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180° ELECTRON SCATTERING FROM ^{3}He AND ^{4}He AT 56 MeV

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The nuclear magnetic structure of ^{3}He has been investigated by 180° scattering of 56.6-MeV electrons. The first observation of the $M1$ continuum in ^{3}He from 6 to 20 MeV is reported. The $M1$ component of the breakup from $^3\mathrm{He}(e,e')d,p$ together with $^3\mathrm{He}(e,e')p,p,n$ has been measured and is discussed in light of possible isovector and isoscalar meson-exchange currents in the trinucleon system. The elastic magnetic form factor of ^{3}He at $q=0.561$ fm^{-1} is 0.80, giving a rms magnetic radius $a=1.94\pm0.19$ fm.

The nuclear magnetic structure of ^{3}He has been investigated by 180° scattering of 56.6-MeV electrons from a gaseous ^{3}He target. For comparison, an identical gas target of ^{4}He, which has no known magnetic nuclear structure, was bombarded under the same experimental conditions.

We present here a report of the preliminary results which include measurement of a magnetic dipole continuum up to 20-MeV excitation energy in ^{3}He, determination of the magnetic elastic electron scattering cross section at a momentum transfer of $q=0.561$ fm^{-1}, and observation of electrons produced by magnetic bremsstrahlung from ^{3}He. This is the first observation of the $M1$ continuum in ^{3}He and will complement the well-studied $E1$ structure of ^{3}He and ^{3}H obtained by photodisintegration[1-3] and radiative capture measurements,[4] and by electrodisintegration studies.[5,6] The elastic magnetic form factor of ^{3}He has been previously measured over a wide range of momentum transfer, $1.0\leq q^2\leq 8.0$ fm^{-2}, by Collard et al.[7] Electrons produced by magnetic bremsstrahlung from ^{1}H have been observed by Goldemberg[8] and probably by several others.

Any discussion of the nuclear physics of ^{3}He must cite the several experiments on the isospin doublet ^{3}H and ^{3}He which complement one another in a forceful way. At the same time one must draw attention to the rather prodigious theoretical complexities of the trinucleon systems which result from adding just one nucleon to the nucleon-nucleon potential. We shall review briefly the magnetic properties of ^{3}H and ^{3}He.

The ground-state magnetic moments of ^{3}H and ^{3}He are +2.9788 and −2.1274 n.m., respectively. By adding $\mu_{M1}(^3\mathrm{H})+\mu_{M1}(^3\mathrm{He})$ and assuming a small $^4D_{1/2}$ component together with the predominant $^2S_{1/2}$, the $^4D_{1/2}$ weight is fixed at 3.8%. There are reasons for excluding the $P_{1/2}$ states. When the individual moments are then calculated with 3.8% D state, there remains an isovector exchange moment (presumably due to meson currents) of 0.27 n.m.[9] The Stanford measurements of elastic electron scattering from ^{3}H and ^{3}He provide both charge and magnetic form factors over a large range of momentum transfer. To fit these data, Schiff and Gibson[10-12] calculated $T=\frac{1}{2}$ ground-state probabilities and found $P_S=92\%$, $P_D=6\%$, and $P_{S'}\leq 2\%$ using spatial wave functions of the Irving-Gunn form, e^{-aR}/R^n. Their results were also constrained by other measurements, i.e., $\mathrm{D}(n,\gamma)^3\mathrm{H}$, $^3\mathrm{H}\xrightarrow{\beta^-}{}^3\mathrm{He}$, $^3\mathrm{He}(e,e')dp$, and $^3\mathrm{He}(\mu^-,\nu)^3\mathrm{H}$, and by variational calculations of binding energy of the trinucleons. The increased percentage of $^4D_{1/2}$ state and possible very small admixture of $T=\frac{3}{2}$ S' component led Gibson to re-examine the isovector exchange moment which is required by the static magnetic moments. He found that both isovector and isoscalar exchange moments are required to fit the magnetic form factors.[12] Thus there is not only a sizable meson-exchange current in the isodoublet but it is presumably of different magnitude in ^{3}He and ^{3}H. Let us now look at some pertinent properties of the continuum of the trinucleon systems.

Of relevance to our resutls and this discussion is Siegert's theorem that shows that meson-exchange currents are expected in $M1$ but not $E1$ transitions. The continuum magnetic dipole moments of ^{3}He and ^{3}H have been inferred from measurements of thermal neutron capture, D(n, γ)^{3}H, and low-energy proton capture, D(p, γ)^{3}He. Bailey et al. have questioned the pure $M1$ nature of the capture by showing that the ^4D component through $^4P \to {}^4D$ and $^4F \to {}^4D$ $E1$ capture could explain the isotropic yield of capture gamma rays.[13] Fetisov et al., in their difinitive measurement of the $E1$ two- and three-body photodisintegration cross section of ^{3}He, have detected an $E2$ component in the angular distribution of the photoprotons.[1] In earlier inelastic electron scattering from ^{3}He at 60 MeV and $\theta = 130°$, an anomaly above the $E1$ excitation appeared in the 6- to 7-MeV region in ^{3}He.[14,6]

It has been known for some time that in the three-body system the $M1$ operator conserves the antisymmetric spin-isospin eigenstate, namely,[9]

$$\vec{\mu}\,|\varphi(r)\xi^a\rangle = c\,|\varphi(r)\xi^a\rangle. \qquad (1)$$

In addition, from Schiff's interpretation of the charge form-factor anomalies in ^{3}H and ^{3}He in terms of like and unlike nucleon pairs,[10] one might anticipate that the inner products of the spatial states, $\langle dp|^3\mathrm{He}\rangle$ and $\langle ppn|^3\mathrm{He}\rangle$, are to a large extent orthogonal near threshold for the spin flip of one nucleon. This orthogonality for $M1$ transitions, in which 92% of the ground-state wave function is eliminated, is observed as a factor of about 1/700 experimentally. The thermal neutron capture cross section ^{2}H(n, γ)^{3}H is about 0.5 mb compared with 334 mb in the $M1$-allowed reaction ^{1}H(n, γ)^{2}H. One may conclude that any $M1$ strength in ^{3}He(e, e')dp and ^{3}He(e, e')ppn must arise from the mixed-symmetry component, $S' < 2\%$, and/or from meson-exchange current operators which project out the orthogonal components of the symmetric ground state S.[15]

The experimental results are presented in Figs. 1 and 2. The data were taken with the Naval Research Laboratory 180° electron scattering facility.[16] The measurements represent about 100 h of running time at 6- to 9-μA average beam current with $\Delta p/p = 0.5\%$ from the 60-MeV S-band Linac. The $\frac{7}{16}$-in.-diam $\times$ 2.0-in.-long gas chamber[17] was pressurized with 4.4 atm of ^{3}He or separately with ^{4}He, and cooled to about 77°K. The target windows are 0.000 25-in. Havar which is a variety of non-work-hardened alloy. Increasing the chamber diameter to $1\frac{3}{8}$ in. had no appreciable effects on the electrons accepted into the ~1.7-msr solid angle.

This experiment is primarily a difference measurement between ^{3}He and ^{4}He. For this

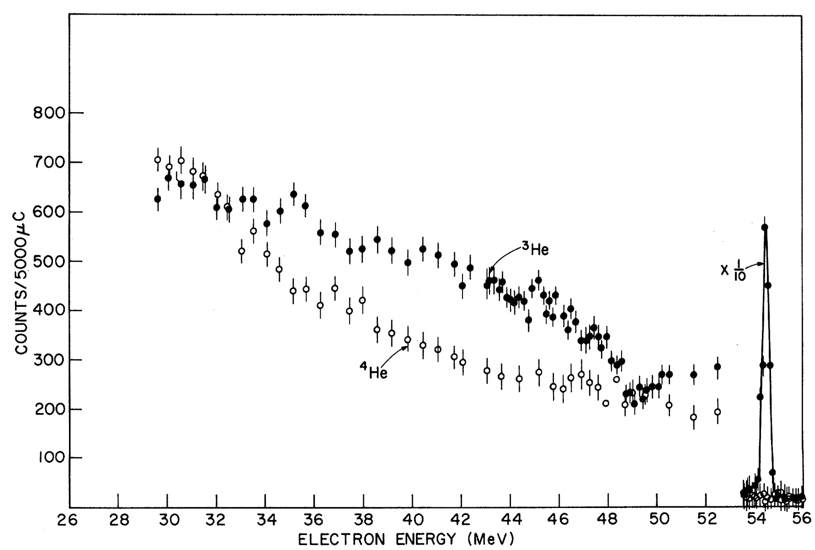

FIG. 1. The electron-scattering spectra of ^{3}He and ^{4}He at $E_0 = 56.6$ MeV, $\theta = 178.9°$, and a resolution $\Delta p/p = 0.5\%$. The data are from three overlapping runs which have been normalized to 5000 μC per point, 4.4-atm gas-target pressure, and equal elastic-peak areas. The variation of the solid angle and efficiency of the plastic scintillators with energy, which would tend to reduce the number of lower energy electrons, has not been folded in. The error bars are from counting statistics.

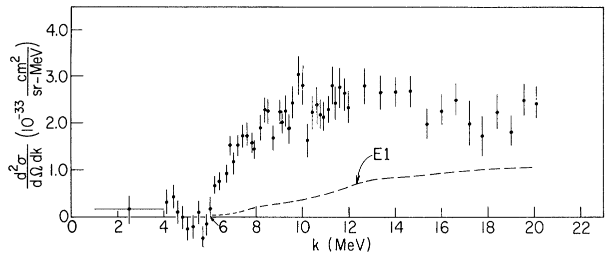

FIG. 2. The $M1$ electroexcitation of ^{3}He plotted versus nuclear excitation energy $\boldsymbol{k}$. The radiative tail from both the elastic peak and the $M1$ continuum is unfolded from Fig. 1 after first removing the background, i.e., ^{3}He$-^4$He, and correcting for the solid angle and efficiency dependency on E. Next the magnetic bremsstrahlung and $E1$ electroexcitation are removed. The magnitude of the latter is computed from Eq. (3) and shown by the dashed line. The error bars are from counting statistics. We estimate the overall uncertainty to be ±25 % per point.

reason weak nuclear excitation, $<5\times10^{-33}$ cm^2/sr MeV, can be determined. Usually, the radiative tail, which is composed of a continuum of degraded electrons from real and virtual processes in the Coulomb field of the nucleus, either masks such weak nuclear excitation or makes the amount of excitation very uncertain. This is especially the case for continuum nuclear excitation. Since there is no known excitation of ^{4}He below 20 MeV, the difference ^{3}He $-^4$He of the electron spectra represents nuclear excitation of ^{3}He plus magnetic bremsstrahlung from ^{3}He, and virtual-photon corrections due to scattering from the elastic and continuum magnetic moments of ^{3}He.

From the ^{3}He elastic electron scattering peak in Fig. 1, one obtains $d\sigma/d\Omega=(3.17\pm10\%)\times10^{-32}$ cm^2/sr. The standard corrections have been applied in the analysis. From the absence of the ^{4}He elastic peak, one can compute the effective scattering angle as $\theta\geqslant178.8°$ from Eq. (2). This angle is in agreement with 178.9° for the 180° system from independent measurements and calculations. The elastic electron scattering cross section from a nucleus with angular momentum I, magnetic moment μ, and charge Ze is given by,[8]

$$\frac{d\sigma}{d\Omega}=\sigma_{\rm Mott}\left\{F_{\rm ch}^{2}+\frac{I+1}{3I}\left(\frac{q\mu}{Ze}\right)^2 \times(1+2\tan^2\tfrac{1}{2}\theta)F_{\rm mag}^{2}\right\}. \qquad (2)$$

With the present parameters, $(d\sigma/d\Omega)_{\rm ch}=3.17\times10^{-34}$ cm^2/sr and $(d\sigma/d\Omega)_{\rm mag}=4.93\times10^{-32}$ cm^2/sr with $F_{\rm mag}=1.0$ from Eq. (2). The magnetic form factor is $F_{\rm mag}(q)=0.80$ at $q=0.561$ fm^{-1}, and this yields a rms magnetic radius of ^{3}He, $a=1.94\pm0.19$ fm. This is in agreement with the results of Collard et al.,[7] $a=1.74\pm0.10$ fm. The difference between ^{3}He and ^{4}He in the region $48.7<E<54.0$ MeV in Fig. 1 can be attributed to elastically scattered electrons which have been degraded by bremsstrahlung in the field of the nucleus or by virtual photon emission. The magnetic bremsstrahlung was computed from the formula of Ginsburg and Pratt[18] using $F_{\rm mag}=1.0$. As is the case in Eq. (2), the electrons degraded by magnetic processes dominate those produced by charge bremsstrahlung for low Z and $\theta\simeq180°$. The magnetic bremsstrahlung decreases rapidly with decreasing E so it is 13% of the (^{3}He$-^4$He) cross section at 47.3 MeV and 3-4% of the excitation at 40 MeV.

In Fig. 2, the $M1$ excitation of ^{3}He is plotted versus excitation energy k. The $M1$ cross section comes from the ^{3}He and ^{4}He difference in Fig. 1, after unfolding and removal of the electron spectrum produced by the magnetic bremsstrahlung and virtual photons, and after subtraction of the $E1$ electroexcitation of ^{3}He. Near 180° and for equal form factors, $B(M1,q)=B(E1,q)$, the $M1$ dominates over the $E1$ cross section by a factor q^2/k^2,[19] or by a factor of 23 at $k=19$ MeV to 220 at $k=7$ MeV. A reliable estimate of the $E1$ electron cross section comes from the measured photon cross sections $\sigma_\gamma(k)$.[1,3] One connects the two with the virtual photon spectrum, $(dn/d\Omega)_L$,[20] by

$$\frac{d^2\sigma}{d\Omega dE}=\frac{dn_L}{d\Omega}(E_0,k,\theta,L)\sigma_{L\gamma}(k). \qquad (3)$$

This estimate worked well for earlier measurements of ^{3}He(e,e') at $\theta=130°$ and $E_0=60$ MeV which were primarily electric dipole transitions to (dp) and (ppn).[14]

It will be noted that the $M1$ cross section in Fig. 2 appears to rise sharply at 6.0 MeV, not at 5.5 MeV which is the two-body threshold in ^{3}He$(e,e')dp$. In part this threshold suppression may be distortion of the disintegration protons in the Coulomb field of the deuteron. A measurement of the two-body electrodisintegration of ^{3}H into a deuteron plus neutron would either verify this explanation or point to some other final-state interaction. The apparent absence of a pronounced increase in the $M1$ cross section at 7.7 MeV, the ppn threshold, may be due to the orthogonalities noted earlier. Beyond 20 MeV, the ^{4}He is no longer a background spectrum. In the continuum of ^{4}He there are $T=1$ 1^- and 2^- states which may be visible under the present experimental conditions.

In conclusion we have measured the magnetic dipole strength of the ^{3}He continuum. The results presented here are preliminary. The $M1$ is certainly present in the two-body and three-body breakup and may be in large part due to meson-exchange currents. Calculations in progress should determine how much of the observed $M1$ is attributable to higher order effects other than meson exchange currents.[21] The astrophysical importance in the p-p burning chain of any $M1$ component of $D(p, \gamma)^3$He at stellar temperatures of a few keV has been stressed by Tombrello.[22] Our results should help determine the $M1$ vs $E1$ mechanism at and near threshold.[13,14] The $M1$ continuum of ^{3}He should add to the experimental constraints on the trinucleon system. Since $M1$ transitions measure direct spatial overlap of the initial and final states compared with the r weighting of $E1$ transitions, one might look for some specific three-body effects in the $M1$ matrix element.

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