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STRUCTURE EFFECTS IN THE $^4He(\gamma, p)^3H$ $E3$ CROSS SECTION

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The ^4He octupole resonance in the $^4He(\gamma, p)$ reaction is investigated by using the generalized R-matrix methodology of Lane and Robson. R-matrix calculations are also utilized to calculate $J^\pi = 3^-$ resonances which dominate the $E3$ cross section. The calculated $^4He(\gamma, p)$ $E3$ cross section peaks at a value of $4.69 \cdot 10^{-3}$ fm^2 at 71.0 MeV excitation energy. Secondary peaks occur at 76.4 MeV ($1.84 \cdot 10^{-3}$ fm^2) and at 80.0 MeV ($1.82 \cdot 10^{-3}$ fm^2).

1. Introduction

The study of the structure of the ^4He nucleus is of fundamental importance, and interesting manifestations of the nuclear structure have been noted in the giant dipole (GDR) and giant quadrupole resonances (GQR)[1-23]. Since the character of these resonances is dictated by the spin, parity, and width of the excited levels, studies of the $^4He(\gamma, p)$ photonuclear reactions have provided insight into the ^4He level spectrum[5-13,17-19]. The $^4He(\gamma, p)$ giant octupole resonance (GOR) also has the potential to add insight into the nature of the ^4He level spectrum, but has yet to be studied, in detail, from either a theoretical or experimental viewpoint.

The possibility of finding structure in the $^4He(\gamma, p)$ and $^4He(\gamma, n)$ $E3$ photonuclear reactions and the importance of this structure in understanding the ^4He level spectrum suggests that a theoretical calculation is warranted. The Lane-

-Robson generalized R-matrix method[24-26] has provided a reasonable description of the ^{4}He system[13,17-19,27-31]. It is applied here to calculate the $E3$ photonuclear cross section in ^{4}He.

2. *Formalism*

The model for the bound and continuum states of the ^{4}He system represents an application of the dynamical equations of the Lane-Robson[24-26] R-matrix methodology to the ^{4}He nucleus. The dynamical equations can be written in the form[32]

$$\sum_{\lambda'} [\langle \lambda | H - E | \lambda' \rangle + \sum_c \gamma_{\lambda c} (b_{\lambda' c} - b_c) \gamma_{\lambda' c}] A_{\lambda'} = 0 \tag{1}$$

where H is the Hamiltonian describing the system of interest and $\gamma_{\lambda c}$ and $b_{\lambda c}$ are the reduced widths[33] and logarithmic derivatives associated with the expansion states $|\lambda\rangle$. The expansion states are introduced in order to describe the nuclear wave function within the interaction region $r_c < a_c$ in all channels. The quantities b_c are related to the radial wave functions $U_c(r_c)$ in the physical channels by

$$b_c = \left(\frac{r_c}{U_c} \frac{\mathrm{d}U_c}{\mathrm{d}r_c} \right) r_c = a_c. \tag{2}$$

They provide the needed connections between the interaction region and the various two-body breakup channels. The A_λ are expansion amplitudes which are to be determined, if necessary, by the solution of Eq. (1).

Within this framework, the model is defined by choosing a form for the Hamiltonian and a set of expansion states and cluster wave functions[27]. The calculations include the p + ^{3}H, n + ^{3}He, and d + ^{2}H breakup channels in addition to an explicit set of structure states, whose total oscillator energy does not exceed $4\hbar\omega$.

The nuclear Hamiltonian is expressed as

$$H = -\sum_K (\hbar^2/2\mu_K) \Delta_K^2 + \sum_{i<j} V_{ij} \tag{3}$$

where K runs over the alpha particle internal coordinates and i and j run over nucleon coordinates. Using standard techniques, the desired many-body matrix elements of the Hamiltonian can be expressed in terms of standing one- or two-body matrix elements evaluated over all space. The matrix elements of the Coulomb interaction and the kinetic energy require corrections to remove contributions arising from those parts of the oscillator eigenfunctions which extend beyond the interaction region. Similar corrections to the nuclear interaction matrix elements are taken to be negligible and are ignored.

Solutions of Eq. (1) are obtained by the methods outlined in Ref. 34. After utilizing the transformations of Ref. 34, the R-matrix takes on the standard form[33]

$$R_{cc'} = \sum_{\mu} \frac{\gamma_{\mu c}\, \gamma_{\mu c'}}{E_{\mu} - E}, \tag{4}$$

where the quantities E_{μ} and $\gamma_{\mu c}$ are calculated directly from the information appearing in Eq. (1). In a similar manner, the resonance structure of the theory is made more explicit. Scattering and reaction information are obtained from the R-matrix via the S-matrix by means of standard formulae[33].

Specific formulae for the positions and widths of R-matrix resonances are available in the literature[33,35] and only a brief discussion will be presented herein. The model wave functions which define the resonances contain considerable detail[27]. For example, there are 23 basis states included in the description of $J^{\pi} = 3^{-}$ levels which are expected to be the dominant contributors to the ^{4}He $E3$ giant octupole resonance.

In a similar fashion, model calculations have been used to obtain exit-channel wave functions.

Detailed descriptions of the ^{3}H exit-channel wave-functions, binding energies, and RMS radii are provided in Refs. 27 and 36. The ^{3}H binding energy and RMS radius are within 5% and 2% of experiment, respectively.

The model calculations of Eq. (1) incorporate all three binary breakup channels, namely p + ^{3}H, n + ^{3}He and d + ^{2}H. The inclusion of these reaction channels is important because the width of an energy level is governed by its channel couplings. The total width of a level μ is obtained from the equation[33,35]

$$\Gamma_R^{\mu c} = -2\,\mathrm{Im}\,(E_{\mu} - \xi_{\mu}(E_R^{\mu})) \tag{5}$$

where ξ_{μ} is itself defined in terms of known R-matrix energies and reduced widths E_{μ}, $\gamma_{\mu c}$ and standard Coulomb radial functions[33,35]. The partial width $\Gamma_R^{\mu c}$ is then obtained from the relation[33,35]

$$\Gamma_R^{\mu c} = 2\,|\alpha_{\mu c}(E_R^{\mu})|^2\, P_c(E_R^{\mu}) \tag{6}$$

where P_c is the penetration in channel c and the quantity $\alpha_{\mu c}$ is defined by Philpott[35]. Within our model of the ^{4}He system, the total width Γ_R^{μ} is given by

$$\Gamma_R^{\mu} = \sum_{c} \Gamma_R^{\mu c} \tag{7}$$

where the label c runs over all physical channels: p + ^{3}H, n + ^{3}He, d + ^{2}H, p + n + ^{2}H and 2n + 2p. Within our framework, the total width is given by a sum over all channels in the model[27]

$$\Gamma_R^{\mu} = \Gamma_R^{\mu p} + \Gamma_R^{\mu n} + \Gamma_R^{\mu d} \tag{8}$$

where the labels p, n and d refer to the binary breakup channels. It should be noted that the model does not include couplings to the three- and four-body break-up channels, and therefore does not include these channel components in the R--matrix total width Γ_μ^R.

The resonance energy E_R^μ is defined in an analogous manner[33,35]

$$E_R^\mu = \mathrm{Re}\,(E_\mu - \xi_\mu\,(E_R^\mu)). \tag{9}$$

However, the addition of channels does not significantly influence the magnitude of the resonance energy[27].

Using the formalism outlined in Refs. 17—19 and 37—39, the ^{4}He (γ, p) photoelectric cross section $\sigma_{EN}(E)$ may be written as

$$\sigma_{EN}(E) = a_N \sum_\mu C\,(E_R^\mu, \Gamma_R^\mu, E)\,|\langle\psi_\mu|\mathcal{O}_N\,|\psi_i\rangle|^2 \tag{10}$$

where $N = 0, 1, 2, \ldots$ for the $E0$, $E1$, $E2$, ... reactions. The constant a_N is defined by the multipole transition, the sum over μ is over all final states in the p + ^{3}H channel, $\mathcal{O}_N$ is the multipole operator, E is the proton energy, and C is defined in terms of the photon energy and level width and energy. Examples of the application of Eq. (10) to the $E1$ and $E2$ photonuclear reactions are provided in Refs. 17—19.

The application of Eq. (10) to the ^{4}He (γ, p) $E3$ reaction is facilitated by using the R-matrix methodology[24-26] to obtain entrance (ψ_i) and exit channel (ψ_μ) wave functions and the energy level positions (E_R^μ) and widths (Γ_R^μ).

The use of the R-matrix wave functions, widths, and energies in Eq. (10) has successfully described the $E1$[18,19], and $E2$[17] photonuclear reactions and should also provide a good description of the ^{4}He (γ, p) $E3$ cross section.

3. *Choice of interaction*

In Ref. 27, an effective interaction for oscillator basis states was determined for the two, three-, and four-nucleon systems. This interaction was determined from the Sussex matrix elements[40] and is of the form

$$V^{eff} = C\,V^{Sussex}, \tag{11}$$

where C is a strength parameter of the order of unity. The parameter C and oscillator size parameter b were varied independently to yield the best fit to the ^{4}He ground state binding energy and RMS radius[27]. Good fits to the $A = 2$—4 ground state properties[27], were obtained for $C = 1.168$ and $b = 1.60$ fm. Within our model space, $4\hbar\omega$, this effective interaction also predicts a 4% D-state probability in the deuteron ground state and yields a ^{3}H — ^{3}He Coulomb energy difference in agreement with experiment[27]. 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[40].

The two-body matrix elements utilized in our calculation are defined as

$$\langle N' L' S J | V | N L S J \rangle = \int_0^\infty R_{N' L'} V R_{N L} r^2 \, dr. \tag{12}$$

Specific matrix elements for the $4\hbar\omega$ or lower excitation energy considered in our model are summarized in Table 3. The spectroscopic notation[40] $^{2S+1}L_J$ is utilized in Table 3, i. e.

$$\langle N' L' S J | V | N L S J \rangle = \langle N' \, {}^{2S+1}L'_J | V | N \, {}^{2S+1}L_J \rangle \tag{13}$$

where S is the sum of the spins of the two nucleons (0 or 1), L is the orbital angular momentum, and J is the total angular momentum ($\vec{J} = \vec{L} + \vec{S}$). The quantities N and L are the radial and orbital quantum numbers associated with the model basis states[27].

4. *Energy level results*

Model results for the positions and widths of $J^\pi = 3^-$ levels are summarized in Table 1. The 3^- levels lie above 58 MeV excitation energy and as such are expected to be broad and overlapping[41,42]. Many of the calculated widths are narrow, but these results are not unexpected. Similar widths were noted in calcu-

TABLE 1.

E_x (MeV)	Γ_R^μ (MeV)	$\Gamma_R^{\mu_0}$ (MeV)	$\Gamma_R^{\mu_p}$ (MeV)	$\Gamma_R^{\mu_d}$ (MeV)
58.24	0.05	0.02	0.02	0.01
58.58	1.58	0.15	0.15	1.28
63.71	0.08	0.03	0.03	0.02
65.64	0.09	0.04	0.04	0.01
66.48	0.52	0.22	0.22	0.08
66.56	0.37	0.16	0.16	0.05
67.41	0.41	0.06	0.06	0.02
68.36	0.12	0.05	0.05	0.02
69.30	0.89	0.25	0.25	0.39
70.85	3.11	0.15	0.15	2.81
71.03	0.03	0.01	0.01	0.01
73.12	0.17	0.08	0.08	0.01
74.25	0.38	0.09	0.09	0.20
75.09	0.09	0.02	0.02	0.05
76.38	0.16	0.08	0.08	$<$0.01
76.42	0.04	0.02	0.02	$<$0.01
77.44	0.08	0.04	0.04	$<$0.01
78.80	0.06	0.03	0.03	$<$0.01
80.01	0.04	0.02	0.02	$<$0.01
80.85	0.14	0.07	0.07	$<$0.01

$J^\pi = 3^-$ levels and widths below 81 MeV excitation energy.

lations of ^{4}He $J^\pi = 4^-$, 5^-, 5^+ and 6^+ levels which lie between 56 and 94 MeV excitation energy[42]. The calculated resonance widths only contain contributions from the p + 3H, n + 3He, and d + ^{2}H channels. The three- and four-body channels (n + p + ^{2}H and 2n + 2p) are ignored[27]. These multiparticle breakup channels can provide a sizeable contribution to the total width, but only a minor contribution to the level position[41,42]. In addition, the 3^- states lie high in excitation energy and very likely contain admixtures of states with $5\hbar\omega$ or more oscillator excitation. The combination of a restrictive, although practical maximum[27], model space and the omission of three- and four-body channels leads to a calculated resonance width which may be narrower than the physical widths.

The results of Table 1 suggest broad levels do exist in the 3^- level spectrum. However, many levels are narrow and present an opportunity for enhancements in the $E3$ cross section. These enhancements may be overestimated by the omission of the three- and four-body breakup channels, but the model should still provide a good representation of the $E3$ cross section since the ^{4}He (γ, p) $E1$ and $E2$ cross sections were satisfactorily reproduced within the framework of the generalized R-matrix methodology[13,17–19].

5. *Cross section results*

Model results for ^{4}He (γ, p) $E3$ cross section are summarized in Table 2. Cross section results are presented at the location of the 3^- levels. As expected, the 3^- levels dominate the cross section and the 3^- level positions correspond

TABLE 2.

E_x (MeV)	$\sigma(\gamma, p)$ (μb)[a]
58.24	1.45
58.58	0.04
63.71	3.90
65.64	4.00
66.48	0.31
66.56	0.31
67.41	3.01
68.36	0.08
69.30	2.10
70.85	0.34
71.03	46.85
73.12	0.84
74.25	3.03
75.09	5.33
76.38	4.30
76.42	18.35
77.44	8.99
78.80	13.49
80.01	18.22
80.85	6.80

a) 1 μb = 10^{-4} fm^2.
^{4}He (γ, p) $E3$ cross section.

with peaks in the $E3$ cross section. Similar correlations between cross section peaks and 2^+ levels were noted for the GQR[17]. The peak of the GDR is also governed by the location of 1^- levels[13,18,19].

The calculated $E3$ cross section is generally less than $5 \cdot 10^{-4}$ fm^2 and has a peak value of about $4.7 \cdot 10^{-3}$ fm^2. As a matter of comparison, the experimental ^{4}He (γ, p) $E1$ peak cross section[13] is about $2 \cdot 10^{-3}$ fm^2 and the peak ^{4}He (γ, p) $E2$ cross section is about $2 \cdot 10^{-2}$ fm^2 [17]. As noted in Table 2, the ^{4}He (γ, p) $E3$ cross section exhibits a number of peaks. Below 70 MeV, the peaks are weak, less than $5 \cdot 10^{-4}$ fm^2, and will be difficult to detect. However, the region above 70 MeV exhibits three additional peaks which have a better chance of experimental detection.

For the energy range above 70 MeV excitation energy, the maximum occurs at 71.0 MeV ($4.69 \cdot 10^{-3}$ fm^2). Secondary maxima ($1.84 \cdot 10^{-3}$ and $1.82 \cdot 10^{-3}$

TABLE 3.

Matrix element	$N = 0$	1	2
$\langle n\ ^1S_0 \vert V \vert n\ ^1S_0\rangle$	−8.70	−5.30	−2.58
$\langle n\ ^1S_0 \vert V \vert n+1\ ^1S_0\rangle$	−6.86	−3.69	— — —
$\langle n\ ^1S_0 \vert V \vert n+2\ ^1S_0\rangle$	−4.27	— — —	— — —
$\langle n\ ^3S_1 \vert V \vert n\ ^3S_1\rangle$	−10.40	−6.93	−3.64
$\langle n\ ^3S_1 \vert V \vert n+1\ ^3S_1\rangle$	−7.85	−4.34	— — —
$\langle n+1\ ^3S_1 \vert V \vert n\ ^3D_1\rangle$	−1.50	+0.25	— — —
$\langle n\ ^3S_1 \vert V \vert n\ ^3D_1\rangle$	−7.32	−4.71	— — —
$\langle n+2\ ^3S_1 \vert V \vert n\ ^3D_1\rangle$	+0.07	— — —	— — —
$\langle n\ ^1P_1 \vert V \vert n\ ^1P_1\rangle$	+2.66	+5.34	— — —
$\langle n\ ^1P_1 \vert V \vert n+1\ ^1P_1\rangle$	+3.66	— — —	— — —
$\langle n\ ^3P_0 \vert V \vert n\ ^3P_0\rangle$	−2.87	−1.25	— — —
$\langle n\ ^3P_0 \vert V \vert n+1\ ^3P_0\rangle$	−0.93	— — —	— — —
$\langle n\ ^3P_1 \vert V \vert n\ ^3P_1\rangle$	+2.97	+4.82	— — —
$\langle n\ ^3P_1 \vert V \vert n+1\ ^3P_1\rangle$	+3.07	— — —	— — —
$\langle n\ ^3P_2 \vert V \vert n\ ^3P_2\rangle$	−1.73	−2.63	— — —
$\langle n\ ^3P_2 \vert V \vert n+1\ ^3P_2\rangle$	−1.94	— —	— — —
$\langle n+1\ ^3P_2 \vert V \vert n\ ^3F_2\rangle$	+0.48	— — —	— — —
$\langle n\ ^3P_2 \vert V \vert n\ ^3F_2\rangle$	+1.39	— — —	— — —
$\langle n\ ^1D_2 \vert V \vert n\ ^1D_2\rangle$	−0.93	−1.34	— — —
$\langle n\ ^1D_2 \vert V \vert n+1\ ^1D_2\rangle$	−1.04	— — —	— — —
$\langle n\ ^3D_1 \vert V \vert n\ ^3D_1\rangle$	+2.77	+3.76	— — —
$\langle n\ ^3D_1 \vert V \vert n+1\ ^3D_1\rangle$	+2.88	— — —	— — —
$\langle n\ ^3D_2 \vert V \vert n\ ^3D_2\rangle$	−4.04	−4.45	— — —
$\langle n\ ^3D_2 \vert V \vert n+1\ ^3D_2\rangle$	−3.97	— — —	— — —
$\langle n\ ^3D_3 \vert V \vert n\ ^3D_3\rangle$	−0.30	−0.55	— — —
$\langle n\ ^3D_3 \vert V \vert n+1\ ^3D_3\rangle$	−0.37	— — —	— — —
$\langle n+1\ ^3D_3 \vert V \vert n\ ^3G_3\rangle$	−1.44	— — —	— — —
$\langle n\ ^3D_3 \vert V \vert n\ ^3G_3\rangle$	−2.02	— — —	— — —
$\langle n\ ^1F_3 \vert V \vert n\ ^1F_3\rangle$	+0.74	— — —	— — —
$\langle n\ ^3F_2 \vert V \vert n\ ^3F_2\rangle$	−0.14	— — —	— — —
$\langle n\ ^3F_3 \vert V \vert n\ ^3F_3\rangle$	+0.56	— — —	— — —
$\langle n\ ^3F_4 \vert V \vert n\ ^3F_4\rangle$	−0.08	— — —	— — —
$\langle n\ ^1G_4 \vert V \vert n\ ^1G_4\rangle$	−0.15	— — —	— — —
$\langle n\ ^3G_3 \vert V \vert n\ ^3G_3\rangle$	+0.41	— — —	— — —
$\langle n\ ^3G_4 \vert V \vert n\ ^3G_4\rangle$	−0.86	— — —	— — —
$\langle n\ ^3G_5 \vert V \vert n\ ^3G_5\rangle$	+0.13	— — —	—

Modified Sussex matrix elements.

fm^2) occur at 76.4 and 80.0 MeV, respectively. These three peaks dominate the calculated ^{4}He (γ, p) $E3$ cross section. The 71.0 MeV cross section peak is narrow and this narrow width may complicate experimental detection. The secondary peaks are likely to appear as a broad cross section enhancement between 76 and 80 MeV. These features suggest ranges for experimental investigation. Since these cross section features are highly dependent on the model level properties (energy, width, and wave function), experimental data would provide considerable insight into the model's validity at energies well above the known levels of Fiarman and Meyerhof[7].

6. *Variability of results to the model input parameters*

The sensitivity of the model energy and width predictions in terms of the model interaction parameters has been presented in Refs. 27, 28 and 43. For example, the variation of the energy level position as a function of the oscillator length parameter (b) was discussed in Ref. 43. Using Eq. (11), the $b = 1.4$, 1.6 and 1.8 fm calculations led to ground state binding energies of 28.4, 28.3 and 28.3 MeV, respectively. Excited states are typically found to vary by as much as 5 MeV when the $b = 1.4$ or $b = 1.8$ fm results are compared with the $b = 1.60$ fm results. However, the variation is typically 2.0 MeV or less. In a similar fashion, level width vary by as much as a factor of 2.5.

Using these values, estimates of the $E3$ cross section variation may be made. By penning energy and width variations

$$E_R' = E_R \pm 5.0 \text{ MeV} \tag{14}$$

$$\Gamma_R' = 2.5\,\Gamma_R, \tag{15}$$

the cross section uncertainty (u) may be defined

$$u = \frac{\sigma_{E3}(E, E_R', \Gamma_R')}{\sigma_{E3}(E, E_R, \Gamma_R)}. \tag{16}$$

Model calculations indicate that the E_R' and Γ_R' values of Eqs. (14) and (15) lead to a maximum value of $u = 2.2$. More typical input parameter induced variations of 2 MeV in the level energy and 50% in the level width lead to a value of $u = 1.6$. These results imply that the input parameters can cause the cross section results to vary by a factor of 1.6 to 2.2. However, the calculated results derived from optimized parameters[27] are expected to be considerably closer to the actual experimental values. This expectation has been demonstrated in previous ^{4}He structure and photonuclear studies[13,17–19,27,28–31,36,41–43].

7. *Conclusions*

The R-matrix model predicts a series of distinct peaks in the ^{4}He (γ, p) $E3$ cross section. The dominant peak ($4.69 \cdot 10^{-3}$ fm^2) is expected to occur at 71.0

MeV and secondary peaks ($1.84 \cdot 10^{-3}$ and $1.82 \cdot 10^{-3}$ fm^2) are expected at 76.4 and 80.0 MeV, respectively. Experimental data are needed to better define the $E3$ cross section. These data would provide important information regarding the validity of theoretical wave functions and energy level and width predictions. $E3$ data would also help to refine theoretical models and improve upon their shortcommings.

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STRUKTURNI EFEKTI U $_{\Lambda}{}^{4}$He$(\gamma, \mathrm{p})^{3}$H $E3$ UDARNOM PRESJEKU

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Koristeći generaliziranu metodologiju R matrice Lanea i Robsona razmatrana je ^{4}He oktupolna rezonancija u reakciji ^{4}He(γ, p). Račun R matrice iskorišten je također za proračun $J^{\pi} = 3^{-}$ rezonancije koja dominira u $E3$ udarnom presjeku. Izračunati maksimum u ^{4}He(γ, p) $E3$ udarnom presjeku je na $4{,}69 \cdot 10^{-3}$ fm^{2} za energiju pobuđenja od 71,0 MeV. Sekundarni maksimumi pojavljuju se na 76,4 MeV ($1{,}94 \cdot 10^{-3}$ fm^{2}) i na 80,0 MeV ($1{,}82 \cdot 10^{-3}$ fm^{2}).