\ \frac{p^2f^2(p)}{p^2+K^2} \quad . \qquad (2)$$

The S-wave phase shifts are also obtained from the well-known relation

$$\tan\delta(k) = kf^2(k)/\left[1 - \frac{2}{\pi}\ P\int_0^\infty dp\ \frac{p^2f^2(p)}{p^2-k^2}\right] \quad . \qquad (3)$$

The form factor $f(p)$ defines the shape of the non-local separable alpha-alpha potential given by Eq.(1). These form factors $f(p)$ are suggested in such a way so as to give both attraction and repulsion. In the present work, we use three different types of these form factors. We also use the Yamaguchi [21)], the Gaussian and the Tabakin [22)] form potentials. The Gaussian and Tabakin potentials contain both attraction and repulsion. The Yamaguchi potential is taken to be a purely attractive potential for the purpose of comparison. The different forms of the separable alpha-alpha potentials are given in Ref.10 together with the different values of the different parameters which are used to fit the S-wave nuclear scattering phase shifts. The values of the alpha-alpha binding energies, which are only the nuclear binding energies, as calculated using the different sets of parameters for the different forms of the alpha-alpha interactions,are also listed in Ref.10. We use here the same notations for the alpha-alpha interactions as mentioned in Ref.10. The form factor $f(p)$ for the Yamaguchi potential, for example (which implies the Yukawa-type spatial dependence) and which contain only attraction, has the form

$$f_Y(p) = \alpha(p^2 + b^2) \quad . \qquad (4)$$

To discuss the bound state of four alpha particles forming the ^{16}O nucleus, we have first to consider the bound state of two alpha particles. The parameters of the alpha-alpha potentials listed in Ref.10, of the Yamaguchi, the Gaussian and the Tabakin type poentials give values for the ground-state energies of ^8Be as -2.92 MeV, -3.43 MeV and -3.62 MeV, respectively. These values are only the nuclear binding energies. The Coulomb energy must be added to these values to get the actual binding energies. The Coulomb energy E_c could be calculated approximately from a formula [23)] for a uniform spherical charge distribution. The value of the calculated Coulomb energy due to this formula is $E_c(^8Be) - 2E_c(^4He) = 2.03$ MeV. Adding this value of Coulomb energy to the calculated nuclear binding energies, we are left with a stable ^8Be bound state. Thus, in spite of the fact that the observed ground-state of ^8Be is unstable by about

0.1 MeV, we see that our theoretical calculations produce a stable bound state for ^{8}Be. This difference, which is a little large, could be explained [10] as that the wave functions resulting from the potentials used are too large at small distances.

Following the formalism of Alt, Grassberger and Sandhas [12),13),15),17)], the amplitudes of the four-body system are given by the expression

$$T_{s,r} = \mathcal{V}_{s,r} - \sum_{\nu} \mathcal{V}_{s,\nu}\, t_{\nu}\, T_{\nu,r} \quad . \qquad (5)$$

The expression (5) represents coupled Lippmann-Schwinger equations in the effective two-body formulation of the four-body system. In this equation (5), the non-separable terms in the subsystems are neglected. The potentials and propagators in the Lippmann-Schwinger type equation (5) are developed by Alt et al. [15)] in terms of form factors defined from approximating the off-shell scattering amplitudes by separable expressions of the quasi-Born series [12),13),17),24),25)]. In the case of four bound alpha particles, we are interested in the vertices (^{16}O, $\alpha\,^{12}C$) and (^{16}O, ^{8}Be ^{8}Be).

III. NUMERICAL CALCULATIONS AND RESULTS

The alpha cluster model is used in the present study to describe the ^{16}O nucleus. For this, the ^{16}O nucleus is composed of four alpha particles. To calculate the binding energy of four bound alpha particles we use the integral equations expressed by Eq.(5). We use here non-local separable alpha-alpha interactions which simplify the calculations. The binding energy could be obtained to a high accuracy using only a limited number of terms. In the present bound-state problem, we solve the Lippmann-Schwinger type equation (5) not by matrix inversion, but by using the variational principle introduced by Alt et al. [15)] for the four-nucleon system. So, in this case we are interested in the vertices (^{16}O, $\alpha\,^{12}C$) and (^{16}O, ^{8}Be ^{8}Be). For simplicity, we consider that the trial functions needed for the variational treatment are identical. The form factor could be obtained by approximating it defining its value at some mean momentum. Thus, in the variational principle, the final form factor has the correct threshold behaviour as well as the same asymptotic behaviour. Using this variational method, the integral equations are applied for the case of ^{16}O nucleus as four bound alpha particles. Numerical calculations are performed to obtain the nuclear binding energies. The results of the values obtained of the four-bound alpha particles ground-

state energies of ^{16}O nucleus using the different alpha-alpha potential forms are given in Table I.

These present theoretically calculated values of the binding energies must be compared with the experimental value. The experimental value [26)-28)] of the ground-state energy for the ^{16}O nucleus is -14.44 MeV. We note that our theoretical values listed in Table I are only the nuclear binding energies. Thus, we must add the Coulomb energy resulting from the Coulomb repulsion between the four alpha particles. The Coulomb energy for the four alpha particles in the ^{16}O nucleus is approximately calculated by a simple formula [23)] with a value $E_c(^{16}O) - 4E_c(^{4}He) = 10.03$ MeV. Thus, by adding this value of the Coulomb energy to the values listed in Table I, shows that our theoretically calculated values for the ground-state energies for the ^{16}O nucleus are reasonable and in agreement with the experimentally observed values.

IV. DISCUSSION AND CONCLUSIONS

In the present study, we calculate the binding energy of the ^{16}O nucleus described on the basis of the alpha cluster model. So, we are studying the four-body problem of four bound alpha particles. The alpha-alpha interactions are expressed by non-local separable potentials. The separable potentials which we use in the present calculations can give both attraction and repulsion. Moreover, the potentials already used include the size effect of an alpha particle in that the repulsive part of the potentials originates from the exclusion principle operating between two composite alpha particles. The Yamaguchi form of the interaction used here is purely attractive and is used here for the purpose of comparison to investigate the effect of the short-range repulsive part of the potential. The Gaussian and the Tabakin forms of the interaction contain both attraction and repulsion. This property of the single separable potentials helps in reducing the total number of separable terms needed to reduce the two-body data. This in turn simplifies considerably the four-body problem calculations.

The calculated values of the ground-state energies of ^{16}O as four bound alpha particles, and are listed in Table I, are only the nuclear binding energies. Adding the approximate value, with its rough estimate, of the Coulomb energy to the nuclear values, we obtain reasonable values for the ground-state energies which are not far from the experimental values. However, the Coulomb forces could be treated accurately by treating the pure Coulomb T matrix in the three-alpha system [8)] with extension to the four-alpha system, to get more accurate values for the binding energies.

By comparing the results obtained for both the Gaussian and Tabakin potentials (containing both attraction and repulsion) with the result obtained using the Yamaguchi potential (containing only attraction), the effect of repulsive forces can be estimated. From this comparison, we see that the short-range repulsive forces improve the value of the binding energy by about 10.26%.

Thus, we can conclude with some points concerning the present calculations. In spite of the fact that the Faddeev formalism solves the few-body problems more accuractely and gives better results, it needs complicated numerical calculations and computations. The variational method used in the present calculations gives integral equations which are manageable and suitable for numerical calculations, giving results which are reasonable and in agreement with the experimental values. The short-range repulsive forces in the alpha-alpha interactions are important and should be included to improve the results of the calculated ground-state energies. Also, Coulomb forces should be considered accurately by treating the pure Coulomb T matrix which gives more accurate values for the binding energies.

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Table I

Calculated nuclear binding energies

alpha-alpha potential form	Ground-state energy of ^{8}Be (MeV)	Ground-state energy of ^{12}C (MeV)	Ground-state energy of ^{16}O (MeV)
Yamaguchi	-2.92	-14.83	-28.84
Gaussian	-3.43	-14.08	-27.28
Tabakin	-3.62	-13.75	-26.89

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