Charge independence breaking and the triton binding energy

Mariusz Orlowski and Yeong E. Kim
Department of Physics, Purdue University, West Lafayette, Indiana 47907
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We demonstrate, using an energy-dependent separable-potential model, that the triton binding energy is sensitive to variations of the singlet effective range, r_{nn}, for fixed off-shell and intermediate-energy phase-shift constraints.

I. INTRODUCTION

There have been many calculations of the triton binding energy, $E_B(^3\mathrm{H})$, using the so-called "realistic" charge-independent two-nucleon potentials.[1,2] Most of such calculations have yielded so far the calculated values of $E_B(^3\mathrm{H})$ in the range of -7 to -7.5 MeV compared to the experimental value of $E_B^{\exp}(^3\mathrm{H})=-8.45$ MeV. The difference of $\Delta E_B(^3\mathrm{H})\approx 1-1.5$ MeV between the calculated and experimental values of $E_B(^3\mathrm{H})$ is often attributed (i) to additional effects such as the three-nucleon (3N) forces, the relativistic effect, etc., and/or (ii) to inadequacy of the two-nucleon potentials and nonrelativistic models employed in such calculations.[1,2] Previous estimates of contributions of the 3N forces[3-6] or relativistic[7] effects to $E_B(^3\mathrm{H})$ are the order of 1 MeV or less. However, the magnitude of these effects are not yet convincingly determined because of many uncertainties involved in deriving and estimating them.[3-7]

One of the other possibilities for explaining the discrepancy of $\Delta E_B(^3\mathrm{H})\approx 1-1.5$ MeV due to inadequacies of the so-called "realistic" two-nucleon potential is the possibility of charge dependence and asymmetry which have been neglected in such "realistic" potentials.[8,9] It has been speculated that the measurements of the singlet nucleon-nucleon (N-N) scattering length, a_{nn}, may provide a good test of charge asymmetry [differences between the strong interaction part of the proton-proton (pp) and neutron-neutron (nn) singlet potentials, $V_{pp}^s\neq V_{nn}^s$] since the singlet N-N scattering lengths, a_{pp}, a_{nn}, and a_{np} are large and hence may be sensitive to small differences in the corresponding NN interactions. However, as shown by Gibson and Stephenson,[10] small deviations from charge asymmetry resulting in $|a_{nn}-a_{pp}|<2$ fm are not sufficient to account for the discrepancy of ~ 0.1 MeV between $E_B^{\exp}(^3\mathrm{H})$ and the Coulomb-corrected binding energy of ^{3}He $[E_B^{\exp}(^3\mathrm{He})+E_C(^3\mathrm{He})\approx-(7.69\text{ MeV}+0.66\text{ MeV})\approx-8.35\text{ MeV}]$,[11] but calculated $E_B(^3\mathrm{H})$ is much more sensitive to the small variations of the singlet neutron-neutron effective range, r_{nn}. They have shown that inclusion of the charge dependence in the singlet interaction $V_{np}^s\neq V_{nn}$ can add 0.1–0.25 MeV to $E_B(^3\mathrm{H})$ compared to the usual assumption of charge independence, $V_{np}^s=V_{pp}=V_{nn}$ as in the case of "realistic" potentials, i.e., ~ 0.19 MeV variation of $E_B(^3\mathrm{H})$ can be achieved from ~ 0.1 fm variation of r_{nn} while only ~ 0.03 MeV variation of $E_B(^3\mathrm{H})$ results from ~ 1 fm variation of a_{nn}.

The currently available values[12-15] for the $^1S_0$ scattering lengths and effective ranges are $a_{pp}=-(17.15\pm0.15)$ fm, $r_{pp}=(2.83\pm0.03)$ fm (both values are after Coulomb and vacuum polarization corrections), $a_{np}=-(23.715\pm0.015)$ fm, and $r_{np}=(2.73\pm0.03)$ fm. Although $r_{np}\neq r_{pp}$ is due to the effect of pion electromagnetic mass differences, the fact that $a_{pp}\neq a_{np}$ indicates clearly a breaking of the charge independence, $V_{pp}=V_{np}$. The determinations of the $^1S_0$ scattering length and effective range for the neutron-neutron interaction, a_{nn} and r_{nn}, are still controversial. From the analysis of the kinematically complete d(π^-,2n)γ reaction, Haddock *et al.*[16] obtained $a_{nn}=-(16.4\pm1.9)$ fm using $r_{nn}=2.65$ fm. They found that use of either r_{pp} or r_{np}, rather than 2.65 fm, would only change a_{nn} by 0.1 fm, implying that r_{nn} is not accurately determined. From the analysis of the ^{3}H(d,2n)^{3}He reaction at 32 MeV, Baumgartner *et al.*[17] obtained $a_{nn}=-(16.1\pm1)$ fm and $r_{nn}=(3.2\pm1.6)$ fm. From the ^{3}H(t,α)2n reaction at 22 MeV, Gross *et al.*[18] deduced $a_{nn}=-(16.96\pm0.51)$ fm with a fixed value of $r_{nn}=2.84$ fm, while $r_{nn}=(2.75\pm0.35)$ fm was obtained when a_{nn} was fixed at -17 fm. They obtained a simultaneous fit of $a_{nn}=-(17.4\pm1.8)$ fm and $r_{nn}=(2.4\pm1.5)$ fm when both were adjusted to fit their data. Kühn *et al.*[19] did a similar experiment at a lower energy of 1.39 MeV and obtained $a_{nn}=-(15.0\pm1.0)$ fm with $r_{nn}=2.7$ fm. They claim that a_{nn} is insensitive to a variation of r_{nn} in fitting their data. From the d(n,2n)p reaction at 14.17 MeV, Breunlich *et al.*[20] obtained $a_{nn}=-(16.0\pm1.2)$ fm using $r_{nn}=2.86$ fm, while Zeitnitz *et al.*[21] found $a_{nn}=-(17.1\pm0.8)$ fm with $r_{nn}=2.86$ fm from the same reaction at 18.4 MeV. When Zeitnitz *et al.*[21] adjusted both a_{nn} and r_{nn}, they obtained $a_{nn}=-(16.6\pm0.9)$ fm and $r_{nn}=(3.4\pm0.6)$ fm. Kühn[22] has summarized the values of a_{nn} extracted from 40 different experiments up to 1973 and found the weighted average and standard deviation to be $a_{nn}=-(16.61\pm1.45)$ fm, suggesting that a_{nn} may be slightly less negative than $a_{pp}=-(17.15\pm0.15)$ fm (Refs. 14 and 15).

From the above discussion, we see that the situation for the $^1S_0$ effective range, r_{nn}, is even worse than that of a_{nn}. The values of r_{nn} range from $r_{nn}=(2.4\pm1.5)$ fm (Ref. 18) to (3.4 ± 0.6) fm.[21]

Recently, Jaus and Woolcock[23] have shown that the theoretically calculated forward cross section for deuteron photodisintegration up to 120 MeV is very sensitive to the charge independence breaking effects ($V_{nn} \neq V^s_{np}$) due to pion mass differences (resulting in different πNN coupling constants) for the one-pion-exchange potential. In this paper, we investigate the effect of the small breaking of the charge independence ($V_{nn} \neq V^s_{np}$) on the triton binding energy. A similar work was done originally by Gibson and Stephenson, but our work is different from theirs in that (1) we make the on-shell variation with a fixed off-shell behavior of V_{nn} using energy-dependent separable potentials; (2) we use slightly more "realistic" potentials which give a better fit to the intermediate-energy phase shifts (i.e., change of the sign of phase shift at an intermediate energy is imposed); and (3) we emphasize the possibility of obtaining an extra triton binding energy from the charge dependence (instead of the charge asymmetry).

II. THEORETICAL MODEL

For simplicity, we employ the energy-dependent separable potential model for the nucleon-nucleon interaction, which has been used previously in the three-nucleon bound-state calculations.[24,25] The potentials used are the rank-one s-wave separable potentials of the Yamaguchi form[26] with energy-dependent strength ($\hbar = c = 1$)

$$V(p,p';E) = \lambda(E) g(p) g(p') , \tag{1}$$

where

$$g(p) = (p^2 + \beta^2)^{-1} \tag{2}$$

and

$$\lambda(E) = \lambda_0 \tanh \left[1 + \alpha^2 - \left\{ \left| \frac{E}{E'_c} \right| + \alpha \right\}^2 \right] . \tag{3}$$

For a fixed β, the above potential, Eq. (1), has the same off-shell behavior, Eq. (2). Furthermore, the on-shell variation of $V(p,p',E)$ can be done separately by adjusting α and E'_c, while the off-shell behavior is kept the same with a fixed β. At $E = 0$, the above potential has the same form as the energy-independent Yamaguchi potential

$$V(p,p';0) = \lambda(0) g(p) g(p') , \tag{4}$$

where

$$\lambda(0) = \lambda_0 \tanh(1) . \tag{5}$$

However, the energy-dependent potential, Eq. (1), has additional features which allow us to fit the N-N phase shifts not only for low energies as in the case of the rank-one energy independent Yamaguchi potential, but also the intermediate energy N-N phase shifts up to $\sim$400 MeV, including the change of the sign of the phase shifts, δ, at $E = E_c$, i.e., $\delta(E_c) = 0$. The requirement that $\delta(E_c) = 0$ can be achieved by imposing the condition that $\lambda(E_c) = 0$ for Eq. (3), i.e.,

$$E'_c = E_c[(1+\alpha^2)^{1/2} - \alpha] . \tag{6}$$

The scattering length a and effective range r can be determined from the potential parameters by the following relations:

$$a^{-1} = \frac{\beta}{2} \{ 1 - \beta^3 / [\pi^2 \lambda(0)] \} \tag{7}$$

and

$$r = \frac{1}{\beta} \left\{ 1 + \frac{2\beta^3}{\pi^2 \lambda(0)} - \frac{\beta^5 \lambda[(1+\alpha)^{1/2} - \alpha]}{\pi^2 \lambda_0 [\sinh(1)]^2 E_c} \right\} . \tag{8}$$

Since we are interested in variations of the scattering length a^s_{nn} and effective range r^s_{nn} for the singlet s-wave n-n interaction, we will fix the $^3S_1$ and $^1S_0$ n-p interactions. For the $^3S_1$ n-p interaction, we fix the parameters as $\beta = \beta^t_{np} = 1.45$ fm^{-1}, $\lambda_0 = \lambda^t_0(\text{np}) = 0.415$ fm^{-3}, $\alpha = 0$, and $E'_c = E_c = 2.8581$ fm^{-1}. With the above values of the parameters, our $^3S_1$ n-p potential reproduces the deuteron binding energy and yields $a^t_{np} = 5.4$ fm and $r^t_{np} = 1.72$ fm from Eqs. (7) and (8), respectively. For the $^1S_0$ n-p interaction, we take $\beta = \beta^s_{np} = 1.525$ fm^{-1}, $\lambda_0 = \lambda^s_0(\text{np}) = 0.1445$ fm^{-3}, $\alpha = 0$, and $E'_c = E_c = 2.8581$ fm^{-1}, which yield $a^s_{nn} = -23.7$ fm and $r^s_{np} = 2.73$ fm.

Variations of the $^1S_0$ n-n interaction are achieved by changing a^s_{nn} ($= a_{nn}$) or r^s_{nn} ($= r_{nn}$). The variation of r_{nn} for a fixed a_{nn} (and β) is easily done by changing the parameter α in Eq. (7). For the variation of a_{nn} with fixed values of both r_{nn} and β we solve Eq. (8) for λ_0 with a given value of the parameter α and then determine a_{nn} from Eq. (7).

The triton binding energy is calculated from the N-N potential described by Eqs. (1)–(3). We first calculate the N-N t matrix from the potential $V(p,p',E)$, which is the input for the Faddeev equation. Since the N-N t matrix is also separable, the Faddeev equation reduces to a set of integral equations in one momentum variable. Since the de-

TABLE I. Triton binding energy (MeV) for different values of a_{nn} with fixed values of r_{nn}, β_{nn}, and E_c. $E_c = 2.8581$ fm^{-2} for all cases.

a_{nn} (fm)	$r_{nn} = 2.74$ fm, $\beta_{nn} = 1.1727$ fm^{-1}	$r_{nn} = 2.84$ fm, $\beta_{nn} = 1.1340$ fm^{-1}	$r_{nn} = 2.94$ fm, $\beta_{nn} = 1.1786$ fm^{-1}
−13	−8.275	−8.210	−8.151
−14	−8.254	−8.185	−8.115
−15	−8.232	−8.159	−8.085
−16	−8.210	−8.132	−8.053
−17	−8.186	−8.104	−8.022
−18	−8.167	−8.080	−7.992
−19	−8.145	−8.054	−7.965
−20	−8.138	−8.029	−7.939

TABLE II. The difference (MeV), $\Delta E_B(a_{nn}) = E_B(a_{nn} = 18$ fm$) - E_B(a_{nn} = -16$ fm) for different values of r_{nn}.

r_{nn} (fm)	$\Delta E_B(a_{nn})$ (Present work)	$\Delta E_B(a_{nn})$ (Ref. 10)
2.74	-0.04	-0.08
2.84	-0.05	-0.08
2.94	-0.06	-0.07

tails of the Faddeev equation with separable N-N potentials are well documented,[24] we will not give the explicit form of the Faddeev equation here.

III. RESULTS

We consider first the sensitivity of the calculated triton binding energy to variations of the scattering length a_{nn}, for three sets of fixed values of r_{nn}, $\beta = \beta^s_{nn}$, and E_c. In the following, E_c is set to the same value of $E_c = 2.858\,12$ fm^{-2}. The results are summarized in Table I. As can be seen from Table I, the triton binding energy is insensitive to the variation of a_{nn} as previously observed by Gibson and Stephenson.[10] To compare our results with theirs, we calculate the difference, $\Delta E_B(a_{nn})$, between calculated triton binding energies with $a_{nn} = -16$ and -18 fm, i.e.,

$$\Delta E_B(a_{nn}) \equiv E_B(a_{nn} = -18 \text{ fm}) - E_B(a_{nn} = -16 \text{ fm})$$

and summarized them in Table II. From Table II, we see that the sensitivity of E_B of the same variation of a_{nn} is much more smaller for our results than that of the results of Gibson and Stephenson.[10] The reasons for this may be due to the fact that we impose more restricted constraints of (1) fixed off-shell behavior and (2) fixed intermediate-energy phase shift, $\delta(E_c) = 0$. In both cases,[10] we can draw the same conclusion that E_B is very insensitive to variations of a_{nn} and so there is no hope of discriminating many different experimental measured values of a_{nn} by the constraint imposed from the triton binding energy.

We now consider the sensitivity of the calculated triton binding energy to variation of the effective range, r_{nn}, when a_{nn}, β_{nn}, and E_c are fixed. Our results are summarized in Table III. As can be seen from Table III, the sensitivity of $E_B(^3\text{H})$ to the variation of r_{nn} is much larger than for the case of variation of a_{nn} described above and in Tables I and II. In Table III, changes of $E_B(^3\text{H})$ for different values of a_{nn} with a fixed r_{nn} (i.e., reading across the row) are mainly due to the variation of β_{nn} (off-shell variation) rather than due to the variation of a_{nn}, as demonstrated by the results summarized in Table I. To compare our results with the previous results of Gibson and Stephenson,[10] we calculate the difference, $\Delta E_B(r_{nn})$, between calculated triton binding energies using $r_{nn} = 2.74$ and 2.94 fm, i.e.,

$$\Delta E_B(r_{nn}) = E_B(r_{nn} = 2.94 \text{ fm}) - E_B(r_{nn} = 2.74 \text{ fm}) .$$

The results are summarized in Table IV, and demonstrate that our theoretical model can provide much more sensitivity of $E_B(^3\text{H})$ to the variation of r_{nn} with fixed a_{nn}, β_{nn} (fixed off-shell behavior), and E_c than the model employed by Gibson and Stephenson (by a factor of 3–4).

The reason for the differences between our results and the results of Gibson and Stephenson[10] is due mostly to the off-shell effect, and much less due to our energy dependence of the potential $v(p,p';E)$ given in Eq. (1). In fact, the changes in energy dependence in $\lambda(E)$ in Eq. (3) are not strong and are comparable with the changes in λ_{nn} used in Ref. 10. It is known that both on-shell *and* off-shell effects are contributing to the binding energy (here we define it as a positive number). It is also known[27] that the suppression or even elimination of the off-shell effect results in decreasing the binding energy. In our case as well as in the case of Ref. 10, elimination of the off-shell effect would mean $\beta \rightarrow \infty$ (zero-range limit). Therefore it is clear that an increase in β_{nn} would lead to less binding energy due to a decrease of the off-shell contribution. λ_{nn}, on the other hand, can be regarded as a purely on-shell quantity. An increase in λ_{nn} (defined as a positive number for attractive potential) will obviously lead to more binding.

As a specific example of the above situation, consider two cases presented in Table II of Ref. 10, calculated with the Yamaguchi potential: case (a) $a_{nn} = -16$ fm, $r_{nn} = 2.74$ fm, $E_B = 8.6$ MeV with $\lambda_{nn} = 0.147\,66$ and $\beta_{nn} = 1.1727$; and case (b) $a_{nn} = -16$ fm, $r_{nn} = 2.94$ fm, $E_B = 8.29$ MeV with $\lambda_{nn} = 0.120\,37$ and $\beta_{nn} = 1.097\,86$. For case (a), both λ_{nn} and β_{nn} are larger than those for case (b). This leads to a near cancellation of an increase in E_B due to larger λ_{nn} by a decrease in E_B due to smaller β_{nn}, thus yielding only a small net increase, of 0.32 MeV ($\approx 8.61 - 8.29$ MeV). In our model, we can avoid or minimize such cancellation and thus obtain larger effects than the results of Ref. 10, since parameters corresponding to λ_{nn} or β_{nn} in our model can be varied nearly independently from each other.

Our conclusions with the s-wave potential model are expected to be valid even for a more realistic potential

TABLE III. Triton binding energy (MeV) for different values of r_{nn} with fixed values of a_{nn}, β_{nn}, and E_c. E_c is set to 2.8581 fm^{-2} for all cases.

r_{nn} (fm)	$a_{nn} = -16$ fm $\beta_{nn} = 1.1491$ fm^{-1}	$a_{nn} = -17$ fm $\beta_{nn} = 1.448$ fm^{-1}	$a_{nn} = -18$ fm $\beta_{nn} = 1.1410$ fm^{-1}	$a_{nn} = -19$ fm $\beta_{nn} = 1.1375$ fm^{-1}
2.70	-8.78	-8.78	-8.78	-8.85
2.75	-8.50	-8.50	-8.50	-8.55
2.80	-8.23	-8.19	-8.20	-8.25
2.85	-7.90	-7.88	-7.91	-7.94
2.90	-7.56	-7.57	-7.60	-7.63
2.95	-7.19	-7.36	-7.33	-7.34

TABLE IV. The difference (MeV), $\Delta E_B(r_{nn}) = E_B(r_{nn}=2.94$ fm$) - E_B(r_{nn}=2.74$ fm$)$ for different values of a_{nn}.

a_{nn} (fm)	$\Delta E_B(r_{nn})$ (This work)	$\Delta E_B(r_{nn})$ (Ref. 10)
-16	1.30	0.38
-17	1.25	0.36
-18	1.17	0.37

model which includes the coupled $^3S_1$-$^3D_1$ channel due to the presence of the tensor force, as we discuss below. It has been known[28,29] that the bulk ($\sim 75\%$) of the potential energy arises from the $^3S_1$-$^3D_1$ channel and only about 25% from the $^1S_0$ channel of the realistic potential models, and that the tensor force is responsible for this difference. In our s-wave model, the large contribution from the $^3S_1$-$^3D_1$ channel is simulated effectively by the $^3S_1$ potential which is about three times stronger than the $^1S_0$ potential, i.e., $\lambda_0^t(\text{np}) = 0.415$ fm^{-3} and $\lambda_0^s(\text{np}) = 0.1445$ fm^{-3}, so that the $^1S_0$ potential contributes still about 25% to the potential energy in our s-wave model. Therefore, the effects of changes in the $^1S_0$ potential are expected to be similar between our s-wave model and more realistic models which include the tensor force.

VI. CONCLUSIONS

Our theoretical model leads to the same conclusion as the previous works by Gibson and Stephenson[10] and Kharchenko *et al.*,[27] that the triton binding energy is much more sensitive to small differences in the effective range r_{nn} than to differences in the scattering length a_{nn}. However, our model allows us to explore the sensitivity of $E_B(^3\text{H})$ to different values of a_{nn} and r_{nn} due to the on-shell variation with a fixed off-shell behavior of the N-N potential. Moreover, our model demonstrates a new surprising possibility that a change of ~ 1.25 MeV for $E_B(^3\text{H})$ can be obtained from 0.2 fm variation of r_{nn} (2.74 to 2.94 fm) under rather severe constraints of the same scattering length (a_{nn}), on-shell behavior (β_{nn}), and intermediate-energy phase shift [$\delta(E_c)=0$]. This large sensitivity suggests that it may still be possible to explain a substantial part of $\Delta E_B(^3\text{H}) \approx 1-1.5$ MeV by incorporating the charge dependence ($V_{nn} \neq V_{np}^s$ or $r_{nn} \neq r_{np}^s$) in "realistic" potential models and also to account for the charge asymmetry discrepancy of ~ 0.1 MeV between $E_B(^3\text{H})$ and $E_B(^3\text{He})$ using the charge symmetry breaking potentials ($V_{nn} \neq V_{pp}$ or $r_{nn} \neq r_{pp}$).

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