spectra of electrons bound to superheavy nuclei, however, may offer a more stringent test of nonlinear electrodynamics than high-energy electron-electron scattering experiments,[9] where our inability to quantize nonlinear theories hinders a straightforward comparison of theory and experiment.

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Charge-Exchange and/or Knockout Spectator Poles in the Reaction D(^{3}He,tp)p

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Intense spectator-proton peaks were observed in the reaction D(^{3}He,tp)p. Their shapes were well fitted by plane-wave Born-approximation calculations, assuming either knockout or ^{3}He-n quasielastic scattering accompanied by charge exchange to be the mechanism. Their intensities relative to the quasielastic peaks from D(^{3}He, ^{3}Hep)n were correctly predicted by charge-exchange calculations, but only when an unrealistic mixture of exchange forces was used. All direct knockout calculations gave relative intensities at least ten times too small.

This paper reports, for the first time, intense spectator peaks from the reaction D(^{3}He, tp)p, which may result from quasielastic scattering (QES) accompanied by charge exchange (CE). Quasielastic scattering was first observed by Kuckes, Wilson, and Cooper,[1] who found that large peaks (called spectator peaks) are observed in the p-p coincidence cross sections from the reaction D(p, 2p)n when momentum is transferred only between the two protons, and the neutron (called the spectator particle) remains nearly at rest in the laboratory. QES from the proton in the deuteron has also been studied[2-4] in the reactions D(d, dp)n, D(^{3}He, ^{3}Hep)n, and D(α, αp)n. In CE QES for the reaction D(^{3}He, tp)p [see Fig. 1(a)], the ^{3}He and neutron would transfer momentum and exchange charge, emerging as a triton and a proton, and the proton from the deuteron would remain nearly at rest. Alternatively, a direct knockout (KO) process [see Fig. 1(b)] might also produce spectator peaks.

A CD_2 target was bombarded with 27-MeV $^3He^{++}$ ions from Chalk River's model MP tandem accelerator. Coincidence events from two ΔE-E counter telescopes, coplanar with and on opposite sides of the beam, were recorded on magnetic

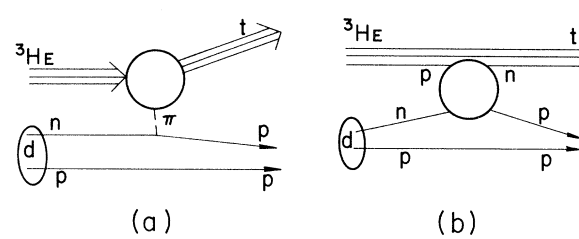

FIG. 1. Feynman diagrams for (a) charge-exchange quasielastic scattering and (b) knockout.

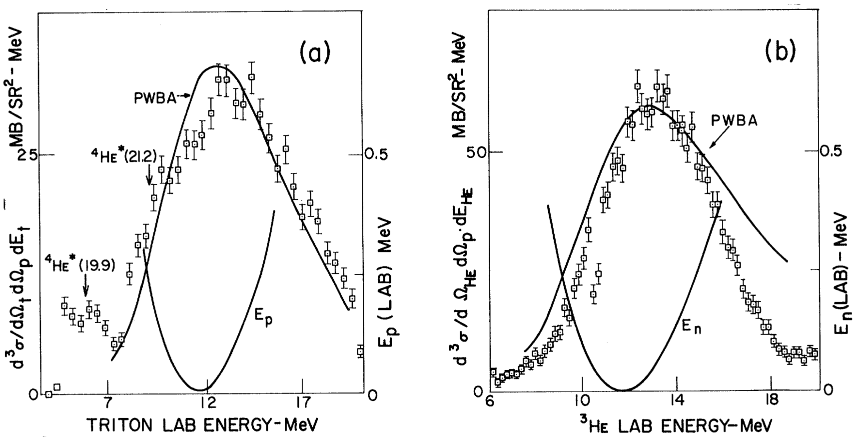

FIG. 2. (a) D(^{3}He,tp)p absolute coincidence cross sections and PWBA predictions (left-hand scale) and spectator-proton lab energy (right-hand scale) plotted versus triton lab energy at ($\theta_t = 15°, \theta_p = 25°$). Arrows show where enhancements due to sequential decay of the ^{4}He excited states at 19.9 and 21.2 MeV may occur. (b) Similar to (a) except D(^{3}He,^{3}He p)n data, predictions for the ordinary QES peak, and spectator-neutron energy are plotted versus ^{3}He lab energy. Both PWBA predictions are multiplied by 0.02.

tape. Particle identification was achieved during analysis, using a triton range-energy table.[5] Our absolute coincidence cross-section data for two geometries appear in Figs. 2 and 3. In Fig. 2(a), for instance, the broad peak near $E_t = 13$ MeV appears to be a spectator peak both because it is near the minimum spectator-particle (undetected proton) energy and because of its large size, 30 mb sr^{-2} MeV^{-1}; it is half as large as the ordinary QES peak from the reaction D(^{3}He, ^{3}Hep)n, which was observed simultaneously at this geometry [Fig. 2(b)]. Peaks observed in previous t-p coincidence studies[6,7] resulted from sequential decay of excited states in ^{4}He, but their magnitudes[7] were only a few mb sr^{-2} MeV^{-1}.

To interpret our data we performed a plane-wave Born-approximation (PWBA) calculation including both CE and KO processes; our development is similar to that of Henley, Richards, and Yu.[8] A Hulthen deuteron wave function[9] with $\alpha = 0.232$ fm^{-1} and $\beta = 1.202$ fm^{-1} and a Gaussian trion (^{3}He or t) function[8] with $\gamma = 0.36$ fm^{-1} were used. The transition potential[8] was

$$V(r_{ij}) = V_0[1 - BP_{\sigma,ij}]\exp(-\delta^2 r_{ij}^2) \tag{1}$$

which contains both ordinary and spin-isospin–exchange interactions, and causes the matrix elements to separate into spin-isospin and spatial factors. The range of the force was fixed with $\delta = 0.656$ fm^{-1}. The latter matrix elements are

$$M_{\mathrm{CE}}^{\pm} = (2V_0\pi^2\hbar^4/\delta^3)[\alpha\beta(\alpha+\beta)^3]^{1/2}\exp(-K^2/4\delta^2)\exp(-K^2/18\gamma^2)\{[\hbar^2\alpha^2+p_3^2)(\hbar^2\beta^2+p_3^2)]^{-1} \pm [(\hbar^2\alpha^2 p_2^2)(\hbar^2\beta^2+p_2^2)]^{-1}\} \tag{2}$$

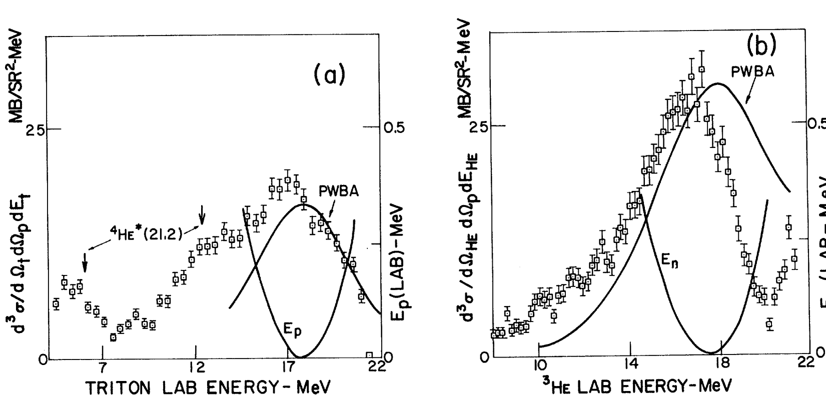

FIG. 3. Like Fig. 2, for the geometry (15°,44°). Both PWBA predictions are multiplied by 0.06. The rise in the ^{3}He spectrum near 21 MeV is attributed to the singlet deuteron final-state interaction.

and

$$M_{\mathrm{KO}}^{\pm}=\frac{16v_0\pi^2\hbar^4}{\epsilon^3}[\alpha\beta(\alpha+\beta)^3]^{1/2}\exp\left(\frac{-K^2}{18\gamma^2}\right)\left\{\frac{\exp(-C_3^2/\epsilon^2)}{(\hbar^2\alpha^2+p_3^2)(\hbar^2\beta^2+p_3^2)}\pm\frac{\exp(-C_2^2/\epsilon^2)}{(\hbar^2\alpha^2+p_2^2)(\hbar^2\beta^2+p_2^2)}\right\}, \tag{3}$$

where

$$\epsilon^2=4\delta^2+2\gamma^2; \tag{4}$$

$$\hbar\vec{K}=\vec{p}_0-\vec{p}_1; \tag{5}$$

$$\hbar\vec{C}_i=\tfrac{2}{3}\vec{p}_1-\tfrac{1}{3}\vec{p}_0+\vec{p}_i\quad(i=2,3); \tag{6}$$

and $\vec{p}_0$, $\vec{p}_1$, $\vec{p}_2$, and $\vec{p}_3$ are the lab momenta of the incident ^{3}He, final trion, detected nucleon, and undetected nucleon, respectively. The + (−) superscripts on the M's denote even (odd) parity of the final nucleons. Finally, after combining the space and spin-isospin factors and summing over final states and averaging over initial states, the matrix elements for the two reactions are, for $t+p+p$,

$$\overline{\sum}(M_{fi})^2=\tfrac{1}{12}(BM_{\mathrm{CE}}^{+}+M_{\mathrm{KO}}^{+})^2+\tfrac{1}{4}(BM_{\mathrm{CE}}^{-}+M_{\mathrm{KO}}^{-})^2, \tag{7}$$

and for $^3\mathrm{He}+p+n$,

$$\overline{\sum}(M_{fi})^2=\tfrac{1}{6}(BM_{\mathrm{CE}}^{-}+M_{\mathrm{KO}}^{-})^2+M_{\mathrm{KO}}^{+2}(6B^2-3B+\tfrac{1}{2})+M_{\mathrm{CE}}^{+2}(6-3B+\tfrac{1}{2}B^2)$$
$$+M_{\mathrm{KO}}^{+}M_{\mathrm{CE}}^{+}(\tfrac{475}{72}B-\tfrac{3}{2}-\tfrac{3}{2}B^2). \tag{8}$$

The shapes of the spectra calculated from these matrix elements are insensitive to B and to whether CE and/or KO is assumed to take place. Renormalized cross sections obtained for CE with $B=2.3$ appear in Figs. 2 and 3, and the peaks are generally well fitted by them. At (15°, 25°) the observed and calculated peaks for both reactions are displaced about 1.5 MeV upward from the minimum spectator energy. A closer examination of Eq. (2) provides a physical interpretation for these shifts. The first term in curly brackets is the probability of finding the undetected (spectator) nucleon in the deuteron with its final-state momentum; the second term is an exchange term having similar meaning for the detected proton. These terms have the strongest energy dependence and (neglecting the exchange term, which is small) peak at the minimum spectator energy. The factor $\exp(-K^2/18\gamma^2)$ is proportional to the probability that the two noninteracting nucleons in the initial trion have the same velocity as the final trion's center of mass, and $\exp(-K^2/4\delta^2)$ is proportional to the probability that the potential will cause trion momentum transfer $\hbar\vec{K}$. Both factors increase monotonically with increasing trion energy, thus shifting the peak above minimum spectator energy. At (15°, 44°) K is smaller and the trion-structure and potential-shape shifts are only 0.5 MeV upward; the observed shift, for unknown reasons, is 0.5 MeV downward.

"Coulomb pushing"[3] is another proposed mechanism for QES peak shifts; the deuteron is set in motion by Coulomb forces before the nuclear force knocks out one nucleon. We doubt that this effect is solely responsible for the shifts observed here, since they are so much larger than those seen in α-d QES.[4] Evidently the tightly bound α particle acts as a unit and structure-related shifts are absent.

Since we expect the PWBA to predict the ratio

$$R=d^3\sigma(t+p+p)/d^3\sigma(^3\mathrm{He}+p+n)$$

more reliably than the magnitudes of the cross sections, equal but otherwise arbitrary normalization factors were used for the two reactions at each geometry. Acceptable values of R, close to the observed values of $\frac{1}{2}$ to $\frac{2}{3}$, could be obtained only for pure CE with $B=2.3$. Those predicted assuming both CE and KO, or KO alone, were only about 0.05 at $B=0$ and decreased monotonically with increasing B. For CE alone the ratio was only 0.08 for $B=1.0$, the Serber value.[10]

Henley, Richards, and Yu[8] deduced that both pickup and charge exchange are important in the reaction D(^{3}He, tp)p at the highest triton energies, where the p-p final-state interaction occurs. The present work provides additional evidence for the existence and strength of charge exchange, but underlines the need for a more sophisticated theoretical approach. The two most striking failures of our model are its inability to give a proper account of the strength of the KO process and, even assuming that only CE takes place, the unrealistic exchange force required to give the observed $(t+p+p)/(^3\mathrm{He}+p+n)$ cross-section ratio. Perhaps these shortcomings could be rectified by straightforward changes within the PWBA framework, such as including tensor forces or other types of exchange forces, by completely antisymmetrizing the wave functions for exchange of all five nucleons, or by considering higher-order processes. They may instead require a radically different and more sophisticated approach, such as a solution of the Faddeev equations.

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Photoproduction of π^0's from Neutrons at 4 GeV*

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We have measured the reaction $\gamma+n\to\pi^0+n$ at a photon energy of 4 GeV for $0.2\leq -t \leq 1.8$ (GeV/c)^2. The cross section is slightly less than that with protons as a target.

Photoproduction reactions have contributed significantly to elucidating the complexities of high-energy reactions including the necessity for Regge cuts or absorption corrections.[1] One missing experiment in pseudoscalar meson photoproduction was π^0 photoproduction from neutrons. This is of particular interest since the process occurs predominantly (presumably) by ρ and ω exchange and the neutron-proton comparison can, in principle, separate these two, one being an isovector and the other an isoscalar exchange.

The experimental arrangement used is shown in Fig. 1. We used a standard bremsstrahlung photon beam from the high-energy electrons at the Cambridge Electron Accelerator. The two π^0 γ rays were each measured in position and energy by two 4×6 arrays of lead glass counters. From this measurement one can reconstruct the mass of the parent particle; we obtain a peak at the π^0 mass with a full width at half-maximum of 20%. On the other side of the beam at the angular position of the recoil nucleon we have a 4×5 array of scintillation counters; the stack is 37.5 cm deep along the nucleon direction. Two counters between this array and the deuterium target determine whether the nucleon recoil is charged or not. Pulse-height and timing information are also obtained for each event. A lead sheet (of variable thickness at different t) protects the counter stack from low-energy background.

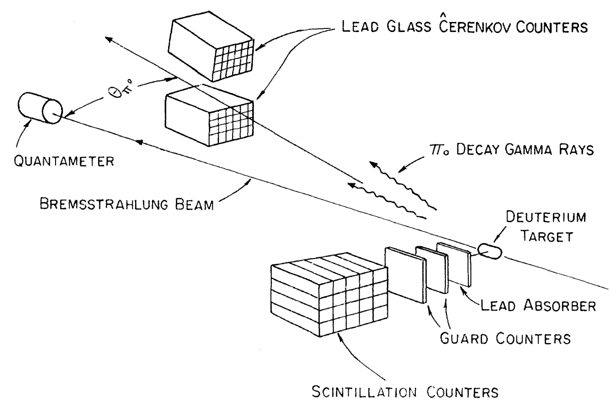

FIG. 1. Schematic layout of this experiment showing the π^0 and nucleon detectors.