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New photodisintegration threshold observable in ^{3}He

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Measurements of the cross section, vector and tensor analyzing powers, and linear gamma-ray polarization in the radiative capture reactions $D(p,\gamma)^3$He and $p(d,\gamma)^3$He at c.m. energies in the range 0–53 keV allow the determination of the reduced matrix elements (RMEs) relevant for these transitions. From these RMEs the value of the integral which determines the Gerasimov-Drell-Hearn sum rule for ^{3}He is obtained in the threshold region, corresponding to two-body breakup, and compared with the results of an *ab initio* microscopic three-body model calculation. The theoretical predictions for the value of this integral based on a ''nucleons-only'' assumption are an order of magnitude smaller than experiment. The discrepancy is reduced to about a factor of 2 when two-body currents are taken into account. This factor of 2 is due to an almost exact cancellation between the dominant $E1$ RMEs in the theoretical calculation. The excess $E1$ strength observed experimentally could provide useful insights into the nuclear interaction at low energies.

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Previous measurements and calculations in the threshold region of the $D(n,\gamma)^3$H and the $D(p,\gamma)^3$He reactions have demonstrated the important role played by non-nucleonic degrees of freedom in this reaction at these energies. For example, the inclusion of two-body currents (meson-exchange currents) increases the thermal $D(n,\gamma)^3$H capture cross section by a factor of 2 [1], in accord with experiment. In the case of $D(p,\gamma)^3$He, it has been observed [2] that the vector analyzing power measured at $E_p=80$ keV is about a factor of 2 smaller than calculated if two-body currents are neglected.

In the present work, we have been able to evaluate the integral which determines the Gerasimov-Drell-Hearn (GDH) sum rule [3,4] in the threshold photodisintegration region of ^{3}He. The results indicate that this region contains a negligible contribution to the total value of the GDH sum rule for ^{3}He. However, we also find that the experimentally determined value of this ''GDH integral'' is about a factor of 10 greater than calculated if two-body currents are neglected. In fact, a factor of 2 discrepancy remains even with two-body currents included. The integral shows great promise as a sensitive new means for studying the subnucleonic degrees of freedom of ^{3}He and the detailed nature of the the two- and three-body nuclear force.

The GDH sum rule connects the helicity structure of the photo-absorption cross section to the anomalous magnetic moment of the nuclear target. It is derived using Lorentz and gauge invariance, crossing symmetry, causality, and unitarity of the forward Compton scattering amplitude, and is explicitly given by

$$I_T=\int_{\omega_{\rm th}}^{\infty}d\omega\,\frac{\sigma_P(\omega)-\sigma_A(\omega)}{\omega}=4\pi^2\alpha s_T\left(\frac{\kappa_T}{m_T}\right)^2, \qquad (1)$$

where σ_P and σ_A are the cross sections for the absorption of polarized photons of energy ω and helicities parallel and antiparallel to the target spin s_T (in its maximum state), $\omega_{\rm th}$ is the threshold photon energy for inelastic processes, α is the fine-structure constant, and m_T and κ_T are the target mass and anomalous magnetic moment, respectively.

The recent interest in the nucleon and deuteron GDH sum rules stems from the study of the spin-dependent structure functions in deep inelastic scattering [5]. Since the proton and neutron have relatively large anomalous moments ($\kappa_p=1.793$ and $\kappa_n=-1.913$), the corresponding values of I_T obtained from Eq. (1) are large, $I_p=204.8$ μb and $I_n=232.5$ μb, while the deuteron, for which $\kappa_d=-0.143$, has a comparatively small $I_d=0.652$ μb. As has been previously discussed [6,7], one should expect to observe the sum of the proton and neutron strengths (and more) in the deuteron above pion threshold, indicating that a large negative contribution of about this size (-436 μb) should exist below this threshold. Indeed, the authors of Ref. [8] point out that the photodisintegration channel, which is the only photoabsorption process below the pion threshold, should give a large negative contribution arising from the $M1$ transition to the resonant $^1S_0$ state just above the deuteron breakup threshold ($\omega-\omega_{\rm th}<100$ keV), since this state can only be formed if the deuteron spin and photon helicity are antiparallel. This has not, to our knowledge, been observed experimentally. In ^{3}He, the GDH sum rule is $I_{^3{\rm He}}=498$ μb, using the experimental value $\kappa_{^3{\rm He}}=-8.366$. As in the case of the deuteron, it is useful to divide the integral into the part up to pion threshold, and the part above this threshold. For the part above pion threshold, the ^{3}He nucleus should have roughly the same strength as the neutron, i.e., $\simeq 230\ \mu$b. Such an expectation is based on the fact that the ^{3}He ground state consists predominantly of a spherically symmetric *S*-wave component, in which the proton spin projections are opposite and the net polarization is therefore due entirely to the neutron. Ignoring corrections to this naive estimate, it is expected that the ω region from the photodisintegration threshold ($\omega_{\rm th}=5.4949$ MeV) up to the pion threshold should contribute about 266 μb to the ^{3}He GDH sum rule. Following the case of the deuteron, it is of interest to study ^{3}He in the region just above breakup threshold. As will be seen below, the experimental results for ^{3}He indicate that a very insignificant amount of the GDH sum rule for ^{3}He is located in the threshold region. However, it is found that the value of the integral which determines this sum-rule [see Eq. (1)] is extremely sensitive to non-nucleonic degrees of freedom in the region of $\omega-\omega_{\rm th}<53$ keV.

We define (limiting our discussion hereafter to the ^{3}He case)

$$I(\bar{\omega})=\int_{\omega_{\rm th}}^{\bar{\omega}} d\omega \frac{\sigma_P(\omega)-\sigma_A(\omega)}{\omega}, \tag{2}$$

with, obviously, $I(\bar{\omega}\to\infty)=I_{^3{\rm He}}$. We have not made a direct measurement of the σ_P and σ_A photoabsorption cross sections to determine the contribution to $I(\bar{\omega})$. Instead we have determined its value from measurements of the cross sections, and vector and tensor analyzing powers for the radiative capture reactions $D(p,\gamma)^3$He and $p(d,\gamma)^3$He. In fact, these measurements allow the determination of the complex reduced matrix elements (RMEs) of these reactions. This has been performed at Triangle Universities Nuclear Laboratory (TUNL) for proton and deuteron incident energies in the range 0–80 keV, corresponding to values $\omega_{\rm th}\leqslant\omega\leqslant 5.548$ MeV.

The pd continuum states are specified by the relative orbital angular momentum *L* between the *p* and *d* clusters, the channel spin *S* ($S=1/2,3/2$), and the total angular momentum *J*. The amplitude for absorption of a photon of momentum **q** and helicity λ on a ^{3}He nucleus with spin projection σ_3 resulting in a transition to a pd state with quantum numbers $LSJJ_z$ is given by

$$j^{LSJ}_{J_z\lambda\sigma_3}(\mathbf{q})=\langle\Psi^{LSJJ_z}_{2+1}|\hat{\epsilon}_\lambda(\mathbf{q})\cdot\mathbf{j}(\mathbf{q})|\Psi^{(1/2)\sigma_3}_3\rangle, \tag{3}$$

where $\hat{\epsilon}_{\lambda=\pm1}$ is the photon polarization vector and $\mathbf{j}(\mathbf{q})$ is the nuclear electromagnetic current operator. The c.m. photodisintegration cross section then reads

$$\sigma_{\lambda\sigma_3}(\omega)=\frac{8\pi\alpha\mu p}{\omega}\sum_{LSJJ_z}|j^{LSJ}_{J_z\lambda\sigma_3}(\omega\hat{\mathbf{z}})|^2, \tag{4}$$

where $\omega=|\mathbf{q}|$ is the photon energy, μ is the pd reduced mass, and p is their relative momentum, which is fixed by energy conservation. In the energy region under consideration here (pd relative energies less than 53 keV), there are only six significant RMEs corresponding to magnetic and electric dipole transitions ($M1$ and $E1$, respectively) resulting in emission of pd pairs in relative *S*- and *P*-wave states. Thus, ignoring the contribution of higher order multipoles, we find [16]

$$\Delta\sigma\equiv\sigma_P-\sigma_A$$
$$=\frac{16\pi^2\alpha\mu p}{\omega}\left[-|s_2|^2+\frac{|s_4|^2}{2}-|p_2|^2+\frac{|p_4|^2}{2}-|q_2|^2+\frac{|q_4|^2}{2}\right], \tag{5}$$

where for ease of presentation we have introduced the notation $s_{2J+1}\equiv M_1^{0JJ}$, $p_{2J+1}\equiv E_1^{1(1/2)J}$, and $q_{2J+1}\equiv E_1^{1(3/2)J}$ for $J=1/2$ and 3/2 (the superscripts in X_l^{LSJ}, $X=M,E$, refer respectively to the quantum numbers LSJ defined above). The energy dependence of the RMEs and $\Delta\sigma$ is understood.

The RMEs have been determined by fitting our polarized capture data obtained using polarized proton and polarized deuteron beams incident on unpolarized deuteron and proton targets, respectively. Because of time reversal invariance, the RMEs for the capture reaction are related to those for the photoabsorption reaction by phase factors, which are irrelevant for the $\Delta\sigma$ defined above. The current data set are shown in Fig. 1 along with the fit used to determine the amplitudes and phases of the six contributing transition matrix elements. These data are all at a c.m. energy of $E_{\rm c.m.}=26.6$ keV, corresponding to $E_d=80$ keV or $E_p=40$ keV. Although many of these data have been previously published [2], additional data have been added to the A_y set. Furthermore, new data have been obtained for the tensor analyzing powers T_{21} and T_{22}, the linear gamma-ray polarization data have been remeasured, and data for the new observable A_γ, corresponding to the difference in the linear gamma-ray polarizations for spin-up versus spin-down incident polarized protons, have been added.

These data are sufficient to determine the six contributing matrix elements and their five relative phases in an unconstrained fit. However, in order to reduce the error on the amplitudes of the RMEs, the $E1$ $S=1/2$ and $M1$ phases were held equal to the theory values. The initial values of the other phases and amplitudes were set equal to the calculated ones [9]. Fixing these phases causes a less than 2% change in the total χ^2 of the fit relative to the unconstrained result.

The results of this procedure provide the value of $\Delta\sigma$ at $\bar{\omega}_1=5.522$ MeV. Our previous work [2] gave the value of the absolute cross section for E_p from 0 to 80 keV (corresponding to ω from 5.495 MeV up to 5.548 MeV), and also extracted the fraction of this cross section which was due to $M1$ (versus $E1$) as a function of energy. If we assume that the ratio of the doublet-to-quartet $M1$ strengths and the $J=3/2$ to 1/2 $E1$ strengths are equal to the values we obtained at $E_{\rm c.m.}=26.6$ keV (the uncertainty in our results due to this assumption will be evaluated, see below), we can perform the integral of Eq. (2). The results corresponding to integrating up to $\bar{\omega}_1=5.522$ MeV ($E_p=40$ keV) or to $\bar{\omega}_2=5.548$ MeV ($E_p=80$ keV) are presented in Table I. While this is an insignificant (negative) contribution to the

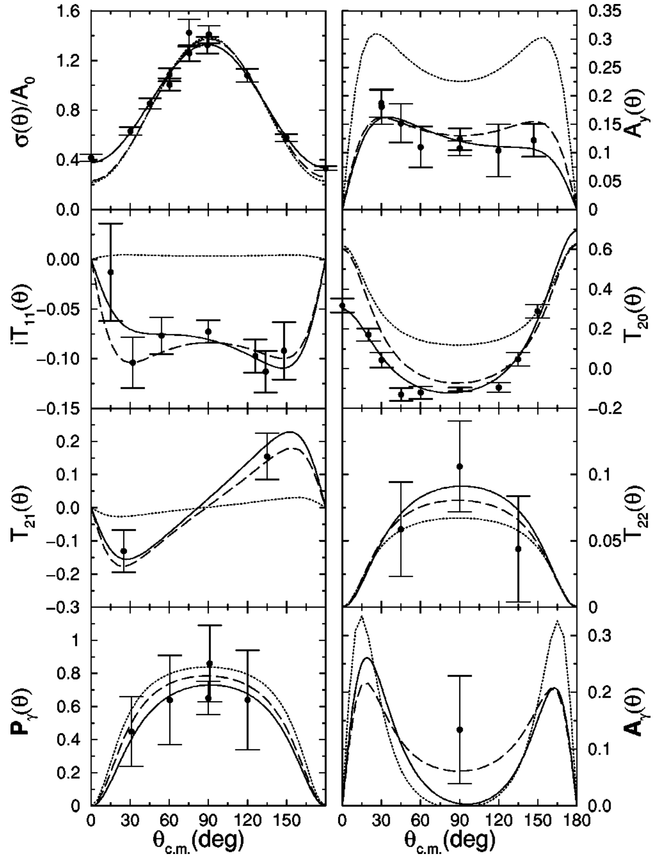

FIG. 1. *pd* capture observables (full dots with error bars) and their fit (solid lines) used to determine the six leading RMEs. Theoretical predictions including one-body only and both one- and two-body currents are shown by the dotted and dashed lines, respectively.

total strength expected below pion threshold, it is an interesting result which can be compared directly with theory. The uncertainties given on the value obtained in Eq. (5) come primarily from the uncertainty in the absolute cross sections quoted in Ref. [2] (9%), and the statistical uncertainties associated with the RME fit which determined the various amplitudes. The contribution to the uncertainty resulting from the assumption of constant ratios as a function of energy, described above, was found to be small due to the fact that the cross section falls rapidly as the energy decreases, so that large changes in these ratios (say 20%, which is twice the value predicted by theory [9]) at low energies (say near 20 keV) have a small effect (less than 2%) on our result. Since theory indicates changes of less than 10% in the value of these ratios when going from 10 to 40 keV, it is unlikely that this assumption affects our results, especially in the case where we integrate only up to $E_p = 40$ keV.

TABLE I. The contributions $I(\overline{\omega})$ (in nb) for two energies $\overline{\omega}$. In the third column, the values obtained from a fit of the experimental *pd* capture data are reported. The results of the theoretical calculations obtained with one-body only and both one- and two-body currents are listed in the fourth and fifth columns, labeled IA and FULL, respectively. The lines denoted by $M1$, $E1$ $S=1/2$ and $E1$ $S=3/2$ report the partial contributions to $I(\overline{\omega}=5.522$ MeV) of the corresponding RMEs.

$\overline{\omega}$ (MeV)	$I(\overline{\omega})$	FIT	IA	FULL
5.522	$M1$	-0.0530 ± 0.0077	-0.0029	-0.0609
5.522	$E1$ $S=1/2$	-0.0373 ± 0.0092	-0.0030	$+0.0027$
5.522	$E1$ $S=3/2$	-0.0024 ± 0.0007	-0.0050	-0.0001
5.522	Total	-0.0928 ± 0.0121	-0.0112	-0.0583
5.548	Total	-1.144 ± 0.212	-0.161	-0.582

A detailed description of the theoretical calculations which provide the basis for a comparison and interpretation of the experimental capture results obtained above has been previously published [9]. With respect to this earlier reference, however, we note that in the present work the variational treatment of the *pd* continuum states has been improved. As a result, the present calculations which include both one- and two-body currents are in better agreement than reported in 1996 [9] with the many experimental capture data obtained below 80 keV [2]. In particular, the discrepancy between the calculated and measured A_y observable has been reduced substantially. Theoretical predictions for this and a number of other observables are compared with data in Fig. 1 where the results for both one-body (nucleons only) and one- and two-body currents are presented.

As in Ref. [9], we use the correlated-hyperspherical-harmonics (CHH) method [10] to generate the $A=3$ bound- and scattering-state wave functions from a realistic Hamiltonian consisting of the Argonne v_{18} two-nucleon [11] and Urbana-IX three nucleon [12] interactions. The nuclear electromagnetic current includes a one-body component of the standard impulse approximation (IA) form, and two-body components [13], leading terms of which are constructed from the charge independent part of the Argonne v_{18} interaction. A comprehensive review of this aspect of the calculation as well as issues related to the treatment of Δ-isobar degrees of freedom can be found in Refs. [9,14]. Here, we only emphasize that this model for the current (and charge) operators has been shown to provide, at low and moderate values of momentum transfers (≤ 1 GeV/c), a satisfactory description of many few-nucleon electromagnetic observables, such as the deuteron threshold electrodisintegration, the $^1H(n,\gamma)^2H$ radiative capture cross section at thermal neutron energies, the magnetic moments and form factors of the trinucleons, and the $d(p,\gamma)^3He$ radiative capture cross section at low energies (again, see Ref. [14] for a review).

The value of the GDH sum rule integral $I(\overline{\omega})$ predicted with inclusion of one-body only and both one- and two-body currents (columns labeled IA and FULL, respectively) are reported in Table I for $\overline{\omega}_1=5.522$ MeV and $\overline{\omega}_2=5.548$ MeV. Table I also lists the individual contributions to $I(\overline{\omega}_1)$ from the $-|s_2|^2+|s_4|^2/2$, $-|p_2|^2+|p_4|^2/2$, and $-|q_2|^2+|q_4|^2/2$ RME combinations (rows labeled $M1$, $E1$ $S=1/2$, and $E1$ $S=3/2$, respectively).

The total contributions in IA including the $M1$, $E1$ $S=1/2$ and $E1$ $S=3/2$ strengths are found to be an order of magnitude smaller than data. This is because in IA $|s_2|^2 \simeq 0.5\times|s_4|^2$, $|p_2|^2\simeq 0.5\times|p_4|^2$ and the quartet $(S=3/2)E1$

strength is very small. If we consider the long-wavelength approximation in which the $E1$-multipole operator is spin independent, then transitions from the ^{3}He ground state to the $S=3/2$ channel pd states are inhibited since they must proceed through the relatively small D-wave component of the ^{3}He wave function. Hence the quartet $E1$ RMEs are individually small. Such is not the case for the doublet $E1$ RMEs, which result from transitions involving the $S=1/2$ pd states and the dominant S-wave component of the ^{3}He ground state. Yet, the doublet $E1$ strength combination occurring in $\Delta\sigma$ happens to nearly vanish. The ratio $\simeq 0.5$ for the doublet to quartet $M1$ strength obtained in IA is consistent with predictions for the pd capture at zero relative energy obtained with the Faddeev method using a variety of realistic Hamiltonians [15] (the ratio is found to have only a weak energy dependence).

When two-body currents are included, the doublet $M1$ strength $|s_2|^2$ becomes roughly twice as large as the quartet $M1$ strength $|s_4|^2$, a result also consistent with the earlier calculations [15]. This makes the overall $M1$ contribution to $I(\overline{\omega})$ negative and relatively large. The quartet $E1$ RMEs remain negligible. However, the nearly exact cancellation between the doublet $E1$ strengths $|p_2|^2$ and $|p_4|^2/2$ is not significantly influenced by the inclusion of two-body currents. Thus the total contribution to $I(\overline{\omega})$ according to theory is mostly due to $M1$ strength.

The factor of ten discrepancy between the integral of Eq. (1) for the IA calculation and experiment (see Table I) can also be observed as discrepancies with several of the observables of Fig. 1. Note, for example the large discrepancies in $A_y(\theta)$, $iT_{11}(\theta)$, and $T_{20}(\theta)$. While these are largely removed when two-body currents are included (see Fig. 1), the remaining discrepancy of a factor of two for the GDH integral observable show up in Fig. 1 primarily as discrepancies in $\sigma(0°)$ and $T_{20}(0°)$. These discrepancies, quantified most succinctly in the value of the GDH integral, arise mainly from the difference between the $|p_2|^2$ and the $|p_4|^2/2$ $E1$ strengths, as Table I makes clear. The physical origin of this effect could be hidden in the detailed nature of the p-wave part of the NN force or even a possible spin-dependent three-body force [17], but remains unexplained.

In summary, polarized capture data have made it possible to determine the value of the integral which defines the GDH sum rule in the region just above threshold in ^{3}He. While the results indicate that an extremely tiny piece of the total sum-rule strength is located in this region, we have found, by direct comparison with theory, that this integral is very sensitive to the effects of two-body currents. The inclusion of these currents reduces the discrepancy between theory and experiment from a factor of 10 to a factor of 2. Further theoretical progress is needed to understand the physical origin of the difference in the p-wave $E1$ RMEs responsible for the remaining discrepancy. This first glimpse of the GDH integral for ^{3}He, although insignificant to the sum rule value, demonstrates the new knowledge contained in this quantity and emphasizes the need for measurements at higher energies.

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