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Implications of the experimental results on the photodisintegration of ^{4}He

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The photoproton and photoneutron cross sections for ^{4}He are evaluated in the light of several recent measurements, and are found to be substantially different in the energy region below 30 MeV. Because these cross sections are dominated by $\Delta S=0$, $\Delta T=1$ $E1$ transitions, this result implies strong isospin mixing in the four-nucleon system. Furthermore, since available continuum shell-model calculations including Coulomb effects predict only small differences in the photoproton and photoneutron cross sections except near threshold, this result suggests that a nonzero charge asymmetry is present in the nuclear force.

[NUCLEAR REACTIONS ^{4}He$(\gamma,p)^3$H, ^{4}He$(\gamma,n)^3$He, evaluated cross sections, cross-section ratio; isospin mixing, charge asymmetry.]

I. INTRODUCTION

The charge symmetry of the nuclear force[1] has been considered by many physicists over the years (see, for example, Refs. 2–4). Up to now, however, there has not been any clear-cut case for a nonzero charge-asymmetric component. This has been so for a variety of reasons, both experimental and theoretical, including the calculational difficulties in obtaining the amount of charge asymmetry which results exclusively from the effects of the electromagnetic (rather than the strong) interaction.

Photonuclear reactions offer the possibility of extracting a small but nonzero charge asymmetry from experimental observations of the decay branches of the giant dipole resonance (GDR) for self-conjugate nuclei,[5–7] because of the extreme sensitivity of the cross sections to the degree of isospin mixing.[7,8] In particular, for such nuclei, the ratio of the photoproton to photoneutron cross sections R is given by

$$R=\frac{\sigma(\gamma,p)}{\sigma(\gamma,n)}=\frac{P_p(E_p)}{P_n(E_n)}\frac{|a_{T=1}+a_{T=0}|^2}{|a_{T=1}-a_{T=0}|^2}\ , \qquad (1)$$

where P_p (P_n) are the penetrabilities for the proton (neutron) emission and a_T are the (complex) reaction amplitudes for the isospin $T=0$, 1 channels. For unretarded electric-dipole transitions the $T=1$ channel is the isospin-conserving one; the $T=0$ channel arises from isospin mixing. Contained within these amplitudes are $S=0$ (non-spin-flip) and $S=1$ (spin-flip) amplitudes, so that the cross sections and ratio in Eq. (1) involve amplitudes a_{TS}. Two observations are important here[7]: (a) care must be taken to eliminate the spurious center-of-mass motion from the calculation of the electric-dipole contribution to the amplitude a_{00}; and (b) if the $S=1$ (spin-flip) amplitudes are negligible, as is usually the case (see below), then Eq. (1) reduces to the form published in Ref. 7.

For light nuclei, the penetrabilities, resulting from both Coulomb- and angular-momentum-barrier effects, become nearly equal a few MeV above the photonucleon thresholds. Furthermore, the contribution from the $S=1$ channels is usually considered to be negligible. Therefore, with these simplifications Eq. (1) can be written

$$R=\frac{1+2D}{1-2D}\ , \qquad (2)$$

where

$$D=\frac{1}{2}\frac{R-1}{R+1}=\frac{\mathrm{Re}\{a_{00}/a_{10}\}}{1+|a_{00}/a_{10}|^2} \qquad (3)$$

is a function of energy obtained directly from the experimental values for R. Furthermore, we may write the isospin-mixing ratio in the form

$$a_{00}/a_{10}=\epsilon e^{i\phi} ,$$

with ϵ and ϕ real, and so also obtain

$$D=\frac{\epsilon\cos\phi}{1+\epsilon^2} . \tag{4}$$

This establishes a relationship between the amplitude ϵ and phase ϕ of the mixing ratio a_{00}/a_{10} (ϕ is the relative phase of a_{00} and a_{10}) and the experimental quantity R. Note that even relatively small isospin mixing can result in significant deviations of R from unity. For example, if $D=0.1$, Eq. (2) yields $R=1.5$. Thus R is sensitively dependent upon isospin-mixing effects.

For the ^{4}He nucleus, the situation is especially favorable. The isospin of the ground state is very pure (the lowest-lying $T=1$ state is located[9] at 26.4 MeV, and J^π for this state is 2^-). The (γ,p) and (γ,n) thresholds are high and close together (19.8 and 20.6 MeV, respectively). The penetrabilities are nearly equal above $\sim$25 MeV; P_p/P_n for p-wave nucleons has been calculated to be 1.075 at 25 MeV and 1.04 at 28 MeV excitation energy.[10] The photon absorption cross section, at least below $\sim$35 MeV, clearly is dominated by $E1$ transitions (to two broad $J^\pi=1^-$, $T=1$ states; there is one broad $J^\pi=1^-$, $T=0$ state in this energy region[9]); the $E2$ strength in this energy region has been measured to be $\sim$6% of the $E1$ strength in the (γ,p) channel, and is perhaps even smaller in the (γ,n) channel (see, for example, Refs. 9 and 11). Moreover, all photonuclear reaction channels other than the (γ,p) and (γ,n) processes are of negligible importance, even up to $\sim$40 MeV.[12] Hence, it is not surprising that numerous attempts have been made to measure the (γ,p) and (γ,n) cross sections for ^{4}He, especially since the publication of Ref. 13, which indicated a large value of R and thus a significant nonzero charge asymmetry.

However, with the assumption, usually made, that the ground state of ^{4}He is a pure $(1s)^4$ shell-model configuration, it is expected that the amplitude a_{00} results entirely from center-of-mass motion. Therefore, to the extent that a_{00} does not contribute to the (γ,p) and (γ,n) reactions, then Eq. (1) reduces to

$$R=\frac{P_p(E_p)}{P_n(E_n)}\frac{|a_{10}|^2[1+\alpha_p(S=1)]}{|a_{10}|^2[1+\alpha_n(S=1)]} \tag{5a}$$

or

$$R=\frac{P_p(E_p)}{P_n(E_n)}\frac{1+\alpha_p(S=1)}{1+\alpha_n(S=1)} , \tag{5b}$$

where the $\alpha_{p,n}(S=1)$ account for the (small) effects stemming from the spin-flip amplitudes. Measurements of the spin-flip amplitudes relative to the amplitude a_{10} with the ^{3}H$(\vec{p},\gamma)^4$He reaction[14] have indicated that

$$|a_{11}+a_{01}|^2/|a_{10}|^2\lesssim 0.02 .$$

Thus it would be expected that, except for possible variations in the penetrabilities (which occur only near threshold), the ratio R should be very close to unity, i.e., $R\lesssim 1.02\, P_p/P_n$.

Recently, we have reported new measurements of $\sigma(\gamma,p)$ and $\sigma(\gamma,n)$ for ^{4}He (Refs. 15 and 16, respectively); the results of another new measurement of $\sigma(\gamma,n)$ at the Triangle Universities Nuclear Laboratory (TUNL) now are available as well.[17] These new measurements also indicate a large value for R below $\sim$30 MeV, whereas previous measurements of R between about 30 and 50 MeV (particularly Refs. 18 and 19) have yielded results (below about 40 MeV, at least) not appreciably different from unity. In addition, all previous measurements of these cross sections up to 50 MeV have been reviewed in Refs. 15 and 16. It is the main function of this paper to present an evaluation of these experimental results and thus to recommend values for the cross sections. From these cross sections we then can derive R as a function of photon energy. If we then allow for some mechanism (such as the inclusion of open-shell effects) to produce a small but nonzero reaction amplitude a_{00}, then Eq. (4) enables us to estimate the energy dependence of the isospin-mixing ratio a_{00}/a_{10} for the four-body system. If, however, at any energy $|a_{00}/a_{10}|^2$ exceeds the amount that can be accounted for by the Coulomb force alone (which is probably no more than a few tenths of a percent[20]), then the balance must owe its origin to a charge-asymmetric component of the nuclear force.

II. EVALUATIONS

Our recommended values for the (γ,p) and (γ,n) cross sections for ^{4}He are shown as the solid lines in Fig. 1, with our estimates of the uncertainties shown as shaded error bands. Also shown are the results of the three recent measurements: the two (γ,p) data points from the ^{3}H(p,γ) measurement at Stanford[15] in Fig. 1(a), and the (γ,n) data from the ^{4}He(γ,n) measurement at Livermore[16] and from the ^{3}He(n,γ) measurement at TUNL (Ref. 17) in Fig. 1(b). All the previously published cross-section data can be found in Refs. 15—17.

The evaluated ^{4}He(γ,p) cross section shown in Fig. 1(a) relies most heavily upon the ^{3}H$(p,\gamma)^4$He capture data[15,21–25] in the region below $E_\gamma\simeq$38 MeV. Above 38 MeV it agrees both with the cap-

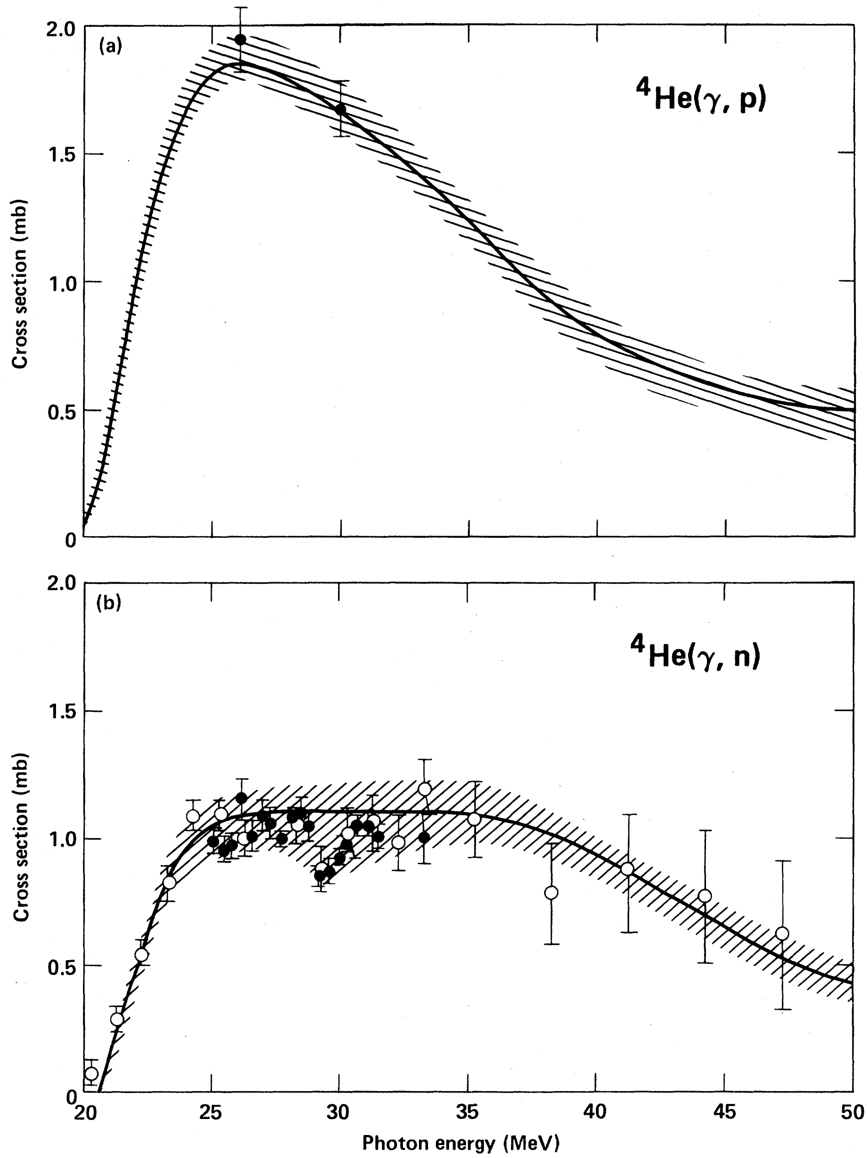

FIG. 1. Evaluated (a) $^4He(\gamma,p)$ and (b) $^4He(\gamma,n)$ cross sections (solid lines). The shaded bands indicate our estimates of the uncertainties in the individual cross sections. All of the data upon which these evaluations are based can be found in Refs. 15—17. The new data from Refs. 15—17 are shown here as well: data points in (a) Ref. 15; open circles in (b) Ref. 16; closed circles in (b) Ref. 17. It can be seen in (b) that the data of Refs. 16 and 17, although obtained independently, agree with each other nearly perfectly. Discrepancies with the results of earlier measurements are discussed in the text.

ture results from TUNL (Ref. 25) and with most of the data from $^4He(\gamma,t)^1H$ (Refs. 18 and 26—29) but is lower than the phototriton data from Saskatchewan,[30] while it is higher than the (γ,t) results from Torino[31] between 38 and 42 MeV but in agreement above 42 MeV. Below 38 MeV our recommended cross section is in agreement with all the capture results[15,21—25] and with the phototriton results from the National Bureau of Standards (NBS),[18] Moscow,[26] and Saskatchewan[30] but higher than the results from Yale[28] and Torino.[31] The data from Kharkov[27] are low below 31 MeV but in agreement at higher energies. Because of the excellent consistency of the capture results and their agreement with at least half of the (γ,t) results below 30 MeV, and because of the inconsistency of the phototriton cloud-chamber results[26,27,31] below $\sim$35 MeV (this inconsistency, which leads us to conclude that the technique is much less reliable at low charged-particle energies,[15] is discussed below), the error band reflects mainly the scatter in the capture data in this region. Above 38 MeV, the percentage width in the error band increases, which reflects the larger scatter in the phototriton results. Finally, we have used no photoproton data for which a triton was not observed and identified, either by the use of a spectrometer or by unambiguous coincidence with a proton. While there are definite inconsistencies even in the phototriton data at low energies, the results from single-proton detection exhibit enormous disagreements not only in magnitude but also in energy dependence. These are discussed in detail in Ref. 15.

The evaluated ^{4}He(γ,n) cross section shown in Fig. 1(b) relies most heavily upon the recent Livermore[16] and TUNL (Ref. 17) data, which are seen to be in excellent agreement with each other despite having been obtained at different laboratories using different techniques. Also, the authors of both Refs. 16 and 17 did their work knowing of the previous results and controversies, and thus made special effort to reduce as much as possible their systematic uncertainties. Moreover, these two efforts were completely independent; not until after both sets of results were obtained did the authors of Refs. 16 and 17 learn of each other's measurements.

The evaluated (γ,n) cross section is in good agreement with the earlier data from Livermore,[32] Yale,[33] and Toronto[34] (see below) at energies lower than $\sim$28 MeV, but takes into account other data as well, particularly at the higher energies. The evaluated cross section also is constrained to contain no structure; this feature is particularly significant in the energy regions near 30 and 43 MeV. The evaluated cross section agrees, within the uncertainties shown in Fig. 1(b), with the new data of Refs. 16 and 17 at all energies. In the most critical region, from 25 to 27 MeV, the evaluation passes through these data. Near 29 MeV, where the data show an apparent dip, the evaluation is somewhat higher (in order that it contain no structure); if it were not, the (γ,p)-to-(γ,n) ratio would be still larger there.

Below $\sim$24 MeV, the evaluated (γ,n) cross section agrees as well with the ^{3}He(n,γ) datum from Pennsylvania[35] and is lower than the ^{4}He(γ,n) data from Pennsylvania[36] and Torino.[37] Between 24 and $\sim$27.5 MeV it agrees with the data from Yale,[33] Pennsylvania,[36] and Torino[37] and with those from Toronto[38] if the last are not renormalized (see Refs. 16 and 39), and is lower than the data from Moscow,[26] Torino,[31] Saskatchewan,[40] and Kharkov[41] and those from Toronto[38] if they *are* renormalized. Between 27.5 and $\sim$31 MeV it is lower than the data of Refs. 26, 31, 37, 40, 41, and 38 (if renormalized), and is higher than the data of Refs. 32, 33, and 38 (if not renormalized). Between 31 and $\sim$35 MeV it agrees with the data of Refs. 18, 26, and 37, and is lower than the data of Refs. 40 and 41. Between 35 and $\sim$50 MeV it agrees with the data of Refs. 26, 31, 37, 40, and 41, and is higher than the data from NBS (Ref. 18) and Queens.[42] In the energy region near 50 MeV it agrees with all the data considered, namely, those of Refs. 16, 18, 26, 30, and 40—42.

The existence of a dip in the ^{4}He(γ,n) cross section at $\sim$30 MeV is supported by the data of Refs. 16, 17, 31—33, 37, and 38. The possible structure [and the discrepancies between data sets (see the discussion in Ref. 16)] is reflected by the broadened error band near 30 MeV. The existence of a broad bump in the (γ,n) cross section near $\sim$43 MeV is suggested by the data of Refs. 16, 31, and 37 as well as by the cross-section-ratio data from Livermore.[19] This possible structure is shallow and the error band near 43 MeV is sufficiently large to contain it.

Because the results of the cloud-chamber measurements (Refs. 26, 27, 31, and 41) are strikingly inconsistent with each other below $\sim$35 MeV, both for the (γ,p) and (γ,n) reactions, it is clear that one cannot attach much weight to the disagreements between these results and our recommended cross sections below that energy. The previous reviews of the (γ,p) and (γ,n) cross sections (Refs. 15 and 16, respectively) have concluded that the most likely source of these inconsistencies is the difficulty of observing the very short tracks of low-energy ^{3}H and ^{3}He ions.

The principal focus of this paper is the large difference between the (γ,p) and (γ,n) cross sections near 25 MeV, and there is relatively little disagreement between the recent and older (γ,p) cross-section data. Therefore, we must try to understand the discrepancies between the present evaluation of the (γ,n) cross section and the results of previous measurements, particularly those measurements which resulted in a (γ,n) cross section substantially larger than our evaluated one in this energy region, namely, those from Moscow,[26] Toronto (when renormalized),[38] Saskatchewan,[40] and Kharkov.[41] References 26 and 41 report $(\gamma,^3\mathrm{He})$ cloud-chamber measurements, which we consider to be generally untrustworthy below $\sim$35 MeV (^{3}He particles having energy <4 MeV) because of the aforementioned difficulties of detecting short single tracks near the beam; these data also exhibit large uncertainties and scatter. At energies >35 MeV, where the tracks are long enough to lessen the uncertainty, this inconsistency is reduced substantially. Reference 40 reports a neutron-time-of-flight measurement done with high-end-point bremsstrahlung which contains a large and uncertain component at the lower energies of neutrons emitted in the three-body and four-body breakup of ^{4}He at higher energies; in fact, it is pointed out in Ref. 15 that *all* the measurements which include three-body and four-body contributions yield results in this energy region that disagree with those for which the final state is known unambiguously to be two-body. Reference 38 reports a (γ,n_0) measurement done with a liquid-helium sample which gave a low cross-section result (Ref. 34), but which was renormalized to a (higher) gaseous-sample measurement because of the uncertainty of the liquid-helium density in a bremsstrahlung beam; we believe that the normalization constant used (1.9) is too large and probably should contain some energy dependence as well, but we have no obvious justification for our preference of the liquid-sample to the gaseous-sample result other than that the former is in good agreement with the data of Refs. 16, 17, 32, 33, 36, and 37 (and with our evaluation). We note, however, that the Yale experiment (Ref. 33) might have suffered from the same problem. We also note that the very old data from Pennsylvania (Refs. 35 and 36) bracket the present evaluation. Finally, the old Livermore data (Ref. 32) were analyzed without accounting for the (then unsuspected) falloff of the neutron-detector efficiency above the ^{12}C(n,α) threshold at $\sim$6 MeV (corresponding to $\sim$28 MeV in ^{4}He), which, if accounted for, would raise the cross section above this energy. But the old Livermore data did not suffer from any beam-dependent helium density, since the heat input into the liquid-helium sample from the annihilation-photon beam was microscopic; therefore, we believe the old Livermore data can be trusted up to $\sim$28 MeV, and these data agree very well with the present evaluation.

Our recommended values for the ^{4}He(γ,p) and ^{4}He(γ,n) cross sections are superposed in Fig. 2(a) [note the apparent crossover(s) at the higher energies]. Our recommended values for the ratio

$$R=\sigma(\gamma,p)/\sigma(\gamma,n)$$

are shown in Fig. 2(b), again with our estimated uncertainty shown as a shaded error band. The values for R and their uncertainties plotted here have been obtained from the cross sections of Fig. 1. Also shown in Fig. 2(b) are the cross-section-ratio data from NBS (Ref. 18) and Livermore.[19] Although the individual cross-section values from Ref. 18 were used in the evaluations of Fig. 1, the ratio results (as well as those from Ref. 19) were not used in the determination of R for Fig. 2(b). Therefore, it is significant that there is such good agreement between the data points and the curve of Fig. 2(b), particularly with the results of Ref. 19 near 43 MeV. [This is where R makes an excursion below unity, which means that $\sigma(\gamma,n)>\sigma(\gamma,p)$ there.] It is even more significant that the data of Refs. 18 and 19, which have been cited as evidence that R is never much larger than unity [even though there is a slight upward trend in R with decreasing energy (down to $\sim$31 MeV) in the data of Ref. 19], agree so well with an evaluation that yields a value of R equal to 1.7 near 25 MeV.

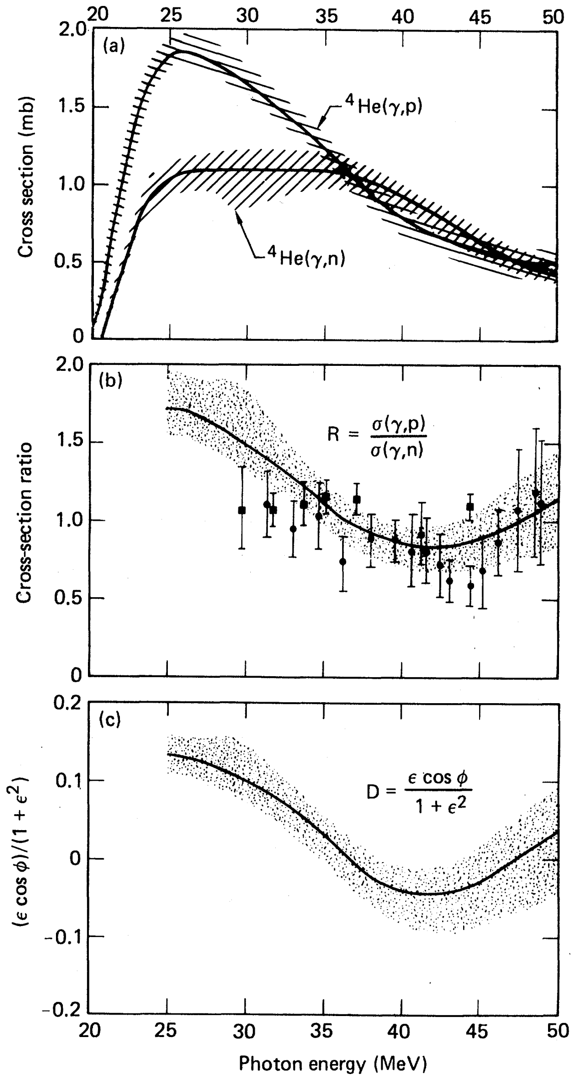

FIG. 2. (a) The evaluations of Fig. 1 superposed. (b) The ratio R of $\sigma(\gamma,p)$ to $\sigma(\gamma,n)$ for ^{4}He. The curve and shaded band have been obtained from the evaluated cross sections and uncertainties (the latter slightly smoothed) of Fig. 1. The experimental data points are from Ref. 18 (squares) and Ref. 19 (circles). (c) The function D of the isospin-mixing amplitude ratio a_{00}/a_{10} [Eq. (3)] and its uncertainty (shaded band) obtained from the curve and error band of (b) for the cross-section ratio R.

Figure 2(c) shows the values and uncertainties (the shaded error band) for

$$D=(\epsilon\cos\phi)/(1+\epsilon^2)$$

computed with Eq. (3) from the values and uncertainties for R [the curve of Fig. 2(b)]. It is seen that D varies smoothly, is 0.13 ± 0.03 near 25 MeV and 0.10 ± 0.03 at 30 MeV, changes sign at $\sim$36.6 MeV and again at $\sim$47.3 MeV, and reaches its largest negative value of -0.04 ± 0.03 at $\sim$43 MeV. Since the phase angle ϕ need not be zero everywhere (and undoubtedly is not), the resulting values for $|D|^2$ represent (and are nearly equal to) *minimum* values for

$$\epsilon^2=|a_{00}/a_{10}|^2\ ,$$

and this quantity reaches a value of 0.017 ± 0.007 near 25 MeV. Since this value clearly exceeds a few tenths of a percent (which is the most that can be accounted for, according to recent estimates, by electromagnetic effects[20]), one is led to conclude that most of the isospin mixing is probably caused by isospin-symmetry-breaking terms in the strong interaction. We note that this value is consistent with the small but statistically significant ($\sim$2%) differences between the ^{3}H$+n$ and ^{3}He$+p$ (corrected for Coulomb effects) total cross sections.[43,44]

III. THEORY

We now consider some of the theoretical work done on the ^{4}He(γ,p) and ^{4}He(γ,n) reactions. Several calculations of the cross sections for these reactions have been performed using continuum shell models.[45–49] For example, the work of Chung, Johnson, and Donnelly[45] (denoted CJD here) is an early attempt to study these reactions in a straightforward manner. There the ^{4}He ground state was taken to be a closed $1s_{1/2}$ shell, the final states were taken to be linear combinations of 1p-1h states (with the particles in the continuum), configuration-mixed by a zero-range effective interaction, and only isovector non-spin-flip $E1$ transitions were considered. One feature of this simple model is that the bound and continuum single-particle wave functions are computed using the same potential well, thus maintaining orthogonality and completeness for the states considered (see later comments on this point). In Fig. 3 we reproduce the results of this calculation for the (γ,p) and (γ,n) cross sections and their ratio (curves labeled CJD). Clearly the model is incapable of producing large differences in the two photonucleon reactions, since the only mechanism allowing this to happen under the assumptions made is via the different thresholds for the ^{3}H$+p$ and ^{3}He$+n$ channels. In fact, in this model the ratio R falls

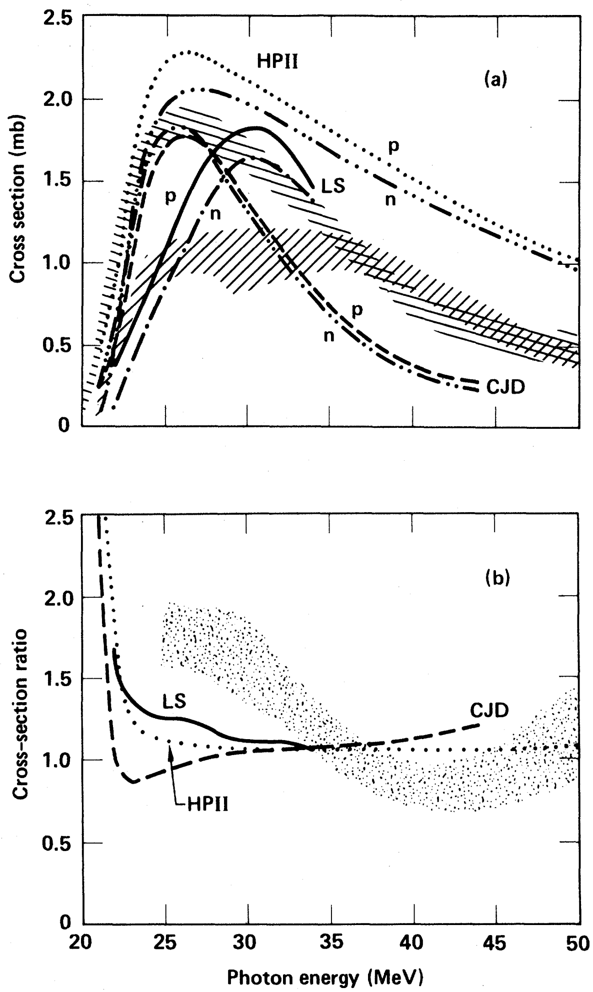

FIG. 3. (a) Comparison of the evaluated cross sections (shaded bands) with results of theoretical calculations: dashed and dash-dot-dotted lines, $\sigma(\gamma,p)$ and $\sigma(\gamma,n)$ from Ref. 45 (CJD); solid and dash-dotted lines, from Ref. 46 (LS); and dotted and dash-dot-dot-dotted lines, from Ref. 49 (Set II, HPII). (b) Comparison of the evaluated ratio R (shaded band) with results of theoretical calculations: dashed line, CJD; solid line, LS; and dotted line, HPII.

rapidly from threshold and becomes somewhat less than unity in the region around 23 MeV, in marked contrast to the behavior of the data [see Fig. 3(b)].

A more ambitious calculation was undertaken in the work of Londergan and Shakin[46] (denoted LS here) in which a coupled-channel continuum shell model was employed. There, channel-spin mixing and isospin mixing via the Coulomb interaction were incorporated into the model, and $E1$, $E2$, and $M2$ multipoles all were considered. Comparisons were made with nucleon-channel elastic and charge-exchange scattering, showing good agreement with measurements at higher energies (although only qualitative agreement at lower energies). The LS results for the (γ,p) and (γ,n) cross sections also are shown in Fig. 3, as is their result for the ratio R. One must conclude from this, that within the context of the model, only small differences between the (γ,p) and (γ,n) cross sections can be attributed to Coulomb mixing as well as threshold differences, and that the higher multipoles [for example, $E2$, which does differ for (γ,p) and (γ,n)] are relatively unimportant. In fact, LS find that if a low-lying resonance with $S=0$, $T=0$, and $J^{\pi}=1^-$ were to be present (this would apparently have 3p-3h components, since the 1p-1h configuration is spurious) and were mixed via the Coulomb interaction with the $S=0$, $T=1$ strength, then the resulting ratio R would be less than unity over a wide range of energies from near threshold to above 30 MeV.

Recently, a series of even more extensive calculations has been reported by Halderson and Philpott[47–49] (denoted HP here). These calculations also employ the continuum shell model but now with the center-of-mass problem corrected for (and called the recoil-corrected continuum shell model, RCCSM). In addition, a more complete NN interaction, containing noncentral components, was used. While this interaction was designed to work for systems heavier than $A=4$, in fact, when comparisons of nucleon-channel scattering predictions are made with existing data, generally excellent agreement is seen.[49] As for the LS calculations, Coulomb mixing has been included in the scattering states. The photonucleon cross sections obtained by HP also are shown in Fig. 3 (these are Set II taken from Ref. 49; the earlier results[47] must be corrected[48]). Once again, only relatively small differences between the (γ,n) and (γ,p) cross sections are seen to be attributable to the mechanisms contained in the model (Coulomb isospin mixing, threshold effects, effects of multipoles other than non-spin-flip unretarded $E1$). HP show results for a closed-$1s_{1/2}$-shell ^{4}He ground state (denoted HPI) and for a ground state with $ns_{1/2}$-$1s_{1/2}{}^{-1}$ $(n>1)$ components (denoted HPII). This latter modified ground state is not really a correlated one (that would contain, for example, 2p-2h configurations), but is a redefinition of the radial wave function for the bound $s_{1/2}$ single-particle state. Indeed, in Fig. 3 we show only this case; the other (HPI), with a closed $1s_{1/2}$ harmonic-oscillator shell, is $\sim 50\%$ higher still. This raises the question of the magnitude of the (γ,p) and (γ,n) cross sections themselves. If orthogonality is not maintained (as it was in the CJD calculation) it is possible to obtain widely differing photonuclear results even with ground-state wave functions which have been adjusted to fit a variety of ground-state properties (see Ref. 50 for a discussion of this point for the $A=3$ photonucleon cross sections). Be this as it may, as HP point out, the *ratio* of the (γ,p) and (γ,n) cross sections may be less subject to such considerations and, once again, we see that their model calculations do not yield the behavior seen in the experimental data [Fig. 3(b)].

One final model calculation should be mentioned: the bound-state calculation of Gibson.[51] In this calculation, the harmonic-oscillator shell model (with spurious states removed) was employed with a realistic NN interaction and with Coulomb mixing of the $S=0$, $T=0$ and 1 dipole states. As stated by Gibson, "by using effective interactions with parameters chosen to illustrate the point," it is possible to obtain significant $(T=0)$-$(T=1)$ mixing. He has obtained for the ratio of the integrated cross sections

$$\int \sigma(\gamma,p)dE \Big/ \int \sigma(\gamma,n)dE$$

the value 1.8. However, in a such a bound-state calculation, all of the strength is concentrated at specific energies. In the continuum shell-model calculations discussed above (LS and HP) the effect of the Coulomb mixing is dissipated owing to the broad nature of the resonances considered, and the cross-section ratio is found to be close to unity except near threshold.

We turn now to the total photonucleon cross section. The sum of the (γ,p) and (γ,n) cross sections is shown in Fig. 4. The shaded area is the *sum* of the evaluated (γ,p) and (γ,n) cross sections shown in Fig. 1. Also given are the summed theoretical curves from Refs. 45, 46, and 49 [including now the closed $1s_{1/2}$-shell curve (HPI)]. One might hope that, even if the p/n channel differences are not accounted for by the models, this total cross section might be in better agreement with experiment; however, this is evidently not the case. Weaker still might be the hope that the integrated cross sections, which are shown in Fig. 5, or energy-weighted integrated cross sections might fall closer to the experimental data. In fact, for the CJD and LS calculations this is the case (see Fig. 5), although the HP results do not—the HPI results in particular are more than a factor of 2 too high. Similar results are obtained for the inverse-energy-weighted integrated cross sections

$$\sigma_{-1}(E_\gamma^*) = \int^{E_\gamma^*} \sigma(E_\gamma) E_\gamma^{-1} dE_\gamma \, .$$

It should be noted here that the integrated evaluated cross sections up to $E_\gamma^*=32$ MeV are 18.0 ± 1.2 MeV mb for ^{4}He(γ,p) and 10.2 ± 1.2 MeV mb for ^{4}He(γ,n); their sum (shown in Fig. 5), 28.2 ± 2.4 MeV mb, agrees, within the experimental uncertainties, with the value of 21 ± 5 MeV mb ob-

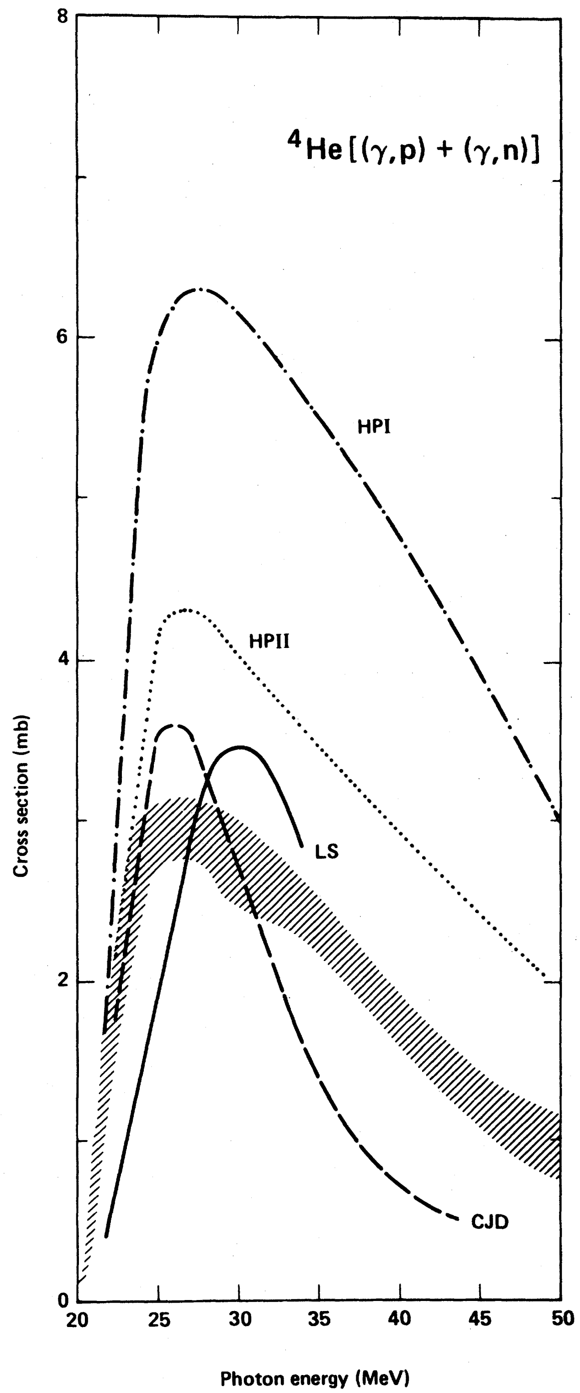

FIG. 4. Comparison of the sum of the evaluated (γ,p) and (γ,n) cross sections shown in Fig. 1 (shaded band) with results of the theoretical calculations for the same quantity: dashed line, from Ref. 45 (CJD); solid line, from Ref. 46 (LS); and from Ref. 49 (HP), results for Set I (dash-dotted line, HPI) and for Set II (dotted line, HPII).

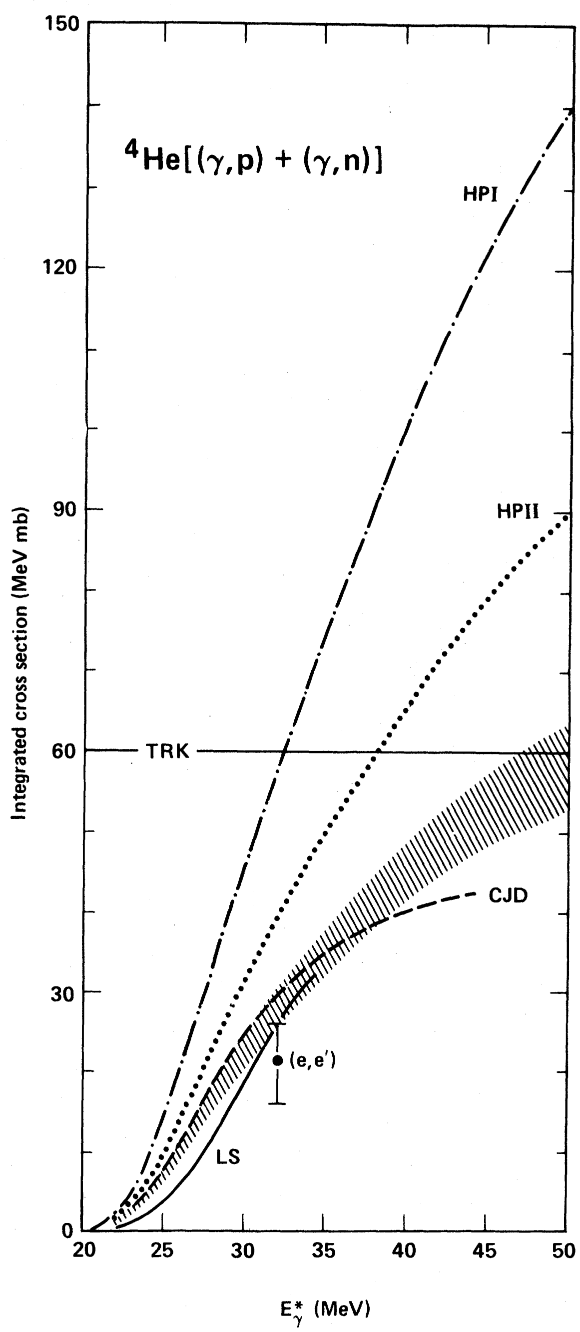

FIG. 5. Integrated cross sections $\int^{E_\gamma^*} \sigma(E_\gamma)dE_\gamma$, where $\sigma(E_\gamma)$ is the sum of the (γ,p) and (γ,n) cross sections. (See Fig. 4 for the labeling of the lines.) The shaded region represents the result of the integration for the summed evaluated cross section shown in Fig. 4. Also shown is the datum obtained from the inelastic-electron-scattering result of Walcher (Ref. 52) [indicated (e,e')]. The TRK sum-rule value $60NZ/A$ MeV mb is indicated in the figure.

tained from the inelastic-electron-scattering data of Walcher[52] (see Fig. 5). More important, however, is the fact that if the ^{4}He(γ,n) cross section were to be as large as the ^{4}He(γ,p) cross section below 32 MeV, then the integrated sum would be 36.0 ± 2.4 MeV mb, which exceeds significantly the experimental value from Ref. 52.

As seen in Fig. 5, the Thomas-Reiche-Kuhn (TRK) sum-rule value for the cross section is reached at $E_\gamma^*\simeq50$ MeV. Of course, from terms in the nuclear Hamiltonian which do not commute with the electric-dipole operator, one expects that the integrated cross section up to the pion thresholds will exceed the TRK value somewhat (perhaps by $\sim50\%$), and thus the behavior of the evaluated integrated cross section shown in the figure is entirely reasonable.

Finally, for completeness, the bremsstrahlung-weighted cross section $\sigma_{-1}(E_\gamma^*)$ defined above also was extracted from the evaluated experimental data to yield

$$\sigma_{-1}(E_\gamma^*=50\text{ MeV})=1.8\pm0.2\text{ mb}$$

(see Ref. 53 for a discussion of the σ_{-1} sum rule).

In summary, the currently available continuum shell-model calculations do not allow for the significant deviations from unity of the (γ,p)-to-(γ,n) ratio R seen experimentally even away from the threshold region. Nor do the calculations do especially well on the energy dependences of the individual cross sections or of their sum. In future theoretical work, certainly all of the ingredients summarized here should be incorporated: correct treatment of recoil (the spurious-state problem), inclusion of noncentral terms in the effective interaction, comparisons in the continuum channels with nucleon-scattering information, consistent treatment of bound and continuum states (the orthogonality-completeness question), inclusion of isospin breaking via the Coulomb interaction, and treatment of all required multipoles to higher than unretarded order. In addition, it may be necessary to address the question of how important are the roles played by np-nh ($n>1$) correlations in the ground- and excited-state wave functions. At present, to the extent that all conventional reasons for differing (γ,p) and (γ,n) cross sections (such as Coulomb mixing, threshold differences, $E2$ multipoles, etc.) have been investigated sufficiently, one again is led to conclude that a nonzero charge asymmetry in the nuclear force is suggested as the mechanism for the large experimental difference.

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