ISOSPIN MIXING AND THE ^{4}HE (γ,p) -TO- HE (γ,n) CROSS SECTION RATIO IN THE ^{4}HE GIANT DIPOLE RESONANCE REGION

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(recibido abril 13, 1983; aceptado mayo 30, 1983)

ABSTRACT

R-matrix calculations which include Coulomb and charge symmetric nuclear interactions are used to evaluate photonuclear data near the giant dipole resonance (GDR) in ^{4}He. The calculations are motivated by the discovery by Grüebler et al. of a new $(J^\pi,T) = (1^-,0)$ level at 24.1 MeV excitation energy in ^{4}He. R-matrix calculations, which include the three 1^- levels of Fiarman and Meyerhof, lead to a ^{4}He(γ,p) - to - ^{4}He(γ,n) cross section ratio at the GDR peak of 1.2. Calculations using four 1^- levels, the three levels of Fiarman and Meyerhof and the new 24.1 MeV level, increase the ratio to about 1.3. Additional calculations are able to explain the measured ^{4}He(γ,p) - to - ^{4}He(γ,n) cross section ratio if a new $(1^-,0)$ state occurs at about 29 MeV excitation energy. The addition of this state to the level spectrum of Fiarman and Meyerhof leads to a cross section ratio of 1.7 which falls within the experimental range of 1.6 - 1.9 without utilizing charge symmetry violating forces.

RESUMEN

Cálculos de la matriz R que incluyen interacciones de Coulomb e interacciones nucleares de carga simétrica se usan para evaluar datos nucleares cerca de la resonancia dipolar gigante (RDG) en ^{4}He. Los cálculos fueron motivados por el descubrimiento de Grüebler et al. de un nuevo nivel $(J^\pi,T) = (1^-,0)$ en ^{4}He con una energía de excitación de 24.1 MeV. Los cálculos de la matriz R, que incluyen los tres niveles 1^- de Fiarman y Meyerhof, conducen a un cociente de secciones transversales de ^{4}He(γ,p)/^{4}He(γ,n) en el pico de la RDG de 1.2. Los cálculos que incluyen además de los tres niveles de Fiarman y Meyerhof el nuevo nivel 1^- de 24.1 MeV aumentan el cociente a 1.3. Cálculos adicionales pueden explicar el cociente de secciones transversales ^{4}He(γ,p)/^{4}He(γ,n) medido si existe un nuevo estado $(1^-,0)$ con una energía de excitación de aproximadamente 29 MeV. La adición de este estado al espectro de niveles de Fiarman y Meyerhof produce un cociente de secciones transversales de 1.7 que cae en el intervalo experimental de 1.6-1.9 sin utilizar fuerzas que violen la simetría de carga.

1. INTRODUCTION

Questions of violations of charge symmetry of the nuclear force in ^{4}He have been raised through experimental efforts involving the ^{3}H(p,n)[1], ^{3}H($\vec{p}$,p)[2], ^{3}He($\vec{n}$,n)[3], ^{2}H($\vec{d}$,p) and ^{2}H($\vec{d}$,n)[4] reactions. Most recently, Berman et al.[5] compared the ratios of the ^{4}He(γ,p) and ^{4}He(γ,n) reactions, and this ratio suggests charge symmetry violations as a possible explanation. The experimental cross section ratio for energies between 26 and 29 MeV in ^{4}He is between 1.6 and 1.9. This ratio has not been predicted by conventional nuclear structure calculations[6-10]. The experimental ratio of Berman et al. has recently been confirmed by Ward et al.[11]

The experimental (γ,p) - to - (γ,n) ratio has been used to infer the existence of large charge asymmetry components in the nuclear interaction near the ^{4}He giant dipole resonance (GDR) at 27 MeV[5,12,13]. In view of the importance of the charge asymmetry components, this paper will attempt to understand the (γ,p) - to - (γ,n) ratio in terms of Coulomb and level effects. The present work represents an expansion of a preliminary survey of isospin mixing in the ^{4}He giant dipole resonance region[14].

The reader should note that the ^{4}He(γ,p) - to - ^{4}He(γ,n) cross section ratio is influenced by the location and structure of $J^\pi = 1^-$ levels in the ^{4}He spectrum. The ^{4}He level spectrum has changed with additional data[15-17] and the present view, as noted in the most recent compilation of Fiarman and Meyerhof[17], suggests three 1^- levels at 27.4, 30.5 and 31.0 MeV excitation energy. Most recently, Grüebler et al.[18] have discovered a new $(J^\pi,T) = (1^-,0)$ level at 24.1 MeV excitation energy. The existence of the new 1^- level provides the potential for increased isospin mixing and hence a calculated cross section ratio which would be larger than the near unity values of conventional nuclear structure calculations[6-10]. Therefore, the addition of a new 1^- state to the three 1^- levels of the Fiarman and Meyerhof compilation presents an interesting possibility for resolving the discrepancy between the calculations and the measured (γ,p) - to - (γ,n) cross section ratio.

2. EXPERIMENTAL IMPLICATIONS

Berman et al.'s data in the 26 - 29 MeV region of ^{4}He indicate a cross section ratio between 1.6 and 1.9. This ratio implies a ratio of isospin T = 0 and T = 1 amplitudes (a_0/a_1) of the excited ^{4}He wave functions of 0.14± 0.02. Ref. 5 suggests that this amount of isospin mixing is greater than that expected from Coulomb effects alone, and that a significant charge-asymmetry component of the nuclear force exists in ^{4}He near 27 MeV.

There are two possible explanations for the large (γ,p) - to - (γ,n) cross section ratio[12]. The first is that the nn interaction in the n + ^{3}He channel differs from the pp interaction in the p + ^{3}H exit channel —i.e., a breaking of charge symmetry in the nuclear force. The second is that a large amount of Coulomb mixing exists. The mixing is due to the overlap of adjacent $J^\pi = 1^-$ levels in the vicinity of the ^{4}He GDR at about 27 MeV excitation.

If either phenomena is the cause of the photonuclear cross section ratio, it should also be present in other ^{4}He reaction channels as well. Examples of reactions in which charge symmetry effects have been discussed include the ^{3}H(p,n) reaction[1,19], the ^{3}H($\vec{p}$,p) and ^{3}He($\vec{n}$,n) reactions[2,3,20], and the ^{2}H($\vec{d}$,p) and ^{2}H($\vec{d}$,n) reactions[4,21].

Theoretical studies of these reactions suggest that ^{4}He data are consistent with Coulomb effects alone[(19-21)]. For this reason, it is plausible to assume that the photonuclear data is at least partially explained by Coulomb effects. The net effect of the Coulomb interaction at the GDR peak is the mixing of the $T=0$ and $T=1$, $J^{\pi} = 1^{-}$ levels near 27 MeV excitation[(17)], with the degree of mixing being determined by the level positions and widths.

3. FORMULATION

The method used in determining the ^{4}He resonance positions and widths has been discussed in previous papers[(19-22)]. The model is constructed within the framework of the dynamical R-matrix methodology of Lane and Robson[(23)]. The internal states are expanded on a basis of properly symmetrized translationally invariant harmonic oscillator eigenstates including all states of up to $4\hbar\omega$ of oscillator excitation. All three two-body break-up channels, namely $p + {}^3H$, $n + {}^3He$ and $d + {}^2H$ are explicitely included. The charge symmetric two-body interaction is based on the Sussex matrix elements[(24)].

The level eigenenergies and widths are obtained by solving the equation

$$\sum_{\lambda'=1}^{N} \left[\langle \lambda | H - E | \lambda' \rangle + \sum_{c} \gamma_{\lambda c} (b_{\lambda' c} - b_c) \gamma_{\lambda' c} \right] A_{\lambda'} = 0 \quad , \qquad (1)$$

where H is the ^{4}He Hamiltonian and $|\lambda\rangle$ are the model basis states[(22)]. For the $J^{\pi} = 1^{-}$ problem considered herein, there are 37 basis states (N). The second term in Eq. (1) includes a sum over physical two-body channels (c), and this term leads to level width information[(22,25,26)]. The quantities appearing in Eq. (1) and its solution are discussed in Refs. 22, 23 and 27.

4. CONVENTIONAL MODEL RESULTS

The location of the aforementioned $J^{\pi} = 1^{-}$ levels and their corresponding widths are obtained from the solution of Eq. (1). The resulting level properties are summarized in Table I (RM-I) along with their corresponding ratios of isospin components (M) —i.e., the ratio of isospin amplitudes a_0/a_1 for T = 1 levels and a_1/a_0 for T = 0 levels. The T = 1 levels at 27.4 MeV and 30.5 MeV have a_0/a_1 values of 0.045 and 0.057 while the T = 0 level at 31.0 MeV has an a_1/a_0 value of 0.073. The sum of these values is 0.18 which exceeds the experimental ratio of 0.14 ± 0.02 at the GDR peak(5). However, the experimental cross section ratio of 1.6 - 1.9 is not reproduced and the model leads to a ratio of only 1.2. This ratio is expected from the isospin mixing in the 27.4 MeV and 30.5 MeV levels. The theoretical ratio is also consistent with shell model calculations of Londergan and Shakin(6) and Halderson and Philpott(9). In addition, a paper by Gibson(28) suggests the RM-I levels (see Table I) are split too far to provide an explanation of the (γ,p) - to - (γ,n) ratio in terms of Coulomb mixing.

The cross section ratio (γ,p)/(γ,n) has not been reproduced by the currently accepted $J^{\pi} = 1^-$ level spectrum of Fiarman and Meyerhof (FM)(17). The FM spectrum explains a considerable portion of the ^{4}He data but omissions and theoretical uncertainties remain. For example, the $(0^+,0)$ 20.1 MeV level eigenenergy has yet to be reproduced within the framework of a $2\hbar\omega$ or $4\hbar\omega$ shell model basis if the 0^+ spectrum is constrained to reproduce the 28.3 MeV ground state binding energy(22). However, Robson(29) has shown that for a semi-rigid tetrahedron structure (non-shell model state), the first excited state in ^{4}He can be predicted to be a totally symmetric vibration of the correlated four nucleon system. Although the $(0^+,0)$ 20.1 MeV state is within the SU(4) [15] supermultiplet, other states in the ^{4}He spectrum may not be.

For example, a recently proposed 2^+ level at about 40 MeV appears to be at least partially outside the supermultiplet structure(30,31). This state and a state at 37 MeV excitation(2,3,20) are omitted from the FM spectrum.

In addition to the omissions noted above, the T = 0 spectrum in the ^{4}He has presented theoretical difficulties. The theoretical T = 0 spectrum tends to lie above the corresponding experimental levels whenever the binding energy constraint is imposed. The T = 0 difficulties are

TABLE I

(J^{π},T)	Experiment E_x (MeV)	Experiment Γ (MeV)	Experiment M[b)]	RM-I E_x (MeV)	RM-I Γ (MeV)	RM-I M	RM-II E_x (MeV)	RM-II Γ (MeV)	RM-II M	RM-III E_x (MeV)	RM-III Γ (MeV)	RM-III M
$(1^-,1)$	27.4	10.0	—	27.4	4.4	.045	27.4	4.2	.050	27.3	4.2	.090
$(1^-,0)$	not observed			—	—	—	24.1	2.0	.069	28.9	5.0	.126
$(1^-,1)$	30.5	10.0	—	30.5	5.1	.057	30.5	5.1	.078	30.5	5.1	.161
$(1^-,0)$	31.0	3.1 5.3	—	31.0	8.3	.073	31.0	8.5	.091	31.1	8.5	.135

a) Energy and width references are provided in Ref. 17.

b) Ratio of isospin amplitudes.

Table I. Isospin mixing near the ^{4}He GDR peak[a)].

greatest for the first three T = 0 levels[22].

Since theoretical calculations do not yield the correct cross section ratio and also fail to completely explain the ^{4}He spectrum, it is reasonable to determine if modifications to the currently accepted spectrum can yield an enhanced cross section ratio. Before discussing specific modifications, the $J^\pi = 1^-$ problem will be considered in more detail.

5. MODIFIED MODEL RESULTS (ADDITION OF THE 24.1 MeV LEVEL OF GRÜEBLER ET AL.)

The eigenspectrum of the 1^- levels is obtained by using the 37 $|\lambda\rangle$ basis states which have a $J^\pi = 1^-$ coupling structure[22]. For example, the shell model portion of Eq. (1) involves the diagonalization of a 37 × 37 array:

$$\begin{vmatrix} H_{11} - E & H_{12} & \cdots & H_{1\,37} \\ \vdots & & & \vdots \\ \cdot & H_{22} - E & \cdots & \cdot \\ \vdots & & \ddots & \vdots \\ H_{37\,1} & H_{37\,2} & \cdot & H_{37\,37} - E \end{vmatrix} = 0 \quad , \tag{2}$$

where

$$H_{ij} = \langle \lambda_i | H | \lambda_j \rangle \quad . \tag{3}$$

The reader should note that the complete array of Eq. (1) should be illustrated in Eq. (2). The shell model example is used to simplify the illustration.

The diagonalization of Eq. (2) leads to eigenvalues E_1, E_2, E_3, ..., E_i, ... E_{37} with corresponding wave functions

$$\Psi^{(i)} = \sum_\lambda A_\lambda^{(i)} |\lambda\rangle \quad . \tag{4}$$

For completeness, we label $\Psi^{(1)}$ to be the 27.4 MeV state, $\Psi^{(2)}$ is the

30.5 MeV state, and $\Psi^{(3)}$ is the 31.0 MeV level. The $J^{\pi} = 1^{-}$ spectrum can be modified by adding additional basis states to the original $4\hbar\omega$ basis. For simplicity, only one additional state is added to the basis.

The additional state (T = 0) is added with the constraint that

$$\Psi^{(38)} \cong \Psi^{(3)} \quad . \tag{5}$$

This is achieved by assuming that

$$\langle\lambda_3|H|\lambda_i\rangle = \langle\lambda_{38}|H|\lambda_i\rangle \quad ; \quad i \neq 3,\ 38 \quad . \tag{6}$$

In addition, the $\langle\lambda_{38}|H|\lambda_{38}\rangle$

overlap is chosen such that the eigenvalue of the new $(1^-,0)$ state occurs at the position of the 24.1 MeV $(1^-,0)$ level of Grüebler et al.[18]. The 24.1 MeV level is suggested by an analysis of precision measurements of vector and tensor analyzing powers from the $^2H(\vec{d},p)^3H$ reaction, and the level has a width of 1 - 2 MeV[18].

The results of the 38 state diagonalization, including a new $(1^-,0)$ level at 24.1 MeV, will be referred to as RM-II and are summarized in Table I. The RM-II eigenvalues are very similar to the RM-I energies. As expected, the addition of the new $(1^-,0)$ level at 24.1 MeV (with a model width of 2 MeV) enhances the isosping mixing ratio, but the increase is less than the measured mixing ratio of 0.14 ± 0.02[5]. The model predicts a mixing ratio which varies between 0.05 and 0.09 for the four 1^- states in the vicinity of the ^{4}He GDR. In addition, the RM-II spectrum leads to a GDR peak cross section ratio of 1.34 which is less than the experimental ratio of 1.6 to 1.9[5].

6. MODIFIED MODEL RESULTS (ADDITION OF A SPECULATIVE 28.9 MeV LEVEL)

The addition of the $(1^-,0)$ level of Grüebler et al.[18] increased the isospin mixing ratio but the increase was not enough to resolve the discrepancy between the model calculations and the measured ratio[5]. The model isospin mixing ratio can be further enhanced by adding a new "speculative" state, characterized by Eq. (6) at 28.9 MeV excitation energy and by dropping the 24.1 MeV level of Grüebler et al. from the model basis. Following this addition, the guidelines of Eqs. (5) and (6) lead to a $(1^-,0)$ level which has a width of 5.0 MeV and a position of 28.9 MeV excitation energy. This location should enhance the isospin mixing ratio because it places the new $(1^-,0)$ level between the two $(1^-,1)$ levels of Fiarman and Meyerhof[17].

The reader may wonder why we add a new state with $J^\pi = 1^-$, $T = 0$ rather than shift the energies of the three presently accepted $J^\pi = 1^-$ levels. In order to answer this question, a historical perspective of the ^{4}He system is required. The incorporation of only three $J^\pi = 1^-$ low lying levels in ^{4}He follows from the assumption that the SU(4) multiplet sufficiently describes this system. The multiplet assumption has been strengthened by its early successes in describing the available ^{4}He data. However, ambiguities in resolving ^{4}He data led to two different sets of 1^- levels[16]. As additional data become available, there is no a priori reason to expect that the three level assumption will remain intact. However, analyses of ^{4}He continue to be based on the validity of SU(4). In addition, there is no guarantee that the SU(4) scheme is unique and that perhaps other levels or oscillator excitation higher than the SU(4) $2\hbar\omega$ limit are needed to describe the $J^\pi = 1^-$ spectrum in ^{4}He. In fact, the description of the new $J^\pi = 2^+$ level (40 MeV excitation) appears to fall, at least partially, outside the $2\hbar\omega$ restrictions of the SU(4) multiplet[31].

If the three $J^\pi = 1^-$ levels were shifted (assuming a three level scheme), the shifts would be restricted by the results of the three level analysis of Werntz and Meyerhof[16]. It is the author's opinion, that the available experimental data[17] does not support the size of the shifts (involving three levels) which would be required to yield an a_0/a_1 ratio which agreed with the measured value[5]. For example, Gibson[28] requires a splitting of 250 keV to account for a sizeable a_0/a_1 ratio. The present data compilation of Fiarman and Meyerhof and earlier parameterizations of Werntz and Meyerhof do not suppor level splittings of less than 500 keV. Therefore, it does not appear that shifts of sufficient magnitude are permitted if three $J^\pi = 1^-$ levels are included in the analysis of the photonuclear data. This difficulty may be removed by introducing a new $(1^-,0)$ level as a mechanism for explaining the photonuclear data. Since three level results have failed to resolve the photonuclear difficulties, the use of four levels is worth considering.

The new $(1^-.0)$ level is also motivated by the RM-I results. These results yield an a_0/a_1 ratio which is a factor of 2-3 smaller than the measured value[5]. A larger ratio could be obtained if a new $(1^-,0)$ level existed near the two $(1^-,1)$ levels. The size of the a_0/a_1 ratio depends on both the energy splittings of $(1^-,0)$ and $(1^-,1)$ levels and the nuclear structure properties of these levels. For example, although the $(1^-,1)$ 27.4 MeV level is 3.6 MeV from the $(1^-,0)$ 31.0 MeV level, its a_0/a_1 ratio is only about 20% smaller than the isospin mixing between the 30.5 and 31.0 MeV levels. Therefore, it is expected that the addition of the new $(1^-,0)$ level will enhance the a_0/a_1 ratio even if its location is such that $(1^-,0)$ and $(1^-,1)$ energy differences exceed the guidelines of Gibson[28].

Model results, including the speculative $(1^-,0)$ 28.9 MeV level, will be referred to as RM-III and are summarized in Table I. The RM-III eigenvalues are nearly identical to the RM-I and RM-II energies. The E_{38} energy (28.9 MeV) is about midway between the two lowest $T = 1$ levels, and corresponds to the position of a "bump" in the data (see fig. 4, Ref. 11) which has yet to be explained.

Table I also summarizes the isospin mixing characteristics of the RM-III spectrum. The addition of the new $T = 0$ state considerably enhances the isospin mixing ratio which varies between 0.09 - 0.16 in the vicinity of the GDR. This ratio spans the bound 0.14 ± 0.02 extracted from data[5]. The RM-III spectrum also leads to a GDR peak cross section ratio of 1.67 which falls within the 1.6 - 1.9 experimental range.

Finally, a comment concerning the effect of the new $(1^-,0)$ 28.9 MeV level on other reactions is in order. The new level will not have a distinct signature since it is broad and surrounded by levels which have similar widths. For example, the level will have little effect on reaction or total cross section estimates. This was confirmed by estimating the ^{3}He(n,n) total cross section and the ^{3}H(p,n) and ^{2}H(d,p) reaction cross sections. In a similar fashion, angular distributions for the $^3H(p,p)$, $^3H(p,n)$, $^3He(n,n)$, $^2H(d,p)$, and $^2H(d,n)$ reactions are not significantly altered by the presence of the 28.9 MeV $(1^-,0)$ level.

7. CONCLUSIONS

R-matrix calculations based on a charge symmetric force and the level spectrum of Fiarman and Meyerhof (FM) lead to a theoretical $^4He(\gamma,p)$ - to - $^4He(\gamma,n)$ cross section ratio of 1.2. This ratio is considerably below the 1.6 - 1.9 experimental ratio. However, the calculations are able to explain the measured cross section ratio if a new $J^\pi = 1^-$, $T = 0$ state at about 29 MeV is added to the model spectrum. The addition of this state to the FM level spectrum leads to a cross section ratio of 1.7 which falls within the experimental range without utilizing charge asymmetric components in the nuclear force.

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