the materialization of hadrons only depends upon the SU(3) color topology initially established by the interaction. The specific form suggested by the gluon-emission structure of QED should be regarded more cautiously but nonetheless appears consistent with the data and with expectations concerning the size of α_s.

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Two-Body Photodisintegration of ^{3}He and a New Test of Time-Reversal Invariance in the Electromagnetic Interaction

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We have measured the two-body photodisintegration process $\gamma^3\mathrm{He}\to pd$ in the energy region sensitive to intermediate photoexcitation of one nucleon to the isobar $\Delta(1238)$. We present angular distributions at center-of-mass angles from 30° to 150° for incoming photon energies 200–600 MeV. Magnetic dipole excitation appears to be suppressed.

We have studied the two-body photodisintegration of ^{3}He in the energy region spanning possible intermediate excitation of one nucleon to the $\Delta(1236)$ isobar with incident photon energies from 0.2 to 0.6 GeV. We sought to extract as complete and exact a set of angular distributions as experimentally feasible, as part of a new and independent test of time-reversal invariance in the electromagnetic interaction.

The experiment is motivated by the possibility that the CP-invariance violation in the weak interaction is due to a T-invariance violation in the electromagnetic interaction of hadrons.[1,2] As Hermiticity and current conservation prohibit any T-invariance violation at the γNN vertex, the $\gamma N\Delta$ (1236) vertex is a prime candidate for the observation of such effects. The reactions

$$\gamma n \rightarrow \pi^- p, \tag{1}$$

$$\gamma d \rightarrow np, \tag{2}$$

$$\gamma {}^3\mathrm{He} \rightarrow pd \tag{3}$$

are the simplest electromagnetic interactions which can have a $\Delta(1236)$ in an intermediate state. While early work on Reactions (1) and (2) appeared to show a substantial T-invariance violation,[3,4] further investigations have not confirmed this.[5,6] In this somewhat ambiguous context, an independent check involving the $\gamma N\Delta$ vertex in a different combination of amplitudes was clearly desirable. Process (3) and its inverse are well suited for such a check, since they avoid some of the principal experimental difficulties in processes (1) and (2), which contain two neutral particles. In process (3), only the photon is uncharged; also, the doubly charged ^{3}He is easy to identify. These advantages, while facilitating background-subtraction procedures, are acquired at the expense of a much smaller cross section, and of severe multiple scattering problems for low-energy d and ^{3}He particles. We report here on final data obtained on process (3). The inverse process was measured at the 184-in. Lawrence Berkeley Laboratory cyclotron; results and a data comparison are given in the subsequent Letter.[7] The experimental arrangement is indicated in Fig. 1. The California Institute of Technology electron synchrotron was run at 0.7-GeV endpoint energy. A resulting bremsstrahlung beam was collimated, scraped, and passed through two sweeping magnets. It then traversed a liquid ^{3}He target of thickness 10 or 0.80 g cm^{-2}. The target temperature of 1.5°K was continuously monitored by resistance measurements of a carbon resistor. The total energy in the photon beam was monitored with a thick-plate ion chamber, calibrated daily against two Wilson quantameters.

Of the two charged particles in the final state, the faster (p or d, depending on the kinematical setting) was analyzed in a magnetic spectrometer, the slower in a simple hodoscope with range modules. Laboratory angles varied from 20° to 85°

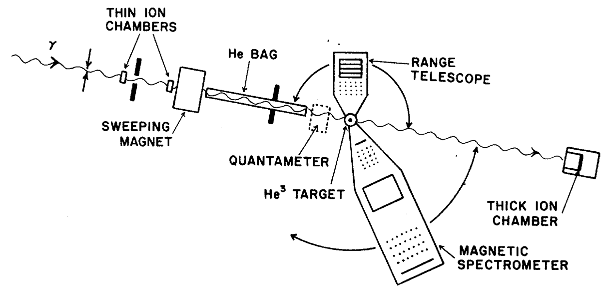

FIG. 1. Schematic layout of experiment at California Institute of Technology electron synchrotron. The faster particle in the pd final state was detected in magnet spectrometer, the slower one in the range telescope. Wire chambers define both trajectories.

for the spectrometer, and from 145° to 75° for the range detector. Each detector included a sequence of scintillation counters for trigger purposes, and magnetostrictive wire chambers for track delineation. Pulse heights were measured and recorded on all critical counters. In the magnet array, the time of flight was determined over a 6.5-m distance between two scintillation counters.

Approximately 300 000 triggers were recorded. Track reconstruction was done in the X and Y views separately. Ambiguities occurred in less than 1% of the events, and were resolved by choosing the track which gave the best coplanarity with the track in the other arm. The momentum of the particle in the magnet spectrometer was calculated using a floating-wire calibration of the magnet.[8] The momentum resolution varied from 0.5 to 1.5%, depending on the amount of multiple Coulomb scattering.

For events with a complete set of tracks, we determined the production angles of both final-state particles and the momentum of one. We thus overconstrained the kinematics by one parameter. To aid in a background subtraction, this constraint was used to calculate the mass of the particle observed in the range array. An additional constraint was provided by the requirement that the two final-state particles be coplanar.

Background events are due to processes such as $\gamma {}^3\mathrm{He} \rightarrow ppn, pd\pi^0$. For the settings where deuterons were detected in the magnet spectrometer, they were clearly separated from protons by the time-of-flight measurement [Fig. 2(a)]. For deuterons detected in the range array, a cruder separation from protons was obtained by placing a cut on a pulse-height distribution [Fig. 2(b)]. The remaining background contamination was typical-

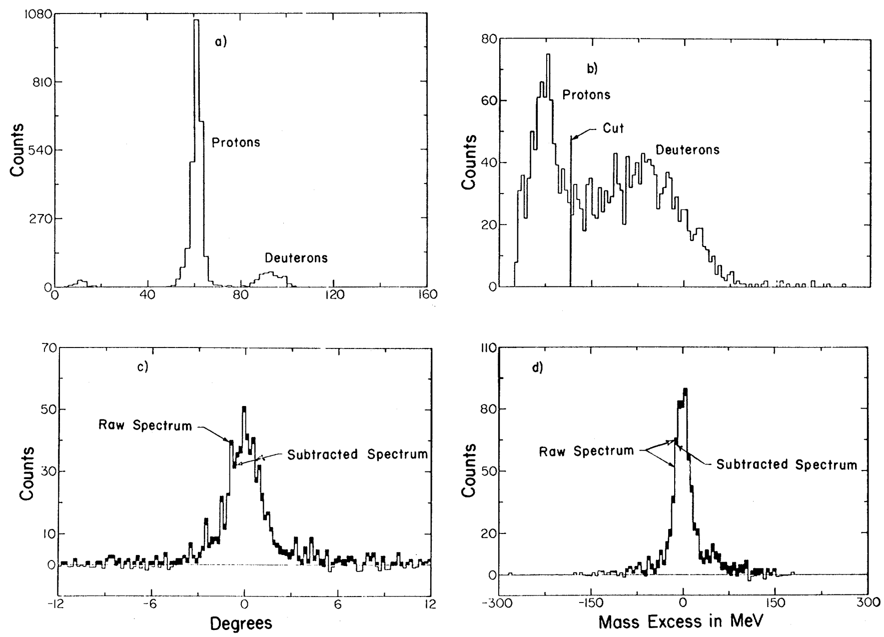

FIG. 2. (a) Time-of-flight distribution in the magnetic spectrometer arm; (b) pulse height distribution in range array; (c) effect of background subtration procedure on coplanarity; and (d) effect of background subtraction procedure on missing-mass distributions.

ly less than 15%. It was eliminated by an extrapolation from the tails of the missing-mass and coplanarity distributions [Figs. 2(c) and 2(d)]. A series of empty-target runs revealed no evidence of any signal due to interactions in the target walls.

To convert numbers of events into cross sections, various efficiencies were estimated. The geometric acceptance, calculated using a Monte Carlo method, was typically a few millisteradians. Nuclear scattering of protons and deuterons in scintillators and plastic filters (inserted to suppress soft-electron tracks in the chambers) reduced the efficiency by about 15%. Dead-time corrections amounted to 1 to 2%. The most serious correction was that due to inefficiencies in the spark chambers, where a complete set of tracks was found in only about 65% of all events. We determined these inefficiencies in two independent ways: First, we observed that the sample of events surviving the time-of-flight and pulse-height cuts described above is composed of 85% of the desired reaction and of 15% background. Assuming that the efficiencies are the same for the two types of events, we can determine them to an accuracy of 2%. Second, we observed individual chamber efficiencies for accepted tracks, defined by the other chambers, and then calculated event efficiencies by combinatorial techniques. The ensuing results, which are statistically less significant than those due to the first technique, always agreed within 5%.

Differential cross sections are shown in Figs. 3(a) and 3(b), as a function of angle and energy. Each datum point is the average over a bin 50 MeV wide in laboratory photon energy and 4° wide in center-of-mass angle. The error bars shown are statistical only. The systematic uncertainty amounts to some 6% in quadrature. The major sources are in beam monitoring and the calculation of the magnet acceptance.

Salient features of the experimental data are the following: (1) At energies below 300 MeV, a forward dip and a maximum at ~ 60° may be indicated. This would coincide with the trend of data at lower energies.[9] (2) With this exception (which makes the 30° cross section peak around 300 MeV), we observe a monotonic decrease of the differential cross section with angle and energy. The energy dependence can be approximated by $\exp[-E_\gamma/(0.1\ \mathrm{GeV})]$. (3) Where there is overlap with previously published data, we find considerable discrepancies in 60° and 90° cross-section values.[10]

In an attempt to understand the significance of the angular distributions, we fitted the data with a set of electromagnetic multipole transitions. We consider only the most plausible $E1$, $M1$, and

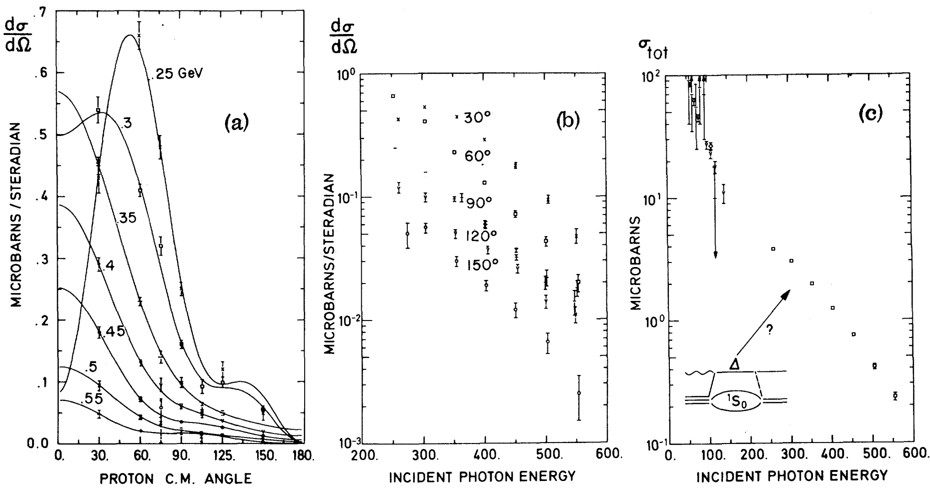

FIG. 3. (a) Angular distributions for the process $\gamma^3\mathrm{He}\rightarrow pd$ at photon energies from 250 to 550 MeV, between 30 and 150° c.m. Solid lines denote fits as described in the text. Note that secondary maxima at ~140° are due to the specific form of our fits at lower energy. They are not seen in these data. (b) Energy dependence of the differential cross section at fixed angles between 30 and 150°. (c) Total cross section for the process $\gamma^3\mathrm{He}\rightarrow pd$ versus photon energy, obtained from polynomial fits to our data. Also shown are previous results at lower energies (Ref. 9). Note that the 250-MeV point could be raised if the forward dip were not as pronounced as emerging from the fit. At $\Delta(1236)$ excitation energy (see inset), at best a hint is visible.

$E2$ transitions leading to S-, P-, or D-wave final states, yielding an angular distribution[11]

$$\sigma(\Theta)\simeq A+B\cos\theta+\sin^2\theta(C+D\cos\theta+E\cos^2\theta).$$

This restriction may be approximately justified for graphs of the type shown in Fig. 3(c), where the interaction of the incoming photon with one nucleon invites an analogy with pion photoproduction. We note, however, that the ^{3}He is a complex object; much higher l values may therefore be involved between the photon and the other nucleons. Also, final-state interactions, notably pd rescattering, may bring in high l values and will tend to build up a forward peak with rising energy.

The results of the fits are the solid lines in Fig. 3(a). If left unconstrained, the fits at 250 and 300 MeV would go negative; consequently, the χ^2's of the constrained fits are poor. Upon integration of the fits, total cross sections are obtained as shown in Fig. 3(c). While no Δ resonance "bump" appears in the total cross section, the trend of the data is somewhat above that of data at lower energies.[9] If a $\Delta(1236)$ is produced internally in the s channel of Reaction (3), its decay pion must be absorbed in a final-state interaction which conserves isospin. Therefore, the two spectator nucleons in the intermediate state must be in some (unbound) isotriplet state, of which the $^1S_0$ is the most likely candidate. This effect smears out any sharp energy-dependent behavior due to the presence of a Δ. Further, as the decay pion is in a P wave relative to the de-excited nucleon, its absorption by another nucleon leads most simply to a $^2D_{3/2}$ final combination of the proton and deuteron. If the predominance of magnetic dipole photons in the photoexcitation of free protons into $\Delta(1236)$ were to be taken over to our case, this would imply an angular distribution of the form $(2+3\sin^2\theta)$ for the $^2D_{3/2}$ final state. No such shape is to be observed in the data. Of the transitions considered, the results of the fits indicate the electric quadrupole $^2D_{3/2}$ transition to be the strongest and most rapidly varying in the vicinity of 300 MeV. While this behavior might well be due to a nonresonant process, the suggestive possibility remains that it is in fact due to Δ production. If we adopt this view, we find the interesting effect that the spin-isospin structure of the ^{3}He nucleus precludes the operation of a spectator-type process that would allow the intermediate Δ excitation to occur by its normally preferred mode (by $M1$ transition); rather, it may be restricted to a normally suppressed mode ($E2$).[12]

The identification of the observed angular dependence with individual transitions is tentative at best, and awaits further interpretation. A detailed-balance check of T invariance involving the reaction $pd\rightarrow\gamma^3\mathrm{He}$ will therefore not base itself on a specific, model-predicted effect, but will be based on a straightforward comparison of data and fits. We investigate this in the following paper.

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Radiative Formation of ^{3}He and a New Test of Time-Reversal Invariance in the Electromagnetic Interaction*

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We report on the measurement of the formation of $^3He^{++}$ in the collision of protons and deuterons, with the emission of a single photon. Energies and angles as chosen allow a comparison with the inverse process $\gamma{}^3He \to pd$. These data restrict possible T-invariance-violation effects in the electromagnetic interaction.

In this Letter, we report on a measurement of the process

$$pd \to {}^3He\gamma. \tag{1}$$

For an incident proton energy of 462 MeV, we collected data at center-of-mass angles of 45°, 60°, 75°, 90°, 105°, 120°, and 135°. Also, we measured 90° cross sections at incident proton energies of 377 and 576 MeV. The kinematical parameters were chosen so as to allow for a detailed-balance comparison of process (1) with its inverse as recently measured by some of us.[1] The energy range was suggested by our wish to probe for the effect of the possible excitation of one nucleon to the isobar $\Delta(1236)$ in the intermediate state.

For a detailed-balance investigation, reaction (1) and its inverse have some distinct advantages over the one- or two-nucleon tests involving the $\Delta \to \gamma N$ vertex, $\pi^- p \rightleftarrows \gamma n$ and $np \rightleftarrows \gamma d$, in both of which T-noninvariance effects had allegedly been observed. There is only one neutral in the system, and the doubly charged $^3He^{++}$ stands out in any Coulomb interaction. The resulting gain in kinematical definition of beam and final state is offset by a severely depressed cross section. It is on the 0.5-μb level, considerably smaller than the scanty previous information on the inverse