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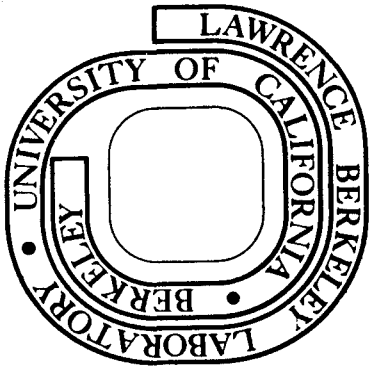

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DISCLAIMER

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ABSTRACT

The photon spectrum from the pion capture reaction $\pi^- + t \rightarrow 3n + \gamma$ was measured with a high-resolution pair-spectrometer to study the A=3 system in a pure T = 3/2 state. The measured branching ratio $(\pi^- t \rightarrow nn\gamma)/(\pi^- t \rightarrow nnn\gamma \text{ or } nnn)$ is $4.5 \pm 0.8\%$. The shape of the photon spectrum is in satisfactory agreement with theoretical calculations which include final state interactions among the three neutrons. No evidence for a bound trineutron is found.

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In only a few reactions can one investigate the A=3 system in a pure T = 3/2 state. Bound and unbound states of the (3p) and (3n) systems have been searched for in various reactions involving pion[1], nucleon[2], and mass-3 (Ref. 2) projectiles on ^{3}H, ^{3}He, and heavier targets. Nevertheless, the available data on the existence of T = 3/2 resonances and possible bound 3n states are scarce, inconclusive, and sometimes conflicting. All reactions previously studied are plagued by the fact that although a (3p) or (3n) system is produced, there is at least one additional strongly interacting particle in the final state. The reaction on which we report here, $\pi^- + t \rightarrow 3n + \gamma$, has only an extra photon in the final state. From our previous experiment[3], $\pi^- + {}^3\text{He} \rightarrow dn\gamma$ and $pnn\gamma$, it is known that the radiative capture of stopped pions produces final states in which three nucleons are preferentially found with low relative momenta – a favorable situation for the search of resonant states. None were found, but since the T = 1/2 channel contributed most of the rate (82%, Ref. 4), possible structures of the weaker T = 3/2 channel could be obscured. In the radiative pion capture on ^{2}H, one also finds the final state neutrons in predominantly low relative momenta states, which has permitted the accurate determination[5] of a_{nn}.

Additional interest in this reaction is in the ^{3}H-π atomic physics. The hydrogen isotopes are unique in the field of π^- capture studies, since in liquid hydrogen (and tritium) the pionic cascade is perturbed[6] by the strong electric fields experienced by the neutral pionic atom as it passes protons of other hydrogen atoms. These induce Stark transitions which force the pion into s orbits with high principal quantum number n, from which capture then takes place. Thus the 2p orbit of ^{3}H is not populated, which contrasts strongly with ^{3}He where an ~ 55% p-state captured probability is estimated[7]. Since the s-state radiative π-capture transition rates can be calculated quite accurately[4] in the impulse approximation (IA), as well as with the PCAC plus soft pion approach[8], the measured branching ratios can be used together with the theoretical radiative rates to predict "experimental" strong absorption s-level widths. These then are used to test assumptions of the 2-nucleon absorption model[4], the evaluation of which is particularly significant for the 3-nucleon system.

The experiment was performed in the low energy pion (LEP) channel of the Clinton P. Anderson Meson Physics Facility (LAMPF). Figure 1 shows the experimental set up. To permit mounting the experiment in parallel with other

activities at the channel, the beam line was extended with an additional quadrupole doublet to produce a second focus 22.2 m from the pion production target. A spot size of ≃ 3x4 cm (rms) was achieved for a π^- momentum of 200 MeV/c with $\Delta p/p = \pm 1\%$, and LEP channel solid angle of 17.6 msr. Typical rates with a 10μA, 800 MeV proton beam incident on a 1 cm Al_2O_3 production target were $2.4 \times 10^5 \pi^-/s$ in the first two elements of our beam telescope, and $2 \times 10^3 \pi^-/s$ pions stopping in the ^3H content of the target (the macro pulse width was 330μsec at a repetition rate of 120 pulses/s). The tritium target cell[9] consisted of a stainless steel (type 304) cylinder with 2.7 cm diameter, 4.1 cm height, and 0.0075 cm wall thickness (Fig. 1, inset) oriented with its axis perpendicular to the beam. For calibration purposes, an identical cell filled with liquid hydrogen was mounted on the same mobile boom, so the two targets could be quickly interchanged by moving the target cart which was mounted on rails. The operating temperatures (densities) for the $^1H_2$ and $^3H_2$ targets respectively were 19.53 ± 0.03 K (0.07188 ± 0.0001 g cm^{-3}) and 23.76 ± 0.03 K (0.261 ± 0.001 g/cm^{-3}). A temperature difference of 3.24 K exists between the $^3H_2$ cell and the liquid hydrogen coolant due to the 1.95 watts/mole liberated in ^3H β-decay. The ^3H target mass was 5.88 g with a radioactivity of 5.7×10^4 Ci.

The photon spectrum was measured with the pair spectrometer employed in our previous work[3,10] at the 184" cyclotron in Berkeley. The trajectories of the e^+-e^- pairs were again measured with 3 sets of magnetostrictive read-out wire chambers with 4 wire planes each at ± 12° and 0° to the magnet midplane and a wire separation of 0.1 cm. Since we were limited to a short running period (8 days), the converter thickness was doubled to 0.44 g/cm^2 (6% radiation length) of gold. This increased the line width at 129.4 MeV to 3.5 MeV (fwhm), as seen in Fig. 2. The absolute efficiency of the spectrometer and its dependence on the photon energy was calculated with a Monte Carlo program described previously[10]. The acceptance curve (Fig. 2) includes the efficiency of our pattern recognition and momentum analysis programs which select the real e^+-e^- pairs originating in the converter from the total triggers. Typically 5% (10%) of the triggers correspond to such events for $^3H_2$($^1H_2$) targets. The acceptance was verified by measuring the branching ratios for $\pi^- p \to n\gamma$ and $\pi^- p \to n\pi^\circ$; $\pi^\circ \to 2\gamma$. For hydrogen data taken throughout the run we obtain 44 ± 4% and 65 ± 6%, respectively (the sum was not constrained to 100%). For the Panofsky ratio we get 1.46 ± 0.16. The best experimental values for these quantities[11] are 39.5 ± 0.3%, 60.5 ± 0.3%, and 1.533 ± 0.021, respectively.

The raw spectrum obtained with the tritium target is shown in Fig. 3a. It contains 2030 events. The absolute normalization for this spectrum is based on the hydrogen runs which were interspersed with the tritium runs. We normalize to the same number of incoming pions, correcting for the small difference in the pion stopping densities of the two targets. The number of ^1H and ^3H atoms in the two targets differed by 21% due to the different operating temperatures (densities) in the otherwise identical cells. The true tritium spectrum is obtained from the raw data by subtracting the following contributions:

(1) The tritium cell contains 1.00 atom-% of $^1H_2$. This corresponds to 139 ± 7 events with the spectral shape taken from the hydrogen data.

(2) The contribution from the 2.79% $^2H_2$ was subtracted using the theoretical shape of Bander[12] for the $\pi^- d \to nn\gamma$ reaction with $a_{nn} = -17F$ folded with the experimental line shape and acceptance. This theory fits well the n-γ angular correlation data of Haddock et al.[5] With the measured branching ratio of 24.7 ± 0.7%[13], this yields a subtraction of 158 ± 13 events.

(3) Pions stopping in the stainless steel target cell and in the scintillator in front of the target produce our most important background. Time limitations permitted only one run with an empty cell with low statistics. From it we deduce a total of 669 ± 133 events to be subtracted. The shape of the stainless steel spectrum and the branching ratio were measured in a separate experiment using the SIN-pair spectrometer[14]; the scintillator (CH) spectrum is known since the carbon spectrum and the fraction of pions stopping in the hydrogen content of CH is known[15]. Using the branching ratios we find that 342 ± 62 events originate in the steel, the rest in the scintillator. We give in Fig. 3b the different background contributions, which were subtracted. The remaining 1064 ± 170 events yield a radiative branching ratio $R_\gamma = 4.5 \pm 0.8\%$. The tritium spectrum is shown in Fig. 3c. As for the $\pi^- {}^3He \to dn\gamma$ and $pnn\gamma$ reaction[3], one sees that the distribution is peaked towards low relative energies of the (3n) system. The kinematical threshold for 3 free neutrons is $E_\gamma = 126.96$ MeV. No indication of a bound trineutron is observed. However the branching ratio to such a state must exceed 0.3% in order to be distinguished from the background induced in the region between 127 and 132 MeV by the hydrogen and deuterium content of our target. As can be seen from Fig. 3b, we have probably overestimated this contribution by normalizing the rate to the atomic fractions of these isotopes. The formation of HT and HD molecules with consequent transfer of the bound pions to the tritium would decrease these contributions. The upper limit

of 0.3% on the other hand is in strong contrast to the 6.6 ± 0.8%[3] branching ratio for forming the triton in the $\pi^{-3}He \rightarrow t\gamma$ reaction.

The measured tritium spectrum and branching ratio arise from a distribution of s-state captures related to the radiative (λ_γ) and total absorption (λ_a) transition rates by the sum $R_\gamma = \Sigma_n [\lambda_\gamma(ns)/\lambda_a(ns)]\omega(ns)$. For liquid hydrogen, Leon and Bethe calculate capture probabilities $\omega(ns)$ = .04, .39, .44, and .09 for n = 2, 3, 4, and 5 respectively. A similar capture schedule is expected for tritium since the Stark transition rates are not significantly affected by the atomic mass. Most theoretical treatments take λ_γ/λ_a to be independent of n. For the hydrogen isotopes this should be an excellent approximation for ns orbits with $n < 10$, since these wave functions are exceedingly constant through the nuclear volume (< 10F) and thus can be factored out of the radial integrals for both λ_γ and λ_a, cancelling in the ratio. The individual rates are proportional to $|\phi_{ns}(0)|^2$ which for hydrogenic wave functions scale as $|\phi_{1s}(0)|^2/n^3$. (Leon and Bethe take $\lambda_a(ns) = 1.1\times10^{15}s\ /n^3$, not too different from our value $\lambda_a(1s) = (1.25 \pm 0.03)\times10^{15}/s$ (Table 1) based on photoproduction cross sections and the Panofsky ratio.) Theoretical radiative capture widths and "experimental" total widths $\lambda_a(1s) = \lambda_\gamma(1s, \text{theory})/R_\gamma(\text{experiment})$ are listed in Table 1 for ^1H, ^2H, ^3H, and ^3He. We expect these to be quite accurate since the $\lambda_\gamma(1s)$ were calculated in the IA, considered[4,18] accurate to better than 12%. The $\lambda_a(1s)$ depend on the assumption that λ_γ/λ_a be independent of n. The value $\lambda_\gamma(1s) = 7\times10^{13}/s$ for ^3H was obtained by Phillips and Roig[16] in a calculation which treats final state interactions in the outgoing neutrons in the Amado model (as in the calculation[4] for ^3He). The non-radiative rate is calculated with the 2-N absorption model, giving $\lambda_n(\pi^- t \rightarrow 3n) = (1.0\pm0.3)\times10^{15}/s$. The resultant 1s state branching ratio $\lambda_\gamma/(\lambda_\gamma+\lambda_n) = 6.5\pm2.0\%$ is in fair agreement with our measurement of 4.5±0.8%. The extracted 1s level width of 1.02 eV is seen to be much smaller than the 37 eV for ^3He and the 3.67 eV for ^3H obtained[17] from the phenomenological extrapolation of data on heavier nuclei.

The data and the theoretical spectrum $d\lambda_\gamma(1s)/dE_\gamma$ of Phillips and Roig[16] are compared in Fig. 3c. The overall fit to the data is satisfactory, although small excesses of events in the low mass region $7<E_x(3n)<16$ MeV are observed. Considering the low statistics and uncertainty in background subtraction, it would be premature to regard this as evidence for a T = 3/2 resonance in the A = 3 system.

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TABLE I. Radiative pion capture branching ratios and 1s-level widths for the isotopes of hydrogen and ^{3}He.

Isotope	Reaction	Radiative Capture Branching Ratio (%)	Radiative Capture 1s Width (theory) (eV)	Total 1s Level Width[a] (eV)
^{1}H	$\pi^- p \rightarrow n\gamma$	39.5 ± 0.3[b]	0.324 ± 0.008[c]	0.82 ± 0.02
^{2}H	$\pi^- d \rightarrow nn\gamma$	24.7 ± 0.7[d]	0.251 ± 0.025[e]	1.02 ± 0.11
^{3}H	$\pi^- t \rightarrow nnn\gamma$	4.5 ± 0.8[f]	0.046[g]	1.02 ± 0.18
^{3}He	$\pi^- {}^3\mathrm{He} \rightarrow t\gamma$	6.6 ± 0.8[h]	2.44[i]	37.0 ± 4.5

[a]Obtained from the theoretical radiative capture rate and the experimental branching ratios. The error reflects the experimental uncertainty.

[b]Reference 11.

[c]Using $|E^{\pi^-}_{0+}| = (3.26 \pm 0.04) \times 10^{-2}/m_\pi$ and

$$\Gamma_\gamma(1s) = \hbar 8 |E^{\pi^-}_{0+}|^2 \, (k/m_\pi)(\alpha m_\pi)^3 (1+m_\pi/m_p)^{-2}$$

[d]Reference 13.

[e]Obtained from $\lambda(\pi^- d \rightarrow nn\gamma)/\lambda(\pi^- p \rightarrow n\gamma) = 0.775 \pm 0.078$ (Ref. 18) and hydrogen rate given above.

[f]This experiment.

[g]Reference 16.

[h]Reference 3.

[i]Reference 4.

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FIGURE CAPTIONS

Fig. 1. The experimental set up at LAMPF showing the pair-spectrometer and liquid tritium target. The insert shows a cross section of the target cell obtained from an x-ray radiograph.

Fig. 2. Calibration spectrum obtained with the hydrogen target cell. The energy dependence of the spectrometer acceptance is also shown.

Fig. 3. (a) Raw photon spectrum obtained from the tritium target.
(b) Background spectra for hydrogen, deuterium, steel and CH.
(c) Spectrum from reaction $\pi^- t \rightarrow nn\gamma$ after subtraction of ^1H, ^2H, steel and scintillator contribution. Solid curve is the theoretical spectrum of Phillips and Roig[16] (text), folded with acceptance and instrumental line shape and normalized to the total number of photons.

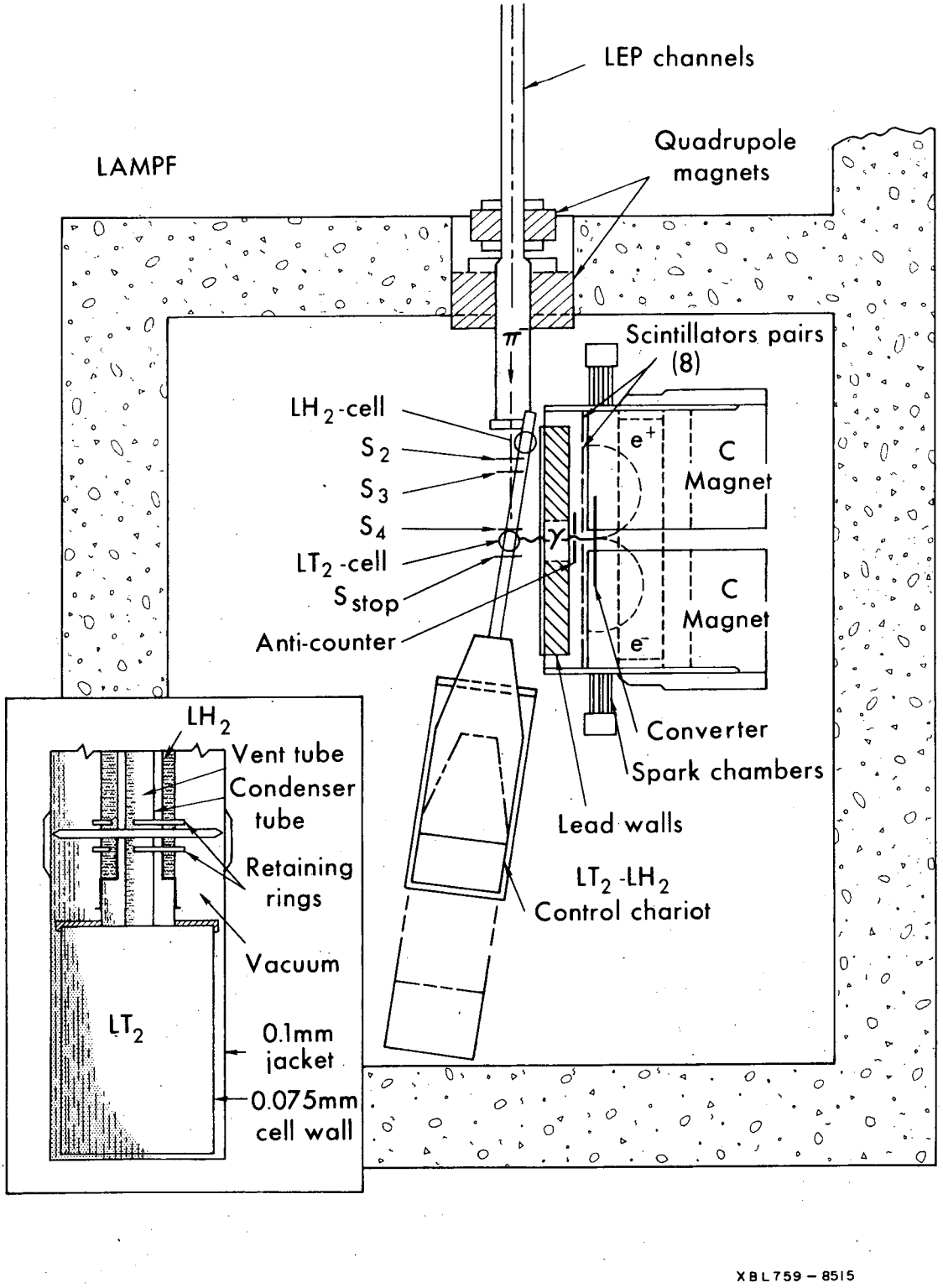
LEP channels
LAMPF
Quadrupole magnets
Scintillators pairs (8)
LH_2-cell
S_2
S_3
S_4
LT_2-cell
S_{stop}
Anti-counter
e^+
C Magnet
γ
C Magnet
e^-
Converter
Spark chambers
Lead walls
LT_2-LH_2 Control chariot
LH_2
Vent tube
Condenser tube
Retaining rings
Vacuum
LT_2
0.1mm jacket
0.075mm cell wall
XBL759-8515

Figure 1.

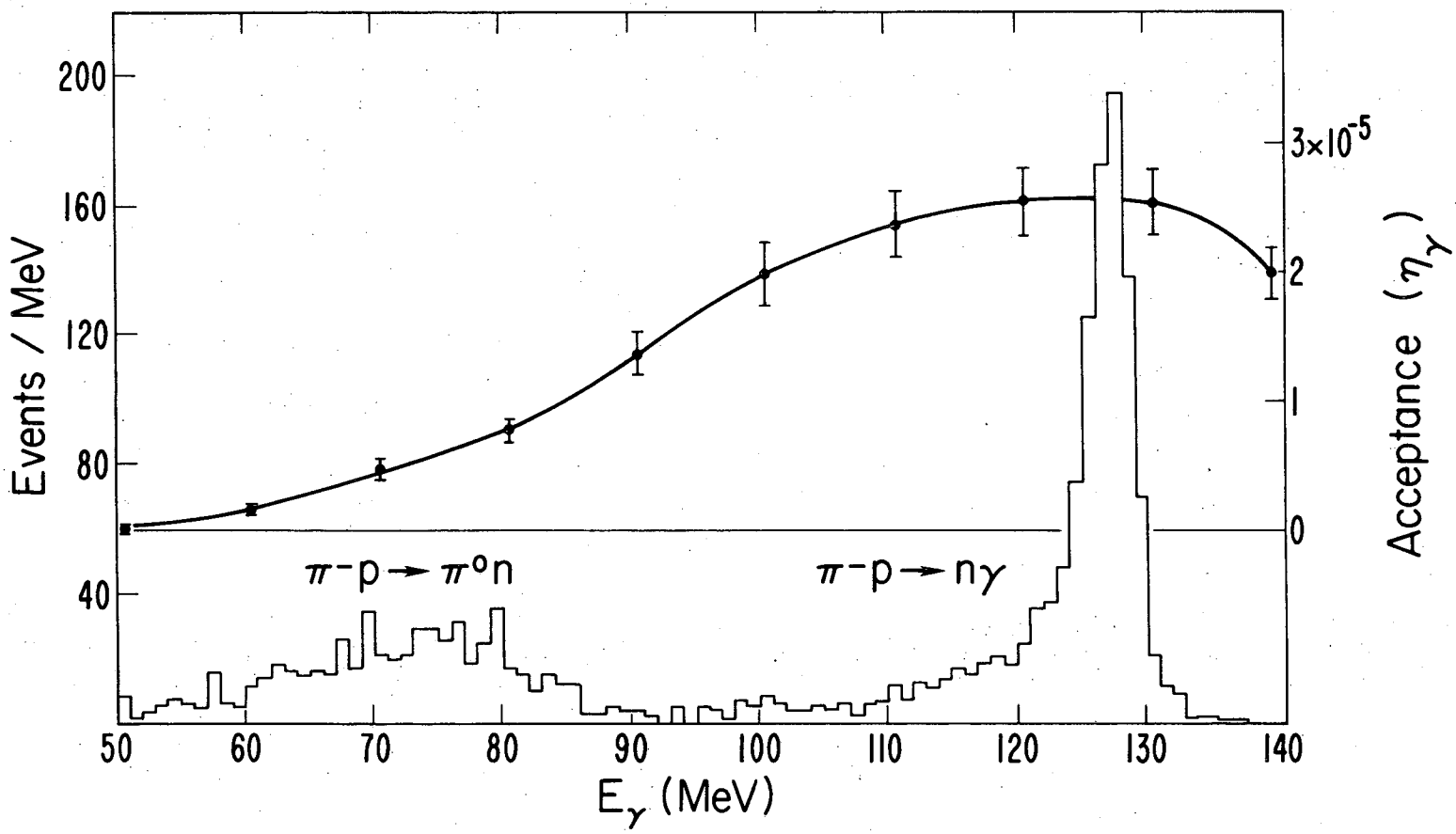

Figure 2

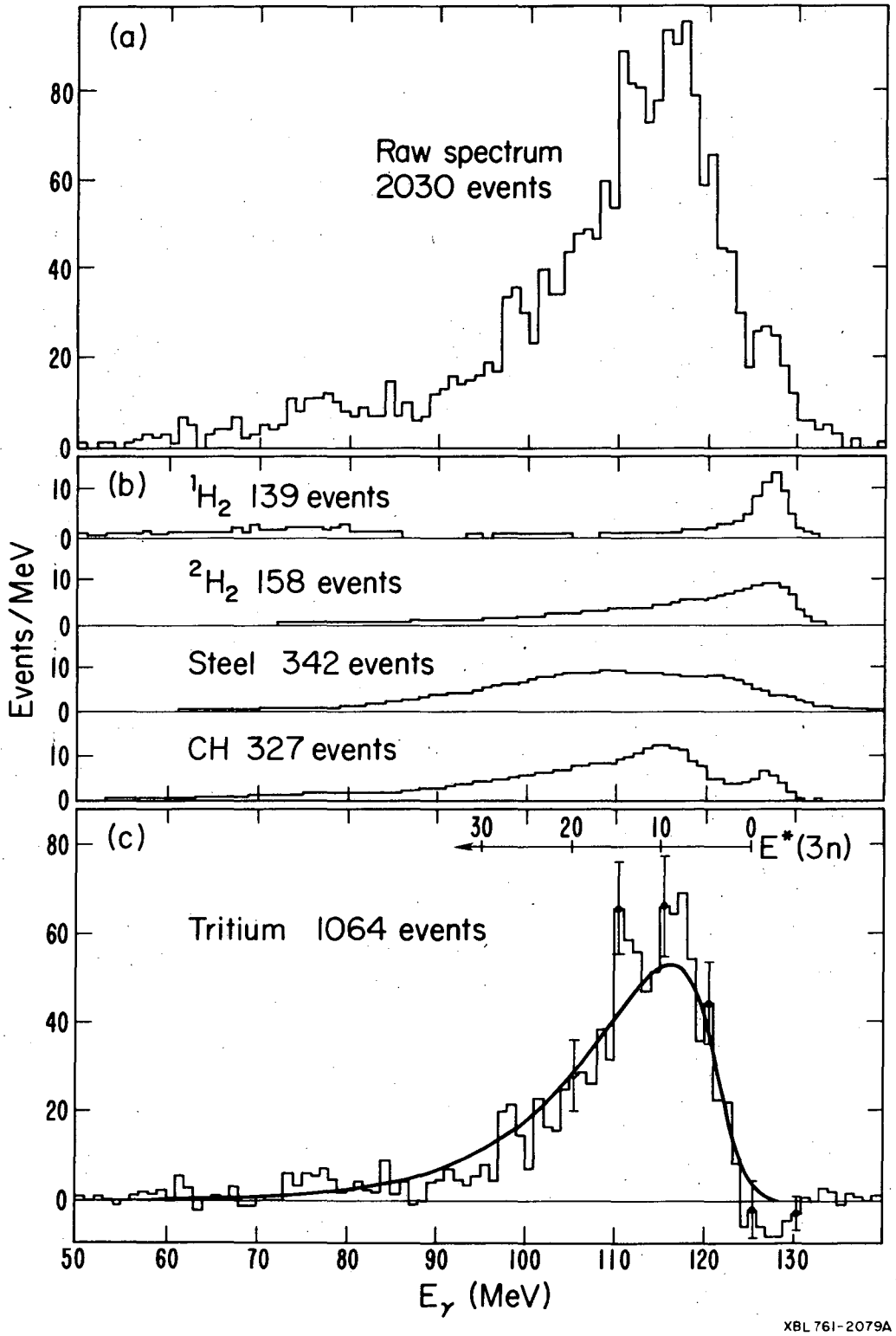
(a)
Raw spectrum
2030 events
(b)
$^1H_2$ 139 events
$^2H_2$ 158 events
Steel 342 events
CH 327 events
Events/MeV
(c)
Tritium 1064 events
30 20 10 0 E*(3n)
E_γ (MeV)
XBL 761-2079A

Figure 3.

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