Is There a Pronounced Giant Dipole Resonance in ^{4}He?

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A four-nucleon calculation of the total ^{4}He photodisintegration cross section is performed. The full final-state interaction is taken into account for the first time. This is achieved via the method of the Lorentz integral transform. Semirealistic *NN* interactions are employed. Different from the known partial two-body $^4\mathrm{He}(\gamma,n)^3\mathrm{He}$ and $^4\mathrm{He}(\gamma,p)^3\mathrm{H}$ cross sections our total cross section exhibits a pronounced giant resonance. Thus, in contrast to older (γ,np) data, we predict quite a strong contribution of the (γ,np) channel at the giant resonance peak energy. [S0031-9007(97)03284-5]

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The photodisintegration of ^{4}He has received much attention in the last 25 years. Experimental work concentrated mainly on the two dominant two-body breakup channels ($^3\mathrm{He}+n$, $^3\mathrm{H}+p$). In a first round of experiments a rather strong peak of the giant dipole resonance was found, while more recent experiments find a much less pronounced peak. The suppression of the two-body breakup peak was confirmed in four-nucleon calculations that take into account the important final-state interaction (FSI) via a semirealistic *NN* potential [1,2]. Much less is known about the total α photoabsorption cross section ($^4\mathrm{He}+\gamma\rightarrow X$). In the vicinity and beyond the peak there are neither theoretical calculations that take into account FSI nor experimental total cross section measurements.

The situation for the ^{4}He photodisintegration seems to be settled only for the two-body breakup channels at lower energies. Yet the results are rather puzzling because it is not understood why the α particle should have such a suppressed giant dipole resonance. Cross sections for transitions to other channels $(\gamma,pn)d$, $(\gamma,2p2n)$, and $(\gamma,d)d$ obtained in the older experiment [3,4] are very small and cannot influence the general picture at all. Furthermore, the new $(\gamma,p)^3\mathrm{H}$ and $(\gamma,n)^3\mathrm{He}$ data combined with those cross sections would lead to a bremsstrahlung weighted sum over the photoabsorption spectrum which is substantially lower than the well known model-independent sum rule estimate. A theoretical calculation of the total photoabsorption cross section would certainly help to get a better understanding of these problems, since the giant resonance is in principle a feature of the total cross section.

In the present work the theoretical calculation of the total cross section is carried out with consideration of the full FSI. Previously the FSI was taken into account completely only below the three-body $p+n+d$ breakup threshold $E_\gamma=26.1$ MeV [1,2]. For the two-body breakup the resonating group calculation of Ref. [1] was extended to somewhat higher energies taking into account FSI due to other channels approximately. At $E_\gamma>50$ MeV the two-body reactions were treated in the plane-wave approximation [2].

We calculate the total photoabsorption cross section in the whole energy range below the pion threshold. We consider the *E*1 transition in the long-wavelength limit using the unretarded dipole transition operator

$$\vec{D}=\sum_{i=1}^{Z}(\vec{r}_i-\vec{R}_{cm}).$$

In this way we take into account meson exchange currents via the Siegert theorem. The *E*2 contributions to the total cross section are small even at high photon energy [2], and they tend to cancel with the *E*1 retardation contributions [5]. Our nuclear Hamiltonian includes central even local *NN* potentials and the Coulomb interaction.

We can write down the total photoabsorption cross section as

$$\sigma_{\mathrm{tot}}(E_\gamma)=4\pi^2(e^2/\hbar c)E_\gamma R(E_\gamma),$$

where R is the dipole response function,

$$R(E_\gamma)=\int df|\langle\Psi_f|D_z|\Psi_0\rangle|^2\delta(E_f-E_0-E_\gamma).$$

Here Ψ_0 is the α-particle wave function and Ψ_f are final-state wave functions normalized as $\langle\Psi_f|\Psi_{f'}\rangle=\delta(f-f')$. In the above relations we neglect the very small nuclear recoil energy. We calculate the response function R via evaluation and subsequent inversion of its Lorentz integral transform, a method we proposed for the response of an arbitrary N particle system to an external probe [6]. The method has already been successfully applied for obtaining the accurate longitudinal (e,e') response functions of the two-, three-, and four-nucleon systems [6–8]. The transform $\mathcal{L}(\sigma)$ of the response R is found as

$$\mathcal{L}(\sigma)=\langle\tilde{\Psi}(\sigma)|\tilde{\Psi}(\sigma)\rangle, \tag{1}$$

$\tilde{\Psi}$ being the solution to the Schrödinger-like equation

$$(\hat{H} - E_0 + \sigma)\tilde{\Psi}(\sigma) = Q, \quad (2)$$

with the source term $Q = D_z\Psi_0$. The function $\tilde{\Psi}$ is localized and continuum calculations are thus avoided in our approach.

We use the same NN potential model, Trento (TN) potential, as in our work on the longitudinal response function [8]. We also consider the Malfliet-Tjon (MT) I + III potential [9], which was used in Ref. [2] for calculating the reaction $\gamma + {}^4\text{He} \rightarrow {}^3\text{He} + n$. We use the value of $\lambda = 1.555\ \text{fm}^{-1}$ entering the attractive part of the MT potential as listed in Ref. [10]. This value just leads to correct low-energy parameters of NN scattering as given in Ref. [9]. In some ^{4}He bound-state calculations the value $\lambda = 1.55\ \text{fm}^{-1}$ listed in Ref. [9] has been used that leads to an increase in the $E_b({}^4\text{He})$ value by about 1.4 MeV.

Our α-particle wave function Ψ_0 is an eigensolution for the same NN potential. The corresponding matter rms radia and binding energies are 1.41 fm and 30.5 MeV for the TN potential, and 1.43 fm and 29.2 MeV for the MT potential. The latter value is close to those reported in the literature, see Ref. [2]. The binding energies are reasonable as compared to the experimental value of 28.3 MeV, and the radia are close to the experimental value of 1.45 fm.

In Fig. 1 we show the s-wave phase shifts (no Coulomb interaction included for ${}^1S_0$) of both potential models in comparison to those of a realistic interaction (Paris potential [11]). It is evident that MT and TN potentials do not lead to significantly different phase shifts than the Paris potential. The ${}^1S_0$ scattering length equals -17.9 fm for the TN potential and -23.3 fm for the MT potential, so the MT potential is a little bit more attractive in the ${}^1S_0$ channel than the TN potential. The TN scattering length is close to the value of nn and pp (no Coulomb force) scattering [$a_{nn}({}^1S_0) = -17.6$ fm for Paris potential], while the MT scattering length is close to that of np scattering [$a_{np}({}^1S_0) = -23.7$ fm].

We solve Eq. (2) for $L = T = 1$ and $S = 0$ with the help of the correlated hyperspherical expansion and the hyperradial expansion of the same form as in Ref. [8]. The $K_{\max}$ value equals 7. The σ value in Eqs. (1) and (2) is of the form $-\sigma_R + i\sigma_I$ with $\sigma_I = \text{const}$, and the values of $\sigma_I = 20$ and 5 MeV have been employed. In Fig. 2 the convergence of the transform, Eq. (1), with respect to $K_{\max}$ is shown for $\sigma_I = 20$ MeV for the MT potential. While inverting the transform the true low-energy behavior $[E_\gamma - (E_\gamma)_{\min}]^{3/2}$ has been incorporated into our trial response. The inversion has been performed both for $\sigma_I = 20$ MeV and for a combination of the transforms with $\sigma_I = 5$ and 20 MeV chosen so that the former transform gives a predominant contribution to the very steeply rising low-energy wing of the response and the latter ones to its high-energy wing. The responses obtained in these two versions practically coincide with each other. The transforms in Fig. 2 with $K_{\max} = 5$ and 7 lead to practically identical responses, and that for $K_{\max} = 3$ is also not very different. For the TN potential one finds a similarly good convergence in $K_{\max}$ as well.

Besides the checks of the convergence, the overall test of the final results is provided by sum rule calculations. We compare the bremsstrahlung weighted sum $\sigma_b = \int_{E_\gamma^{th}}^{\infty} \sigma_{\text{tot}}(E_\gamma) E_\gamma^{-1}\, dE_\gamma$ and the TRK sum $\sigma_{\text{TRK}} = \int_{E_\gamma^{th}}^{\infty} \sigma_{\text{tot}}(E_\gamma)\, dE_\gamma = 59.74(1 + \kappa)$ MeV mb calculated

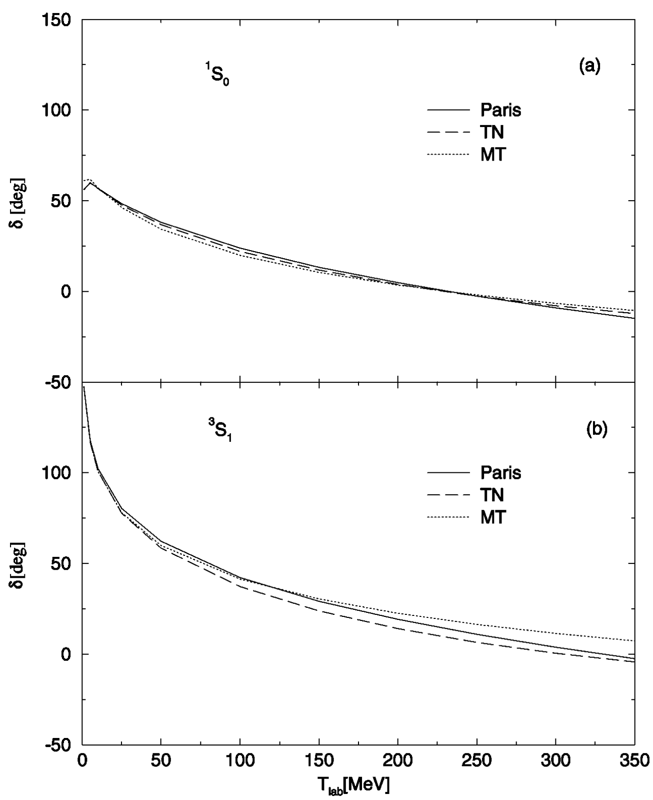

FIG. 1. NN scattering phase shifts of the partial waves ${}^1S_0$ (a) and ${}^3S_1$ (b) for the following potentials: TN (dashed curves), MT (dotted curves), and Paris (full curves).

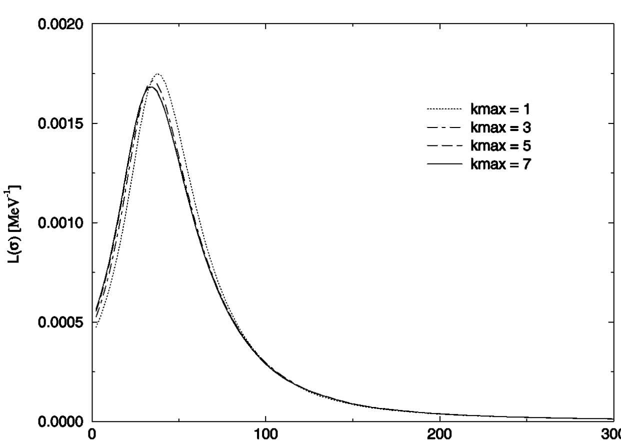

FIG. 2. The Lorentz transform for the MT potential with various $K_{\max}$ values.

with our cross sections with an independent calculation of these quantities using the sum rules $[\sigma_b = 4\pi^2(e^2/\hbar c) \times \langle\Psi_0|D_z D_z|\Psi_0\rangle, \quad \kappa = \langle\Psi_0|[D_z,[V,D_z]]|\Psi_0\rangle(m/\hbar^2)A/NZ]$. The sum rule values are $\sigma_b = 2.41$ mb, $\kappa = 0.727$ for the TN potential and $\sigma_b = 2.48$ mb, $\kappa = 0.684$ for the MT potential. By integrating our cross sections explicitly we obtain $\sigma_b = 2.40$ mb, $\kappa = 0.754$ for the TN potential and $\sigma_b = 2.48$ mb, $\kappa = 0.712$ for the MT potential. The agreement of the σ_b values with the sum rules is perfect that reflects a good accuracy of the low-energy wings of the responses obtained. The resulting relative deviations from the TRK sum rule are about 1.5% for both potentials.

One may note that the κ values for the potentials we use are lower than those provided by fully realistic *NN* interactions. The latter values range from 1.0 to 1.3 [12–14], thus we underestimate $\sigma_{\rm TRK}$ by 15%–25%. We believe that the main part of the missing strength should lead to an increase of the cross section at higher energies, while our potential models should provide quite realistic results up to the pion threshold. In fact, a rough estimate of σ_b, which we performed for realistic *NN* interactions, is close to the σ_b values for our potentials. In any case, an increase in the κ value would only strengthen our conclusions about the strong (γ, np) cross section which we predict below.

At this point we should mention that our calculation is performed consistently with our semirealistic Hamiltonians; i.e., applying the Siegert theorem we use the energy eigenvalues of the Hamiltonian. However, for comparison with experiment we perform the shift $\sigma_{\rm tot}(E_\gamma) \to \sigma_{\rm tot}(E_\gamma + \Delta E_b)$, ΔE_b being the difference of the calculated and experimental binding energies. In this way we obtain the proper breakup threshold thus correcting for some overbinding of our α particle.

Unfortunately there are no direct experimental data on the ^{4}He total photoabsorption cross section. Nevertheless we would like to make a comparison with experimental data. Therefore we proceed as follows. For the low-energy region we make interpolations of the (γ, n) data from [15] and the (γ, p) data from [16] and sum up the resulting (γ, p) and (γ, n) cross sections (dotted curves in Figs. 3 and 4). Since the $(\gamma, d)d$ cross section can be safely neglected (see, e.g., [17]) this should lead to a rather good estimate for the total cross section below the three-body breakup threshold. Furthermore, we also show the cross sections of other low-energy experiments [18–20]. Assuming that (γ, p) and (γ, n) cross sections are more or less equal we double the experimental cross sections in order to have further estimates for the two-body breakup. Beyond 26.1 MeV they represent lower experimental bounds for the total cross section. In Fig. 3 these estimates are shown together with the calculated cross sections for MT and TN potentials. There is a rather good agreement of our responses with the estimated experimental two-body cross section up to the three-body breakup threshold. The MT potential leads to a slightly higher low-energy cross section than the TN potential that may be related to the somewhat stronger attraction in the *NN* $^1S_0$ channel. For the MT potential we find a similar agreement with experimental data as was found in [2] for the same potential model for the $(\gamma, n)^3$He channel.

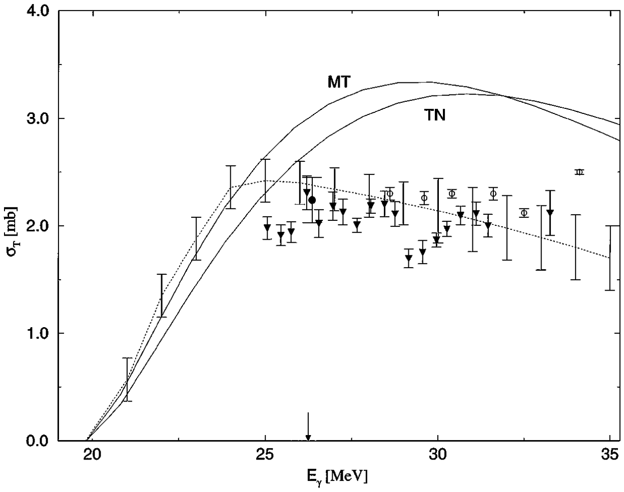

FIG. 3. Theoretical results for the total ^{4}He photoabsorption cross section at low energy with MT (dashed curve) and TN potentials (full curve). Also shown is the estimate for the two-body breakup (dotted curve with typical size of the experimental error), which is based on the experimental results of Refs. [15,16] as well as doubled experimental cross sections for (γ, p) [19] (open circles) and for (γ, n) [18] (triangles) and [20] (full circles) (for further explanation see text). The three-body breakup threshold is marked by an arrow.

Beyond the three-body breakup threshold our cross sections reveal further increase. Since theoretical as well as experimental results for the (γ, p) and (γ, n) cross sections

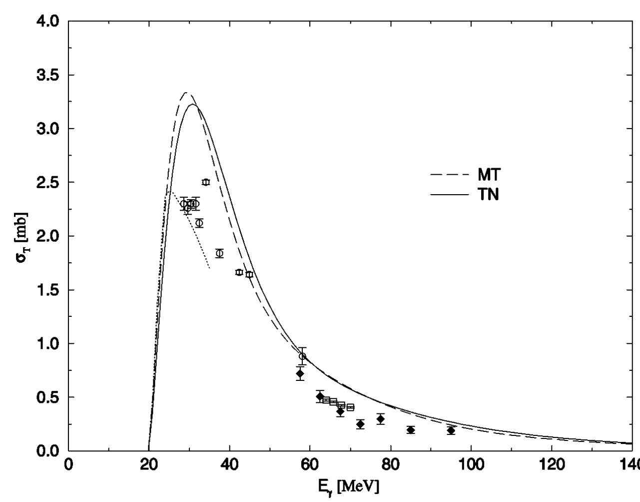

FIG. 4. As Fig. 3, but for an extended energy range up to 140 MeV. Estimate for lower experimental bound (dotted curve) and additional lower bound estimates with data from [3] (diamonds), [19] (open circles), and [21] (squares) (for further explanation see text).

show a flattening beyond the three-body threshold, the further increase has to be attributed to (γ, np) reactions. Thus the (γ, np) channel increases the peak of the giant dipole resonance considerably. As can be seen in Fig. 4 it leads to a rather pronounced resonance peak. Also in the high-energy sector we show lower experimental bounds for the total cross section. They consist of the sum of the $(\gamma, p)^3$H and $(\gamma, n)^3$He cross sections from Ref. [3] and the doubled $(\gamma, p)^3$H data from Ref. [21]. From the comparison of these estimates with our theoretical total cross sections one would expect quite an important contribution of the (γ, np) channel in the whole energy range.

Finally, we summarize our work. For the first time the total cross section of the α-particle photodisintegration was calculated in the framework of four-nucleon dynamics with full FSI. The results show a very pronounced peak of the giant dipole resonance. Therefore it seems that a typical many-body feature emerges also from a genuine few-body calculation of the four-nucleon system. The peak is considerably higher than the sum of the cross sections of the two important two-body breakup channels (^{3}H + p, ^{3}He + n). Thus we predict quite a strong contribution of the (γ, np) channel already at rather low energies. More experimental work is needed to confirm this prediction. At present some data on (γ, np) with high statistics are available only beyond 80 MeV [22], while the energy range between three-body breakup threshold and 80 MeV remains to be explored.

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