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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 ^{3}He^{++} 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 γ^3He$\rightarrow pd$. These data restrict possible T-invariance-violation effects in the electromagnetic interaction.

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

$$pd \rightarrow {}^3\mathrm{He}\gamma\,. \qquad (1)$$

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 $\Delta\rightarrow\gamma N$ 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 ^{3}He^{++} 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

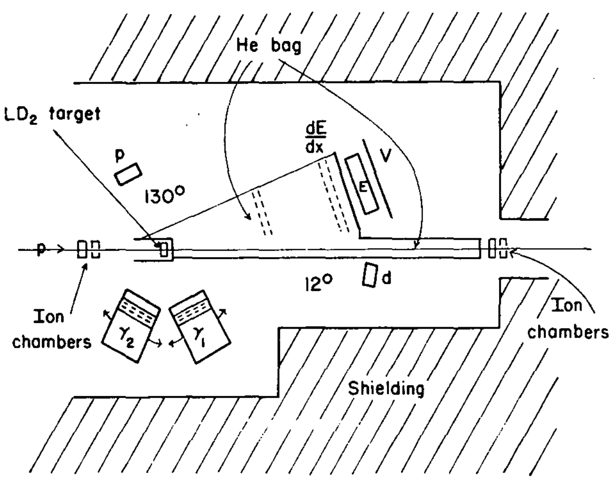

FIG. 1. Experimental setup.

process had indicated.[2] Moreover, the purely strong process $pd \to {}^3\mathrm{He}\pi^0$ dominates the final state associated with ${}^3\mathrm{He}^{++}$.

We therefore designed an experiment that would measure both final states, ${}^3\mathrm{He}\gamma$ and ${}^3\mathrm{He}\pi^0$, while optimizing the means of distinguishing between them.[3] The setup is schematically shown in Fig. 1. A beam of 720-MeV protons was extracted from the Lawrence Berkeley Laboratory 184-in. cyclotron and passed through a degrader to reach the desired energy. Its definition at the target was $\Delta p/p = \pm 0.5\%$, diameter ~5 cm, and divergence ~±8 mrad. Beam location and direction in the horizontal plane were continuously monitored by two split ion chambers separated by 271.5 in. Its energy was measured frequently by observing the Bragg peak in an argon ion chamber preceded by a variable-thickness copper degrader. The beam intensity was indicated by three ion chambers and linear integrators which remained consistent to better than 1% over the entire duration of the experiment.

We used two liquid deuterium targets: They were 1.27 and 0.42 cm thick[4] (for higher and lower ${}^3\mathrm{He}$ energies, respectively) to permit reasonable counting rates at an acceptable level of multiple-scattering errors. Effective target thickness and liquid level were monitored by two scintillator telescopes in coincidence, viewing the target from large-angle positions accessible only to elastic proton-deuteron scattering.

The ${}^3\mathrm{He}$ detection system consisted of a set of two (x, y, u, v) modules of magnetostrictive wire spark chambers for trajectory definition; a differential pulse-height counter to facilitate ${}^3\mathrm{He}^{++}$ separation; a large ($60\times60\times10$ cm^3) total-absorption scintillation counter[5]; and a subsequent veto counter. For runs at very low ${}^3\mathrm{He}$ energies, the differential pulse-height counter was removed.

For photon detection, we used two hodoscope spectrometers[6] thus permitting simultaneous measurements at two angular settings. They were composed of a sequence of a veto counter, V, for charged-particle rejection; a 5-cm, 2-radiation-length slab of lead glass for both conversion and pulse-height information; a scintillation counter, SC, for a photon-conversion trigger; a set of four x-y wire spark chamber planes for shower localization; and a 20-cm- (8-radiation-length-) thick block of lead glass. The total shower energy was determined from the summed output of this block and of the lead-glass converter. Each photon telescope was mounted on a pivot arm and could be positioned at laboratory angles from 23° to 120° with respect to the beam. The conversion efficiencies of the lead-glass converters were determined with a tagged photon beam. They vary from 57% at 150 MeV to 69% at 350 MeV.

We collected a total of over 10^6 triggers, recording all spark locations, all appropriate pulse heights, and the time of flight of the ${}^3\mathrm{He}$. We used standard trajectory-reconstructed techniques to produce kinematical quantities for a constrained least-squares fitting procedure. On the ${}^3\mathrm{He}$ side, tracks were constructed by looking for intersections of active wires in at least three of four planes. On the photon side, the intersection of reconstructed shower tracks with the converter midplane was used to define the photon trajectory. The chamber efficiencies were greater than 90% at all times. To reduce the number of events to be fully processed, we imposed various loose cuts. In Fig. 2(a), we show a raw pulse-height distribution for the differential pulse-height counter, where the ${}^3\mathrm{He}^{++}$ and the singly charged minimum-ionizing peaks are clearly separated. ${}^3\mathrm{He}$ time of flight and energy deposited in the range counter permit a separation of ${}^3\mathrm{He}$-associated events [Fig. 2(b)]. Other cuts were applied on the coplanarity of γ and ${}^3\mathrm{He}$, [Fig. 2(c)], on vertex position in the target, and on ${}^3\mathrm{He}$ trajectory location in the wire chamber.

Assuming the event to be due to reaction (1), we are dealing with a three-constraint fit. For each event a fit was made to the observed kinematic quantities subject to three constraints, and a χ^2 value was calculated, using the resolutions of the various measuring devices. The constraints were taken to be the total laboratory en-

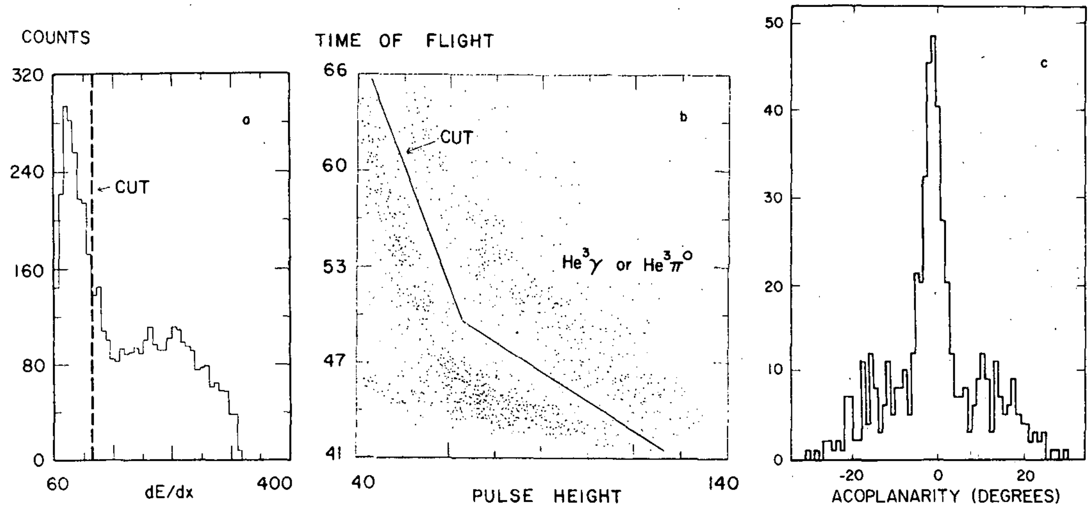

FIG. 2. (a) Pulse height distribution in ^{3}He differential counter; (b) time of flight versus pulse height in ^{3}He total-absorption counter; (c) ^{3}He-γ coplanarity.

ergy and two components of the total laboratory momentum. Background subtraction was performed on the χ^2 distribution, using Monte Carlo generated events normalized to the experimental data with $10<\chi^2<20$. This method is fully described in Ref. 3.

The results of the experiment are shown in Figs. 3(a) and 3(b). In Fig. 3(a), we give the angular distribution for process (1) at a proton energy of $T_p=462$ MeV. The closed points represent the results of this experiment; error bars as shown incorporate statistical effects as well as the systematic uncertainty of 1%. Triangles represent the data of the inverse process weighted according to the detailed-balance relation.

The two sets of data are remarkably consistent; note that there is *no adjustable parameter* in this comparison. Table I gives a quantitative comparison for those angles that were measured in both experiments. For five such comparisons, the χ^2 criterion yields 4.50, corresponding to a confidence level of 50% for the T-invariance hypothesis. We also show the energy dependence of the 90° c.m. differential cross section in Fig. 3(b). There is no visible enhancement at the Δ resonance energy. Again, we compare with the inverse process, and find good statistical agreement ($\chi^2=0.92$ for three points, confidence level 80%).

Within the context of the multipole description of process (1), given in the preceding Letter, we may extract limits on possible T-invariance-violating amplitudes. We suppose all the violation is in the $E2\to{}^2D_{3/2}$ amplitude, corresponding to a $1+\cos^2\theta$ distribution. If we also fit the difference in the angular distribution of process (1) and its inverse with the form $1+\cos^2\theta$, it accounts for $(5\pm5\%)$ of the cross section due to the total $E2$

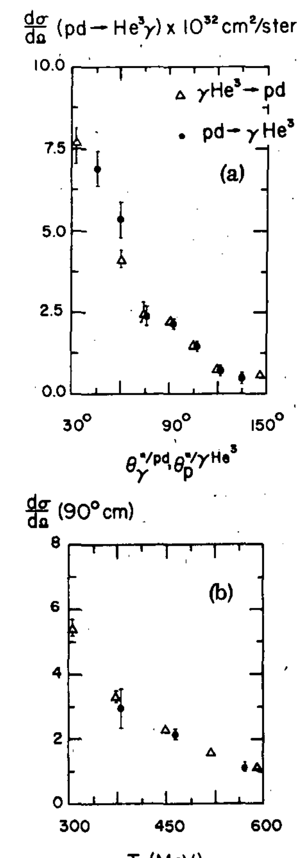

FIG. 3. (a) Angular distributions for $pd\to{}^3$Heγ at $T_p=465$ MeV and $E_\gamma=320$ MeV; (b) energy dependence at 90° (c.m.) for $pd\to{}^3$Heγ.

TABLE I. Quantitative comparison of cross-section data for $pd \to {}^3\text{He}\gamma$ and inverse. The $\gamma{}^3\text{He} \to pd$ data are inverted assuming T invariance to be valid. $\Delta = \sigma(pd) - \sigma(\gamma{}^3\text{He})$.

$\theta_{^3\text{He}}{}^{\text{c.m.}}$	T_p (GeV)	$\sigma(\gamma{}^3\text{He})$ (10^{-32} cm^2)	$\sigma(pd)$ (10^{-32} cm)	$\Delta/\sigma(pd)$	χ^2
60	0.462	0.64 ± 0.15	0.77 ± 0.11	-0.17 ± 0.24	0.46
75	0.462	1.43 ± 0.23	1.48 ± 0.10	0.04 ± 0.17	0.04
90	0.462	2.16 ± 0.17	2.16 ± 0.12	0.00 ± 0.10	0.00
105	0.462	2.63 ± 0.35	2.50 ± 0.17	-0.05 ± 0.16	0.19
120	0.462	4.04 ± 0.21	5.27 ± 0.60	-0.23 ± 0.12	3.81
			average	0.03 ± 0.07	sum 4.50

mode. We suppose this difference arises from the interference of the resonant amplitude with the background. Defining x as the ratio of magnitudes of resonant to nonresonant amplitudes, and φ as the T-invariance-violating phase, we obtain

$$x \sin\varphi = \tfrac{1}{80}\alpha \pm \tfrac{1}{80}\alpha,$$

where $\alpha = 1 - 2x\sin\varphi + x^2$, the ratio of total $E2$ cross section to the nonresonant part. The fits[7] give only a crude estimate for α, but we can roughly say $1 < \alpha < 2$. If the violation is maximal ($x \sim 1$), then the phase is $1.5° \pm 1.5°$. In any case, the real part of the T-invariance-violating amplitude is always 1 to 2% of the $E2$ transition amplitude.

In summary, our test of T invariance in the electromagnetic interaction via the reactions $\gamma{}^3\text{He} \rightleftarrows pd$ yields results completely consistent with the validity of T invariance when comparing both angular distribution and absolute normalization. The latter feature represents an advance over previous work involving the reactions $\gamma n \rightleftarrows \pi^- p$ and $\gamma d \rightleftarrows pn$. The sensitivity of our result is approximately 5% in cross section, in a parameter-free comparison. It corresponds to 2% in amplitude in the context of a multipole model.

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[1]C. A. Heusch *et al.*, preceding Letter [Phys. Rev. Lett. 37, 405 (1976)].

[2]P. Picozza *et al.*, Nucl. Phys. A157, 190 (1970).

[3]For experimental details, see R. V. Kline, Ph.D. thesis, California Institute of Technology, 1973 (unpublished).

[4]The thickness of the thin deuterium target constituted the largest systematic error in this experiment. Bubbling of the target under pressure had to be reconstructed from the monitors and other secondary information.

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[6]C. A. Heusch *et al.*, Nucl. Instrum. Methods 120, 237 (1974)

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