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D—WAVE ASYMPTOTIC NORMALIZATION CONSTANTS FOR THE ^{3}H AND ^{3}He SYSTEMS

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ABSTRACT

Trinucleon wave functions, based on the generalized R-matrix methodology of Lane and Robson, have been previously shown to provide representative binding energies, charge radii, and S-wave asymptotic normalization constants for the ^{3}H and ^{3}He systems. Herein, R-matrix predictions of D-wave asymptotic normalization constants, asymptotic normalization constant ratios, and D-wave parameters are calculated in order to more fully evaluate the adequacy of model wave functions. The R-matrix calculations generally reproduce the ranges of the data and suggest that model trinucleon wave functions are representative of the ^{3}H and ^{3}He systems and will be useful in studies of (d,^{3}H), (d,^{3}He), and other transfer reactions involving ^{3}H or ^{3}He.

RESUMEN

Funciones de onda para trinucleones, basadas en la metodología de Lane y Robson de la matrix R generalizada, han permitido previamente obtener en los sistemas ^{3}H y ^{3}He, las energías de amarre representativas, los radios de las cargas y las constantes de normalización asintótica de la onda S. En este trabajo, con la misma metodología, se calcularon para las ondas D, las constantes asintóticas de normalización, sus cocientes y parámetros. Esto permite evaluar en forma más completa los modelos usados para las funciones de onda. Los cálculos reproducen, en forma general, los datos experimentales y apoyan la hipótesis de representar a los sistemas ^{3}H y ^{3}He por medio de funciones de onda para tres núcleos.

1. INTRODUCTION

Trinucleon asymptotic normalization constants are fundamental quantities which are important in assessing the accuracy of ^{3}H and ^{3}He wave functions. A knowledge of these constants is also an essential aspect of understanding transfer reactions within the distorted-wave Born approximation (DWBA) formalism[1-11]. It is well known that A = 3 ground state wave functions contain D-state terms in addition to the dominant S-state configuration[9,12-18]. D-state effects have been observed in a number of transfer reactions including the $(\vec{d},{}^3H)$, $(\vec{d},{}^3He)$, and $(\vec{d},p)$ reactions on a variety of target nuclei[1-4,6-8,10,11]. For example, it has been shown that measurements of the tensor analyzing powers for the $(\vec{d},{}^3H)$ reaction are sensitive to the presence of D-state terms[10,11] in the triton wave function. Therefore, analyzing power measurements provide a means for obtaining information about the D-state components of the ^{3}H and ^{3}He wave functions.

D-state components also have a profound impact on assessing the accuracy of A = 3 nuclear structure calculations and upon the selection of the best choice of nucleon-nucleon interaction. It has been argued that the A = 3 asymptotic normalization constants should be granted the same fundamental status as the binding energy and charge radius[12]. When considered in conjunction with these quantities, asymptotic normalization constants provide an additional criterion for selecting the most physical trinucleon wave function from a group which has been generated from a variety of realistic nucleon-nucleon interactions.

The purpose of this paper is to extend the scope of our A = 3 calculations by determining theoretical D-wave asymptotic normalization constants for the ^{3}H and ^{3}He systems[5,13-18]. The calculations will also serve to further determine the accuracy of our detailed A = 3 wave functions. These wave functions have been previously shown to yield good binding energies, charge radii, and S-wave asymptotic normalization constants[5,13-18] and further investigation into their accuracy is warranted. Since wave functions are an essential part of DWBA codes[19-24], the use of realistic wave functions eliminates a major theoretical uncer-

tainty in transfer reaction calculations[5,10].

2. EXPERIMENTAL SUMMARY

To date, the trinucleon D-wave asymptotic normalization constants have not been directly extracted from data. Indirect measurements, the ratio of D-wave (C_D) and S-wave (C_S) asymptotic normalization constants and the D-wave parameter D_2, have been determined[1-4,6,8]. The D_2 parameter is a measure of the importance of the trinucleon wave function component in which the nucleon moves with orbital angular momentum L = 2 relative to the deuteron center of mass[4]. The D-wave parameter D_2 is defined as[11]

$$D_2 = -\frac{\int_0^\infty dr_c\ r_c^4\ U_2(r_c)}{15\int_0^\infty dr_c\ r_c^2\ U_0(r_c)}\ , \qquad (1)$$

where $\vec{r}_c$ is the coordinate between the nucleon and the center of mass of the deuteron (see Fig. 1, Ref. 16), $U_2(r_c)$ is the radial wave function in the $\vec{r}_c$ coordinate with L = 2, and $U_0(r_c)$ is the L = 0 wave function. The definition applies to both ^{3}H and ^{3}He. As a matter of notation[9], D_2 represents the D-state parameter for ^{3}H and D_2^C represents the corresponding quantity for ^{3}He. In a similar fashion, C_D and C_S refer to ^{3}H asymptotic normalization constants and C_S^C and C_D^C refer to ^{3}He quantities. The label C refers to the inclusion of the Coulomb interaction in the model hamiltonian and S and D refer to angular momentum zero and two, respectively.

A comparison of model results with measured D_2 and C_D/C_S values is complicated because of both theoretical and experimental uncertainties. As noted earlier, uncertainties in the nuclear interaction present a theoretical complication. From an experimental viewpoint, the values of C_S are not well determined[25-27] because of the inherent difficulty of neutron measurements. There is also a wide range of D_2^C values[1-4] which are between -0.22 fm^2 and -0.339 fm^2.

3. THEORY AND FORMULATION

The model for the A = 3 S-wave asymptotic normalization constant problem was recently presented in Ref. 5. The A = 3 system is modeled within the Lane-Robson R-matrix methodology[28] using the equation

$$\sum_{\lambda'} \left[\langle \lambda | H - E | \lambda' \rangle + \sum_{c} \gamma_{\lambda c} (b_{\lambda' c} - b_c) \gamma_{\lambda' c} \right] A_{\lambda'} = 0 \quad , \tag{2}$$

where H is the A = 3 hamiltonian[16] and $\gamma_{\lambda c}$ and $b_{\lambda c}$ are the reduced widths[29] and logarithmic derivatives associated with the expansion states $|\lambda\rangle$[16]. The expansion states are introduced in order to describe the nuclear wave function (Ψ) within the interaction region, $r_c \leq a_c$, in all channels:

$$\Psi = \sum_{\lambda} A_{\lambda} |\lambda\rangle \quad . \tag{3}$$

The b_c are related to the radial wave function in the physical channels (c) and provide the connection between the interaction region and the various two-body break-up channels[13-18]. The A_λ are expansion amplitudes which are determined by the solution of Eq. (2). Additional details concerning the model, basis states, oscillator model space ($4\hbar\omega$), and method of solution of the model equations are found in Ref. 16.

In Ref. 13, an effective interaction for oscillator basis states was determined for the A = 2-4 systems. Recently, this interaction, based on the Sussex matrix elements[30], has been extended to include the A = 5 system[31]. The effective interaction, the modified Sussex interaction, leads to realistic structure and reaction properties in A = 2-5 systems[13-18,31]. The modified Sussex interaction will be discussed in more detail in section 4.

The A = 3 wave functions, Eq. (3), are written in terms of the internal coordinates $\vec{r}_{12}$ and $\vec{r}_B$ (see Fig. 1, Ref. 16). For ^{3}H, $\vec{r}_{12}$ is the coordinate which joins the two neutrons and $\vec{r}_B$ is the coordinate between the centers of mass of the dineutron and the proton. Using these coordinates, the triton wave function is defined in terms of the basis

states

$$|\lambda(\vec{r}_{12}, \vec{r}_B)\rangle = R_{N_{12}L_{12}}(r_{12})R_{N_BL_B}(r_B)Y_{L_{12}M_{12}}(\hat{r}_{12}) \cdot Y_{L_BM_B}(\hat{r}_B)X(S_{12},S_3,S) \quad , \tag{4}$$

where $R_{NL}(r)$ are radial wave functions[32], $Y_{LM}(\hat{r})$ are spherical harmonics normalized over the unit sphere[33], $X(S_{12},S_3,S)$ are spin wave functions representing the spin coupling structure of the A = 3 system, S_{12} is the result of coupling the spins of the two neutrons (S_1 and S_2), S_3 is the spin of the proton, and S is the total spin representing the coupling of S_{12} and S_3. The angular momentum and spin coupling structure of the triton expansion functions $|\lambda\rangle$ can be explicitly represented by the A = 3 angular momentum coupling diagram summarized in Fig. 1 of Ref. 16. Specifically, the orbital angular momenta L_{12} and L_B are coupled together to form the total orbital angular momentum L. The total angular momentum of the basis state (J^π) is obtained by coupling the total orbital angular momentum and the total spin. For the ^{3}H and ^{3}He ground states, J^π has the value $\frac{1}{2}^+$.

As noted in other work[5,13-18], the $(\vec{r}_{12},\vec{r}_B)$ coordinates are chosen to facilitate antisymmetry requirements. However, formulas for ^{3}H asymptotic normalization constants require coordinates which have a deuteron plus neutron rather than the basis state coordinates of a dineutron plus proton. The desired transformation between the original expansion states $(\vec{r}_{12},\vec{r}_B)$ and the recoupled states $(\vec{r}_{13},\vec{r}_C)$ are developed in terms of standard angular momentum recoupling coefficients and unequal mass Moshinsky brackets[34-36]. In the $(\vec{r}_{13},\vec{r}_C)$ coordinates, $\vec{r}_{13}$ is the deuteron coordinate and the remaining nucleon is joined to the deuteron center of mass by the $\vec{r}_C$ coordinate (see Fig. 1, Ref. 16).

Following Friar et al.[9], the D-state asymptotic normalization constant (C_D) for ^{3}H is defined as

$$\lim_{r_C \to \infty} \Psi(\vec{r}_{13}, \vec{r}_C) \rightarrow C_S \sqrt{2\beta}\ \frac{e^{-\beta r_C}}{r_C} \left\{ \left\{ Y_0(\hat{r}_C) \otimes S_2 \right\}^{\frac{1}{2}}

$$\cdot \otimes \phi_d(\vec{r}_{13}) \Big\}^{1^+}_{\frac{1}{2}} + C_D \sqrt{2\beta}\ \frac{e^{-\beta r_C}}{r_C}$$

$$\cdot \left[1 + \frac{3}{\beta r_C} + \frac{3}{\beta^2 r_C^2} \right]$$

$$\cdot \left\{ \left\{ Y_2(\hat{r}_C) \otimes S_2 \right\}^{\frac{3}{2}} \otimes \phi_d(\vec{r}_{13}) \right\}^{1^+}_{\frac{1}{2}} \quad , \tag{5}$$

where C_S is the triton S-state asymptotic normalization constant[5,9], $Y_L(\hat{r}_C)$ is a spherical harmonic with the M index suppressed[9], S_2 is the spin of the neutron ($\frac{1}{2}^+$) in the $\vec{r}_C$ coordinate, $\phi_d(\vec{r}_{13})$ is the deuteron wave function, and $\Psi(\vec{r}_{13},\vec{r}_C)$ is the triton wave function. The angular momentum of the quantities in the curly brackets (a $\otimes$ b) are coupled to the value indicated by the superscript(s) above the right bracket of a coupling set $\{a \otimes b\}^s$. The quantity β is given by

$$\beta = \left[\frac{8M}{3\hbar^2} \left(|E| - |E_d| \right) \right]^{\frac{1}{2}} \quad , \tag{6}$$

where M is the reduced mass in the d + n channel, $\hbar$ is Planck's constant divided by 2π, $|E|$ is the model triton binding energy, and $|E_d|$ is the model deuteron binding energy.

The deuteron wave function is obtained from the solution of Eq. (2) with the hamiltonian[16]

$$H = -\frac{\hbar^2}{2M_{13}} \nabla^2_{13} + V_{13} \tag{7}$$

and the basis states $|\lambda(\vec{r}_{13})\rangle$. The resulting deuteron wave function $\phi_d(\vec{r}_{13})$ contains both L = 0 and L = 2 components:

$$\phi_d(\vec{r}_{13}) = \sum_i A_i |\lambda_i(\vec{r}_{13})\rangle \quad , \tag{8}$$

where the A_i are determined from the solution of Eq. (2) with an A = 2 hamiltonian and expansion functions.

Using the straightforward although lengthy, inversion approach of Frair et al.[9], Eq. (5) can be recast in a form which yields an ex-

plicit expression for C_D:

$$C_D = -\frac{2M_0}{3}\frac{\sqrt{\pi}}{\beta}\int_0^\infty r_C^{3/2}\, dr_C\, U_{N_C L_C}(\beta r_C)$$
$$\times \langle\, \phi_d(\vec{r}_{13}),\, Y_L(\hat{r}_C),\, S_2 \,|\Psi(\vec{r}_{13},\, \vec{r}_C)\,\rangle \quad , \tag{9}$$

where M_0 is the mass of a nucleon, $U_{N_C L_C}(\beta r_C)$ is a radial wave function in the $\vec{r}_C$ coordinate[9], and the ket $|\phi_d(\vec{r}_{13}),\, Y_L(\hat{r}_C),\, S_2$ is defined as

$$|\phi_d(\vec{r}_{13}), Y_L(\hat{r}_C), S_2\rangle = \left\{\left\{ Y_L(r_C) \otimes S_2 \right\}^j \otimes \phi_d(\vec{r}_{13}) \right\}^{1+}_{\frac{1}{2}} . \tag{10}$$

In Eq. (10), j can assume the values $L \pm \frac{1}{2}$. Since the deuteron has a spin of 1^+, j is limited to $\frac{1}{2}$ or $\frac{3}{2}$. A similar expression[9] may be written for C_D^C.

4. MODEL INTERACTION AND ITS PROPERTIES

One of the major ambiguities which one encounters in a calculation of the present kind lies in the selection of an appropriate form for the nuclear interaction. Although it is desirable to keep as close as possible to forms suggested by the observed nucleon-nucleon scattering data, it is known that modifications to the interaction can be expected to arise when the model space is truncated[37]. Instead of attempting the complex task of generating the required modifications to the nuclear interaction by direct calculation, we have sought a two-body effective interaction which gives reasonable results within our model space ($4\hbar\omega$) for the binding energies and rms radii of the nuclei ^{2}H, ^{3}H, ^{3}He and ^{4}He. The inclusion of the ^{2}H system is required because the deuteron wave function is important in the description of A = 3 fragmentation into a nucleon plus a deuteron. An interaction which described ^{2}H, ^{3}H and ^{3}He would fulfill the goal of this paper. However, including the constraint of properly describing ^{4}He permits additional reactions to be consistently investigated via DWBA calculations —i.e. (^{4}He,n), (^{4}He,p), (^{4}He,d), (^{4}He,^{3}H), (^{4}He,^{3}He), and similar reactions involving excited states of

^{4}He. Although this paper concentrates on the A = 3 wavefunctions, the model interaction is applicable to heavier systems.

Results obtained with a variety of shell-model forces[38-41] failed to satisfy our criteria for a suitable interaction[13]. On the other hand, results obtained with the Sussex interaction[30] suggest an effective interaction candidate is possible if suitable modifications are initiated[13]. Unfortunately, the convergence rate with respect to maximum oscillator energy is slow and the various nuclear systems do not converge at the same rate. For the present application, ^{2}H and A = 3 wave functions are required and the effective interaction must account for the convergence differences of the A = 2 and A = 3 systems. Typical convergence results[41,42] obtained with unmodified Sussex matrix elements are given in Table I.

TABLE I

Maximum oscillator energy ($\hbar\omega$)	$E_B(^2H)$[a] (MeV)	$E_B(^3H)$[b] (MeV)	$E_B(^4He)$[b] (MeV)
2	1.2	1.6	16.0
4	0.1	3.6	18.9
6	0.9	4.1	20.0
8	...	4.4	...
∞ (extrapolated)	2.1	5.5	22.8
experiment	2.21	8.48	28.3

a) Ref. 42.
b) Ref. 41.

Table I. Binding energies of few-nucleon clusters calculated with unmodified Sussex matrix elements.

Given our binding energy and rms radius criteria, it was decided to consider effective interactions of the form

$$V^{\text{modified Sussex}} = C\, V^{\text{Sussex}} , \qquad (11)$$

where C is a strength parameter of order unity. The parameter C and the oscillator size parameter b[30] were varied independently. Good fits to the ground state properties of interest, given in Table II, were obtained for C = 1.168 and b = 1.60 fm. Within our $4\hbar\omega$ model space, the modified Sussex interaction also predicts a 4 percent D-state probability in the deuteron ground state and yields a ^{3}H - ^{3}He Coulomb energy difference in agreement with experiment. The changes from the original Sussex matrix elements implied by our choice of C are typically of the same order of magnitude as the expected uncertainties in the matrix elements themselves[30]. In addition, the interaction of Eq. (11) has been shown to also lead to a realistic description of the structure of the A = 5 system[31].

TABLE II

Cluster	Experimental binding energy (MeV)	Model binding energy (MeV)	Experimental rms radius (fm)	Model rms radius (fm)
^{2}H	2.21	1.77	1.95	1.70
^{3}H	8.48	8.07	1.70	1.67
^{3}He	7.72	7.33	1.88	1.73
^{4}He	28.30	28.30	1.63	1.53

Table II. Properties of few-nucleon clusters using the modified Sussex interaction.

5. RESULTS AND DISCUSSION

The results of R-matrix calculations of β and D-wave asymptotic normalization constant values are summarized and compared with data[43] in Table III. The R-matrix model uses a point Coulomb interaction for ^{3}He. As expected, no Coulomb interaction is included in the R-matrix ^{3}H hamiltonian. As noted in Ref. 5, the R-matrix β values for ^{3}H and ^{3}He are in very close agreement with the experimental values derived from measured ^{2}H, ^{3}H and ^{3}He binding energies. The R-matrix values are within one percent of the experimental β values. Even though the R-matrix values are in agreement with the data there is no guarantee that physical asymptotic normalization constants are generated by the R-matrix wave functions.

TABLE III

$\beta(^3H)$ (fm^{-1})	$C_D(^3H)$	$\beta(^3He)$ (fm^{-1})	$C_D^C(^3He)$	Reference
0.516	0.0963	0.486	0.1029	this work
0.516	not measured	0.483	not measured	43 (experiment)

Table III. D-state asymptotic normalization constants in the A = 3 system.

The model C_D and C_D^C values summarized in Table III are 0.0963 and 0.1029, respectively. As noted earlier, there are no direct measurements of D-wave asymptotic normalization constants. Therefore, the validity of the R-matrix calculations is difficult to assess. However, a clearer understanding of the D-wave trinucleon wave function components is possible by considering measured C_D/C_S, C_D^C/C_S^C, D_2 and D_2^C values[1-4,6,8].

Model and measured D_2, D_2^C, C_D/C_S and C_D^C/C_S^C values are compared in Table IV. The experimental C_D/C_S ratio is about 0.048[6] - 0.051[8]

which is well reproduced by the R-matrix model result of 0.051. Since the model C_S value (1.882[5]) is close to the experimental range of 1.61 to 1.82[26,27], a realistic value for C_D is suggested. The C_D/C_S ratio and the experimental C_S values predict a C_D value of 0.08 - 0.09 which is in reasonable agreement with the R-matrix value of 0.0963.

TABLE IV

D_2 (^{3}H) (fm^2)	D_2^C (^{3}He) (fm^2)	C_D / C_S	C_D^C / C_S^C	Reference
-0.2080	-0.2102	0.051	0.053	this work
-0.279 ± 0.012[a]	----	----	---	3,4 (experiment)
----	-0.339[b]	----	---	3,4 (experiment)
----	-0.37	----	---	1 (experiment)
----	-0.22	----	---	2 (experiment)
----	----	0.051 ± 0.005	---	8 (experiment)
----	----	0.048 ± 0.007	---	6 (experiment)

a) $(\vec{d}, {}^3H)$ measurement reported in both Refs. 3 and 4.
b) $(\vec{d}, {}^3He)$ measurement reported in both Refs. 3 and 4.

Table IV. D-state parameter and asymptotic normalization constant ratios in the A = 3 system.

The model predicts a C_D^C/C_S^C value of 0.053. Without C_D^C/C_S^C data, a comparison of the model results is difficult but an estimate of C_D^C is possible by assuming that $C_S \cong C_S^C$ and $C_D \cong C_D^C$[9]. Furthermore, an assessment of C_D^C from the model result is less clear than in the ^{3}H case because the model C_S^C value (1.948) is larger than the experimental range 1.79 - 1.82[25,26]. The experimental C_S^C range and C_D/C_S ratio suggest a

C_D^C value of about 0.09. The R-matrix value of 0.1029 is close to the estimated value (0.09).

The situation concerning the D_2 and D_2^C parameters is complicated by uncertainties in the experimental measurements[1-4]. However, the R-matrix calculations validate the theoretical prediction of Friar et al.[9] that

$$D_2^C \cong D_2 \quad . \tag{12}$$

Friar et al. find Eq. (12) holds to better than 1.1 per cent. The R-matrix calculations predict agreement of Eq. (12) to within 1.045 per cent.

The magnitude of R-matrix D_2 and D_2^C values are smaller (in magnitude) than the measured D_2 values. Specifically, the R-matrix D_2 value is about -0.21 fm^2 and the experimental value of -0.279 ± 0.012 fm^2 is not reproduced by the model. The experimental D_2^C values lie within the range of -0.22 to -0.37[1-4]. The R-matrix model suggests a value of -0.21 fm^2 which lies slightly outside the experimental range.

6. CONCLUSIONS

R-matrix calculations, based on the modified Sussex interaction and the Lane-Robson theory, are shown to lead to A = 3 D-wave asymptotic normalization constants which are supported by C_D/C_S measurements. However, the model D-wave parameter values are somewhat outside the experimental ranges. The R-matrix calculations generally lead to consistently good results for the binding energies, charge radii and asymptotic normalization constants in the A = 3 systems with the major uncertainties occuring for the D_2 and D_2^C parameters. Since R-matrix trinucleon wave functions provide a reasonable description of A = 3 binding energies, charge radii and asymptotic normalization data, the model provides useful wave functions for A = 3 nuclei. The R-matrix model can be useful in constructing ^{3}H and ^{3}He wave functions for use in DWBA calculations of (d,^{3}H) and (d,^{3}He) transfer reactions.

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