Modeling the double charge exchange response function for a tetraneutron system

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Received February 6, 2017; Revised April 28, 2017; Accepted May 16, 2017; Published July 28, 2017

This work is an attempt to model the \(4n\) response function of a recent RIKEN experimental study of the double charge exchange \(^4\)He\(^8\)He,\(^8\)Be\(^4\)n\) reaction in order to put in evidence an eventual enhancement mechanism of the zero-energy cross section, including a near-threshold resonance. This resonance can indeed be reproduced only by adding to the standard nuclear Hamiltonian an unphysically large \(T=3/2\) attractive \(3n\)-force that destroys the neighboring nuclear chart. No other mechanisms, like cusps or related structures, were found.

Subject Index D13

1. Introduction

In a recent experiment at RIKEN (Refs. [1,2]), it was suggested that the existence of a resonant tetraneutron \((4n)\) state could explain the sharp structure observed in the \(^4\)He\(^8\)He,\(^8\)Be\(^4\)n\) reaction cross section near the \(4n\) threshold. They reported \(E_R = 0.86 \pm 0.65 \pm 1.25\) MeV and \(\Gamma < 2.5\) MeV.

A subsequent theoretical analysis by the same authors (Ref. [3]) as the present work showed the difficulty in accommodating such near-threshold resonance of the \(4n\) system without dramatically disturbing the well-established neighboring nuclear chart. It was, however, pointed out in Ref. [3] that some reaction mechanism, being able to produce an enhancement of the cross section at small energy, should be investigated. It is indeed well known that without the presence of S-matrix poles there exist other possibilities to generate sharp structures in a reaction cross section (Ref. [4]).

The dineutron–dineutron correlation has sometimes been invoked as a possible enhancement mechanism, due to the large value of the scattering length (Refs. [5,6]). However, previous calculations (Refs. [7–9]) indicated that the interaction between 2 (artificially bound) dineutrons is repulsive and so the probability of finding 4 neutrons at the same point of the phase space is very weak. A similar conclusion was reached in the framework of the effective field theories (EFT) for the more general case of fermionic systems close to the unitary limit (Refs. [10–12]). Their conclusions are model independent and rely only on the fact that the fermion–fermion scattering length is much larger than the interaction range, which is the case for the neutron–neutron system. In view of these results, and contrary to some theoretical claims, it seems very unlikely that the tetraneutron system could manifest a near-threshold resonant state.

The aim of this short note is to investigate a particular reaction mechanism that can model the double charge exchange reaction and kinematics involved at the RIKEN experiment and could generate any near-threshold structure in the cross section.
This reaction mechanism is based on factorizing the transition amplitude into a spectator smooth part and a term involving the charge exchange between the initial \( ^4\text{He} \) and final \( 4n \) states, which could be responsible for the sharp structure, either due to a cusp or to the presence of a resonance. The same mechanism, though with different dynamical contents in the initial and final states, was used in the numerical simulation underlying the analysis of the RIKEN result (Refs. [1,2]) and can be a guide to ongoing or future experiments.

We will detail in the next section the reaction mechanism we have considered to model the RIKEN experiment. The formalism allowing us to access the response function, as well as the computational method we have used to obtain the solution of the 4-body Hamiltonian, will be sketched in Sect. 3. Section 4 will be devoted to presenting our results and we will present our conclusions in the last section.

2. Reaction mechanism

The experiment held by Kisamori et al. used a 186 MeV/u \( ^8\text{He} \) beam to bombard \( ^4\text{He} \). The reaction \( ^4\text{He}(^8\text{He},^8\text{Be})4n \) was studied in very particular kinematical conditions, where most of the kinetic energy of the projectile were transferred to the \( ^8\text{Be} \) nucleus. The decay products of \( ^8\text{Be} \), namely the two alpha particles, were detected in order to reconstruct the kinematics. Though an accurate description of this 12-nucleon reaction is far beyond the reach of our numerical tools, the particular kinematics employed in this experiment suggest using approximate methods in order to estimate the possible response.

The principal reaction mechanism is a double charge exchange with little energy transfer to the \( ^4\text{He} \) nucleus target, which transforms it into a tetraneutron. The transition amplitude for such a process might thus be split in two pieces,

\[
A \approx \langle ^4n | \hat{O}_1 | ^4\text{He} \rangle \langle ^8\text{Be} | \hat{O}_2 | ^8\text{He} \rangle ,
\]

where \( O_i \) are some transition operators. These two factors correspond respectively to the “fast” process \( ^8\text{Be}|\hat{O}_2| ^8\text{He} \) carrying most of the 186 MeV/u kinetic energy of the projectile and a “slow” \( ^4n|\hat{O}_1| ^4\text{He} \) constituent of the charge exchange reactions, which remains practically static.

The total reaction cross section then takes the form

\[
\sigma_{\text{tot}}(E) \propto | \langle ^4n | \hat{O}_1 | ^4\text{He} \rangle \langle ^8\text{Be} | \hat{O}_2 | ^8\text{He} \rangle |^2 \delta(E_i - E_f) .
\]

We are interested in the first term \( \langle ^4n | \hat{O}_1 | ^4\text{He} \rangle \) of the last expression, since this term should bring into evidence any resonant features of the tetraneutron or any alternative mechanism for enhancing the cross section (if any). The other term, related to a rapid process and involving large momenta, may affect the overall size of the total cross section, but should not have a significant influence on the low-energy distribution of the \( 4n \) system.

On the other hand, the features of the \( \langle ^4n | \hat{O}_1 | ^4\text{He} \rangle \) matrix element will critically depend on the particular transition operator \( \hat{O}_1 \), which is unknown. In this work we will assume the most probable one. Since \( ^4\text{He} \) and \( 4n \) wave functions are coupled with little momenta transfer, the corresponding transition operator should contain only low-order momenta terms and thus its space-spin structure should have quite a simple form. Furthermore, we will assume that both \( ^4\text{He} \) and \( 4n \) wave functions are \( J = 0^+ \) states since, as pointed out in our previous studies (Refs. [3,8]), this state is the most favorable tetraneutron configuration revealing resonant features. The transition operator \( \hat{O}_1 \) should therefore be a scalar.
One possibility could be $E_0$ or $\sigma_i \sigma_j$ operators. However the effect of these operators would be strongly suppressed by the spatial orthogonality between the $^4\text{He}$ and $^4\text{n}$ wave functions. This follows from the shell model representation of $^4\text{He}$ and $^4\text{n}$ wave functions with s-wave protons replaced by p-wave neutrons. Furthermore the $\sigma_i \sigma_j$ term implies correlated double charge exchange, but since the exchange of the nucleons takes a very short time, the uncorrelated process is expected to dominate. The simplest operator allowing such a transition might be represented as a double spin-dipole term:

$$\hat{O}_1 = (\sigma_i \cdot r_i)(\sigma_j \cdot r_j)\tau_i^- \tau_j^-.$$  \hspace{1cm} (2.3)

In the last expression, $\tau_i^-$ isospin reduction operators are added, which enable charge exchange, i.e., replacing a proton by a neutron.

Once the transition operator is fixed, we are interested in evaluating the response (or strength) function, given by

$$S(E) = \sum |\Psi_\nu \langle \hat{O}_1 | \Psi_0 \rangle|^2 \delta(E - E_\nu),$$  \hspace{1cm} (2.4)

where $\Psi_0$ represents the ground state wave function of the $^4\text{He}$ nucleus, with ground-state energy $E_0$, and $\Psi_\nu$ represents the wave function of the $^4\text{n}$ system in the continuum with an energy $E_\nu$. Both wave functions are solutions of the 4-nucleon Hamiltonian $H$. The energy is measured from some standard value, e.g., a particle-decay threshold energy.

The strength function (Eq. (2.4)) may be rewritten in terms of the forward propagator

$$\hat{G}^+(E) = \frac{1}{E - \hat{H} + i\epsilon}$$

in the form

$$S(E) = -\frac{1}{\pi} \text{Im} \langle \Psi_0 | \hat{O}_1^\dagger \hat{G}^+(E) \hat{O}_1 | \Psi_0 \rangle,$$  \hspace{1cm} (2.5)

in which the summation over the final states is avoided.

The latter expression can still be transformed into

$$S(E) = -\frac{1}{\pi} \text{Im} \langle \Psi_0 | \hat{O}_1^\dagger \hat{G}^+(E) \hat{O}_1 | \Phi_0(E) \rangle,$$  \hspace{1cm} (2.6)

i.e., as a matrix element of the (conjugate) transition operator between the initial state $\Psi_0$ and the outgoing collision wave function $\Phi_0(E)$, defined as

$$\Phi_0(E) = \hat{G}^+(E)\hat{O}_1 \Psi_0.$$  \hspace{1cm} (2.7)

Naturally, this wave function is a solution of the inhomogeneous equation

$$(E - \hat{H} + i\epsilon)\Phi_0(E) = \hat{O}_1 \Psi_0$$  \hspace{1cm} (2.8)

at a chosen energy $E$.

The right-hand side of the former equation is compact, damped by the bound state $\Psi_0$ wave function. The wave function $\Phi_0$ asymptotically contains only outgoing waves. However, the asymptotic structure of this wave function is rather complicated, involving multidimensional 4-neutron break-up amplitudes. Nevertheless, the last inhomogeneous equation may be readily solved using complex scaling techniques, which we present in the next section.
3. Computational techniques: Complex scaling method

To properly account for the boundary conditions of the resonance, we have used the complex scaling method (CSM) (Refs. [13–15]). This computational technique, allowing us to access the scattering solutions with square integrable functions, was applied to the response function in Ref. [16]. Some recent applications and a more complete reference list can be found in Refs. [17–19].

To this aim we have considered the 4-body Hamiltonian $H$ in configuration space and applied to each of the internal Jacobi coordinates—denoted generically by $X$—a complex rotation with angle $\theta$, i.e., a mapping

$$X \rightarrow X e^{i\theta}.$$  

The 4-body Hamiltonian is transformed accordingly, as well as the corresponding Schrödinger equation

$$H^{\theta} \Psi^{\theta} = E^{\theta} \Psi^{\theta}.$$  

By doing so, and according to the so-called ABC theorem (Refs. [13,14]), the resonant poles are—up to numerical inaccuracies—independent of the parameter $\theta$ and are isolated from the discretized nonresonant continuum spectrum, provided some restrictions on the rotation angle are satisfied.

Let us see how the complex scaling method might be used to evaluate a matrix element in Eq. (2.6). To this aim one must just apply the complex-scaled expressions to both sides of Eq. (2.8), which become

$$(E - H^{\theta}) \Phi_0^{\theta}(E) = \hat{O}^{\theta} \Psi_0^{\theta}.$$  

(3.1)

The complex-scaled bound state wave function $\Psi_0^{\theta}$ is obtained by solving a bound state problem with the complex-scaled Hamiltonian

$$(E_0 - H^{\theta}) \Psi_0^{\theta} = 0,$$  

(3.2)

and it finally remains to compute the integral expression

$$S(E) = -\frac{1}{\pi} \text{Im} \left\langle \Psi_0^{\theta} \left| (\hat{O}_1^+)^{\theta} \right| \Phi_0^{\theta}(E) \right\rangle.$$  

(3.3)

The solutions of the 4-body equations (3.1) and (3.2) have been obtained by using two different approaches: the Faddeev–Yakubovsky equations in configuration space and a variational Gaussian expansion method. The details of these calculations and the numerical methods used can be found in Ref. [3].

4. Results

The nuclear Hamiltonian considered in our recent work (Ref. [3]) consists of the Argonne AV8 2-neutron interaction (Ref. [20]) plus 3-nucleon forces in both $T = 1/2$ and $T = 3/2$ total isospin channels. The 2-body and the $T = 1/2$ 3-body parts were fixed in a previous work (Ref. [21]) in order to reproduce some selected $A = 3$ and $A = 4$ phenomenology and have been kept unchanged since. The only part of the Hamiltonian that was tuned in order to accommodate a $4n$ resonant state,
The 2- and 3-body contributions to the potential energy of the $^4n$ system in a $J^\pi = 0^+$ state as a function of $W_1(T = 3/2)$ (all units are in MeV). Results denoted by $^4n$ correspond to the bound state approximation and those denoted by $^4n$ to the continuum resonant states. The results are compared with the $^4$He ground and first excited state with the physical strength $W_1(T = 1/2) = -2.04$. The $T = 3/2$ contribution in $^4n$ required to accommodate a resonant state is more than 1 order of magnitude larger than the $T = 1/2$ (see the rightmost column).

| $W_1(T = 3/2)$ | $E$ | $\langle T \rangle$ | $\langle V_{2N} \rangle$ | $\langle V_{3N} \rangle$ | $\langle P_{2N}^{T,0} \rangle$ | $\langle P_{2N}^{T,1} \rangle$ |
|----------------|-----|---------------------|---------------------|---------------------|-------------------------------|-------------------------------|
| $^4n$          |     |                     |                     |                     |                               |                               |
| -36           | -1.00 | 67.02               | -38.58              | -29.52              | 76.5%                         |                               |
| -33           | +1.18 | 46.67               | -28.13              | -17.35              | 61.7%                         |                               |
| -30           | +2.70 | 29.11               | -18.36              | -8.05               | 43.8%                         |                               |
| -27           | +4.70 | 25.20               | -15.03              | -5.48               | 36.5%                         |                               |
| -24           | +5.18 | 19.83               | -11.98              | -2.66               | 22.2%                         |                               |
| $W_1(T = 3/2)$ |     |                     |                     |                     |                               |                               |
| -36           | -0.98 | 66.79               | -38.47              | -29.31              | 76.2%                         |                               |
| $^4n$          |     |                     |                     |                     |                               |                               |
| -30           | +2.84 - 0.33i | -26.7 + 6.5i | -10.1 + 4.4i | 40.1% |
| -24           | +5.21 - 1.88i | -19.3 + 8.8i | -2.3 + 5.4i | 27.7% |
| $W_1(T = 1/2)$ |     |                     |                     |                     |                               |                               |
| $^4$He        | -2.04 | -28.44              | 106.12              | -131.17             | -3.50                         | 2.59%                         |
| $^4$He*       | -8.13 | 49.36               | -56.71              | -0.78               | 1.38%                         |                               |

was the $T = 3/2$ 3-nucleon force. The latter was chosen to have the same form as the $T = 1/2$ case, i.e., a sum of two (attractive and repulsive) Gaussian terms:

$$V_{ijk}^{3N} = \sum_{T=1/2}^{3/2} \sum_{n=1}^{2} W_n(T) \exp\left(-\left(r_{ij}^2 + r_{jk}^2 + r_{ki}^2/\alpha_n^2\right)\right) \mathcal{P}_{ijk}(T),$$

(4.1)

where $\mathcal{P}_{ijk}(T)$ is a projection operator on the total 3-nucleon isospin $T$ state.

The parameters of this force are

$$W_1(T = 3/2) = \text{free}, \quad b_1 = 4.0 \text{ fm},$$

$$W_2(T = 3/2) = +35.0 \text{ MeV}, \quad b_2 = 0.75 \text{ fm}.$$  

(4.2)

They are all the same as for $T=1/2$ except for the attractive term $W_1(T = 3/2)$, which is considered a free parameter, the only one in our calculations. The model space of our calculations is also identical to one used in a previous study (Ref. [3]). Namely, for FY equations, a partial-wave basis has been limited to angular momenta $\max(l, L, \lambda) \leq 7$, providing a total of 1541 partial amplitudes. Furthermore, 25$^3$ Lagrange-mesh points were used to describe the radial dependence of Faddeev–Yakubovsky components, resulting in a linear-algebra problem of $2.4 \times 10^7$ equations. Such a large basis size ensured accurate results, which can be traced by comparing the FY calculation with a Gaussian expansion method in Table 1. Even for a very shallow tetraneutron state of $\sim 1$ MeV, the difference in calculated binding energy was less than 20 keV, whereas expectation values differed by less than 1%. In the case of the Gaussian expansion method, to obtain the converged energies we included angular momenta $\max(l, L, \lambda) \leq 2$ and 14 000 antisymmetrized 4-body basis functions.

Our strategy to investigate the $^4n$ resonant states was quite simple: keeping unchanged the best-established part of the nuclear forces (2-body and $T = 1/2$ 3-body terms), we first determined the
Fig. 1. The $4n$ resonance trajectory for $J^\pi = 0^+$. The strength parameter $W_1(T = 3/2)$ changes from $-37$ to $-16$ MeV. The parameters suggested in Ref. [1] are indicated by an arrow.

strength of the 3-nucleon force in the $T = 3/2$ channel, which is required to reproduce the resonance parameters given in Ref. [1] and see then the consequences of such a state in the nuclear chart.

In the first step, the critical $W_1(T = 3/2)$ strength value at which the $4n$ system is bound by $E = -1.07$ MeV, the lowest bound compatible with the experimental values given in Ref. [1], was found to be $W_1^0(T = 3/2) = -36$ MeV and the most favorable state was $J^\pi = 0^+$ followed by the sequence $J^\pi = 2^+, 1^+, 2^-, 1^-, 0^-$. The strength parameter was then decreased in order to move the bound state into the continuum and in this way to reproduce the observed resonance. The $S$-matrix pole trajectory in the $4n$ complex energy plane was traced as a function of $W_1(T = 3/2)$. The results, taken from Ref. [3], are displayed in Fig. 1. As one can see, the range of $W_1$ values compatible with the experimental findings (Ref. [1]), indicated by an arrow in the upper part of the figure, is $W_1 \in [-36, -30]$ MeV.

Several comments about this result are in order.

(1) For comparison, the corresponding strength of the $T=1/2$ 3-nucleon forces is $W_1(T = 1/2) = -2.04$ MeV and this allows us to increase the $^4$He binding energy by approximately 5 MeV. The huge value, $W_1(T = 3/2) \approx -30$ MeV, required to generate a $4n$ resonance, a factor $\sim 15$ larger than for $T=1/2$, indicates how deep in the continuum the $4n$ resonant state should be localized when we consider the standard nuclear Hamiltonian, i.e., in particular with the 2-neutron forces alone. Notice that the pole trajectory displayed in Fig. 1 was stopped at $W_1(T = 3/2) = -16$ MeV. We have computed in previous work (see Figs. 3–6 in Ref. [8]) the full trajectory of the state until it is generated only by the 2-neutron forces and it turns to end in the third energy quadrant. This feature is in sharp contrast with some recent works (Refs. [23–25]). The interactions used by these authors are among the best in the literature but we believe that the different conclusions are due to the indirect approach they use to deal with the continuum in the 4-body problem and to estimate the $4n$ resonance positions.

(2) The remarkably large value of the $T=3/2$ strength parameter in the 3-nucleon potential is not understandable in terms of the isospin symmetry of the nuclear force, which is quite accurately observed in phenomenology. It also contradicts the QCD-inspired EFT models, which found the $T=3/2$ contribution of a 3-nucleon force to be of subleading order with respect to the $T=1/2$ ones (Ref. [26]). Any value of $|W_1(T = 3/2)|$ larger than $|W_1(T = 1/2)|$ is unphysical.
Fig. 2. The computed $^3\text{H}+n$ elastic cross sections (in black) using $W_1(T=3/2)=-10$ MeV and $-2.04$ MeV are compared to experimental data Ref. [22] (in red).

(3) We showed in Ref. [3] that for an absolute strength value larger than 20 MeV the neighboring nuclei $^4\text{H}$, $^4\text{Li}$, and $^4\text{He}$ ($T=1$) are bound, contrary to the well-established experimental results. These nuclei become resonant only for $W_1(T = 3/2) \sim -20$ MeV, at which strength the $4n$ system already corresponds to a resonant state with $E_R \sim 6$ MeV and $\Gamma \approx 7$ MeV. Still, $W_1(T = 3/2) \sim -20$ MeV is an unphysical strength: even by taking half of it, the $n-^3\text{H}$ elastic cross section, displayed in Fig. 2, is in strong disagreement with the experimental data.

All the above-discussed results lead us to the conclusion that the existence of a 4$n$ bound or low-energy narrow resonant state is not compatible with the well-established facts of nuclear physics. A similar conclusion is reached in a recent work (Ref. [27]) using totally different interactions and techniques based on the no-core Gamow shell model, which takes the continuum properly into account.

Tetraneutron resonances certainly exist, even with pure nucleon–nucleons forces, and we have computed them in a series of works. They are, however, very far from the physical regions and cannot manifest in a scattering experiment: any enhancement of the reaction cross section involving 4$n$ in the final state should have an alternative dynamical explanation.

We will examine in what follows whether or not the reaction mechanism described in the previous section is able to produce any nonresonant enhancement in the cross sections, as well as the consequences that an eventual resonance could have on it. The results are displayed in Fig. 3.

The black curve corresponds to the nuclear Hamiltonian, based on an isospin-independent 3-nucleon force. In this case, the response function is flat without any near-threshold sharp structure.

By increasing the attractive part of the $T = 3/2$ contribution, a resonant peak appears. For $W_1(T = 3/2) = -18$ MeV (blue curve), still far from the values compatible with the RIKEN result, the underlying structure is already visible, although quite broad. It becomes sharper and sharper by further increasing the attraction and moving the resonant pole close to the threshold.

For $W_1(T = 3/2) = -30$ MeV (green curve), the tetraneutron resonance parameters—as given by Fig. 1—are $E_R = 2.8$ MeV and $\Gamma = 0.7$ MeV. In the vicinity of these values, the corresponding response function takes the usual Breit–Wigner form.
When further increasing the attraction the resonance becomes a bound state (orange curve, corresponding to $W_1(T = 3/2) = -36$ MeV). The response function, which has a pole at negative energy, also displays some pronounced structure at positive energies, although with reduced strength.

We would like to emphasize that the results we have presented are essentially independent of the nuclear Hamiltonian and the mechanism considered to artificially produce the $4n$ bound or resonant state. Several 2- and 3- and even 4-nucleon interactions have indeed been examined in previous calculations (Refs. [3,7,8]) and led to very similar results. The underlying reason is that, when any ad hoc mechanism is considered to enhance the $4n$ attraction in order to accommodate a resonant state, this state is, in fact, essentially supported by the artificial binding mechanism adjusted to this aim: the details of the remaining nucleon–nucleon interaction are residual.

This fact is illustrated in Table 1 where we have compared the contributions of the 2- and 3-nucleon forces (averaged values of the corresponding potential energies) both for the $^4$He and the $4n$ system, for several values of the strength parameter $W_1(T)$. As one can see from the results in this table, $V_{2n}$ and $V_{3n}$, the contributions to the $4n$ state in the resonance region, are of the same order and their ratio (the rightmost column) remains in any case more than 1 order of magnitude larger than for the $T = 1/2$ case in $^4$He, the opposite of that expected from physical arguments.

As was pointed out in the introduction, the dineutron–dineutron interaction is repulsive. This repulsion relies on very general arguments and any attempt to bring together 4 neutrons on a near-threshold narrow state can only come from an artificially ad hoc extrabinding.

**5. Conclusion**

Inside the simplistic reaction mechanism we have considered in this paper, we are not able to generate an increase of the cross section at the origin other than by accommodating a sharp $4n$ resonance. No other possibilities, like cusp or related structures, could have been exhibited.
We found in our previous work (Ref. [3]) that the existence of such a resonance is hardly compatible with the well-established properties of nuclear interactions and experimental data on neutron-rich nuclei. This is in agreement with the findings of Ref. [27]. It is worth noticing, however, that opposite conclusions were reached in recent calculations (Refs. [23,25]).

We believe that the reason for such a striking difference is not the neutron–neutron interaction but rather the approximate methods they use to deal with the $4n$ continuum.

The RIKEN $^4$He($^6$He,$^8$Be)$^4n$ experiment (Ref. [1]) has been repeated with improved statistics and is under analysis. Other experiments are scheduled at the same laboratory on $^8$He($p,p\alpha$)$4n$ (Ref. [28]) and at J-PARC (Ref. [29]) on $^4$He($\pi^-,\pi^+$)$^4n$. We hope they will be decisive in clarifying such a challenging problem.

Acknowledgements

The authors thank Dr S. Shimoura, Dr M. Marques, and Dr N. Orr for valuable discussions. The numerical calculations were performed at the IDRIS Computer Center. Some of these results were obtained during the Espace de Structure Nucléaire Théorique (ESNT, http://esnt.cea.fr) workshops at CEA from which the authors benefited. This work was partly supported by the RIKEN iTHERS Project and France-Japan PICS. In addition, this work was supported by JSPS Japan-France Joint Research Project and IN2P3 project “Neutron-rich unstable light nuclei”.

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