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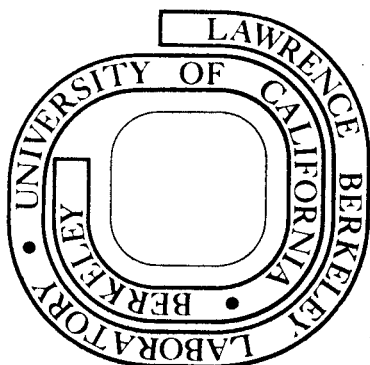
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PHOTON SPECTRUM IN PION CAPTURE ON TRITIUM*

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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. The measured branching ratio $(\pi^- t \rightarrow nnn\gamma)/(\pi^- t \rightarrow nnn\gamma \text{ or } nnn)$ 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 ${}^3\text{H}$, ${}^3\text{He}$, 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, at least one additional strongly interacting particle is 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. Our previous experiment,³ $\pi^- + {}^3\text{He} \rightarrow dn\gamma$ and $pnn\gamma$, demonstrated that 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 $T = 1/2$ channel contributed most of the rate (82%),⁴ possible structures of the weaker $T = 3/2$ channel could be obscured.

Additional interest in this reaction is in the ${}^3\text{H}-\pi$ atomic physics. The hydrogen isotopes are unique in the field of π^- capture studies, since the pions are exclusively absorbed from $1s$ -orbits.⁵ Since the s -state radiative π -capture transition rates can be calculated quite accurately⁴ in the impulse approximation (IA) as well as with the PCAC-plus-soft-pion approach,⁶ 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-nuclear 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. A beam spot size of $\sim 3 \times 4$ cm (rms) focused 22.2 m from the pion production target 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 were $2.4 \times 10^5 \pi^-/\text{sec}$ in the first two elements of our beam telescope, and $2 \times 10^3 \pi^-/\text{sec}$ stopping in the ^3H target. The tritium target cell⁷ made of a stainless steel (type 304) cylinder (Fig. 1, insert) was 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. The operating temperatures (densities) for the $^1\text{H}_2$ and $^3\text{H}_2$ targets respectively were $19.53 \pm 0.03^\circ\text{K}$ ($0.07188 \pm 0.0001 \text{ g/cm}^3$) and $23.76 \pm 0.03^\circ\text{K}$ ($0.261 \pm 0.001 \text{ g/cm}^3$). A temperature difference of 3.24°K existed between the $^3\text{H}_2$ cell and the liquid hydrogen coolant due to the 1.95 W/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^{3,8} at the 184-inch cyclotron in Berkeley. The absolute efficiency of the spectrometer and its dependence on the photon energy was calculated with a Monte Carlo program described previously.⁸ The efficiency of our pattern recognition and momentum analysis programs was verified by measuring the branch ratios for $\pi^- p \rightarrow n\gamma$ and $\pi^- p \rightarrow n\pi^0$; $\pi^0 \rightarrow 2\gamma$. For hydrogen data taken throughout the run we obtain $44 \pm 4\%$ and $65 \pm 6\%$, respectively (the sum was not constrained to 100%). For the Panofsky ratio we get $1.46 \pm .16$. The best experimental values for these quantities⁹ are $39.5 \pm 0.3\%$, $60.5 \pm 0.3\%$, and 1.533 ± 0.021 , respectively.

The raw spectrum obtained with the tritium target is shown in Fig. 2a. 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 21% difference in the pion stopping densities of the two targets. The true tritium spectrum is obtained from the raw data by subtracting the following contributions:

- 1) The tritium cell contains 1.00 atom-percent of $^1\text{H}_2$. This corresponds to 139 ± 7 events with the spectral shape taken from the hydrogen data.
- 2) The contribution from the 2.79% $^2\text{H}_2$ was subtracted using the theoretical shape of Bander¹⁰ for the $\pi^- d \rightarrow nn\gamma$ 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.*¹¹ With the measured branching ratio of $24.7 \pm 0.7\%$ ¹² 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;¹³ the scintillator (CH) spectrum is known since the carbon spectrum and the fraction of pions stopping in the hydrogen content of CH is known.¹⁴ Using the branching ratios we find that 342 ± 62 events

originate in the steel, the rest in the scintillator. The different background contributions which were subtracted are shown in Fig. 2b. The remaining 1064 ± 170 events yield a radiative branching ratio $R_\gamma = 4.5 \pm 0.8\%$. The tritium spectrum is shown in Fig. 2c.

As for the $\pi^- {}^3\text{He} \rightarrow \text{dn}\gamma$ and $\text{pn}\gamma$ reaction,³ one sees that the distribution is peaked towards low relative energies of the $(3n)$ system. The kinematical threshold for three 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. 2b, we may have 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 $6.6 \pm 0.8\%$ ³ branching ratio for forming the triton in the $\pi^- {}^3\text{He} \rightarrow \text{t}\gamma$ reaction.

The measured tritium spectrum and branching ratio arise from a distribution of s-state captures similar to that of liquid hydrogen.⁵ To compare the radiative (λ_γ) and total absorption (λ_a) transition rates to the measured branching ratio R_γ , most theoretical treatments take λ_γ/λ_a to be independent of n . For the hydrogen isotopes, this should be an excellent approximation for s-orbits with $n < 10$ since these wave functions are essentially constant through the nuclear volume and 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

0 0 0 0 4 4 0 2 4 5 7

wave functions scale as $|\phi_{1s}(0)|^2/n^3$. Theoretical radiative capture widths and "experimental" total widths obtained from $\lambda_a(1s) = \lambda_Y(1s, \text{theory})/R_Y(\text{experiment})$ are listed in Table I for ^1H , ^2H , ^3H , and ^3He . The $\lambda_Y(1s)$ were calculated in the IA, considered^{4,15} accurate to better than 12%. The value $\lambda_Y(1s) = 7 \times 10^{13}/\text{sec}$ for ^3H was obtained by Phillips and Roig¹⁶ in a calculation which treats final state interactions in the outgoing neutrons in the Amado model (as in the calculation⁴ for ^3He). The nonradiative rate is calculated with the 2-N absorption model, giving $\lambda_n(\pi^-t \rightarrow 3n) = (1.0 \pm 0.3) \times 10^{15}/\text{sec}$. The resultant 1s state branching ratio $\lambda_Y/(\lambda_Y + \lambda_n) = 6.5 \pm 2.0\%$ is in fair agreement with our measurement of $4.5 \pm 0.8\%$. 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 obtained¹⁷ from the phenomenological extrapolation of data on heavier nuclei.

The data and the theoretical spectrum $d\lambda_Y(1s)/dE_Y$ of Phillips and Roig¹⁶ are compared in Fig. 2c. 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 ^3He .

Isotope	Reaction	Radiative Capture Branching Ratio (%)	Radiative Capture 1s Width (theory) (eV)	Total 1s Level Width(eV) ^a
^1H	$\pi^- p \rightarrow n\gamma$	39.5 ± 0.3^b	0.324 ± 0.008^c	0.82 ± 0.02
^2H	$\pi^- d \rightarrow nn\gamma$	24.7 ± 0.7^d	$.251 \pm .025^e$	$1.02 \pm .11$
^3H	$\pi^- t \rightarrow nnn\gamma$	4.5 ± 0.8^f	$.046^g$	1.02 ± 0.18
^3He	$\pi^- ^3\text{He} \rightarrow t\gamma$	6.6 ± 0.8^h	2.44^i	37.0 ± 4.5

^aObtained from the theoretical radiative capture rate and the experimental branching ratios. The error reflects the experimental uncertainty.

^bReference 9.

^cUsing $|E_{0+}^{\pi^-}| = (3.26 \pm 0.04) \times 10^{-2}/m_\pi$ and

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

^dReference 12.

^eObtained from $\lambda(\pi^- d \rightarrow nn\gamma)/\lambda(\pi^- p \rightarrow n\gamma) = 0.775 \pm 0.078$ (Ref. 15) and hydrogen rate given above.

^fThis experiment.

^gReference 16.

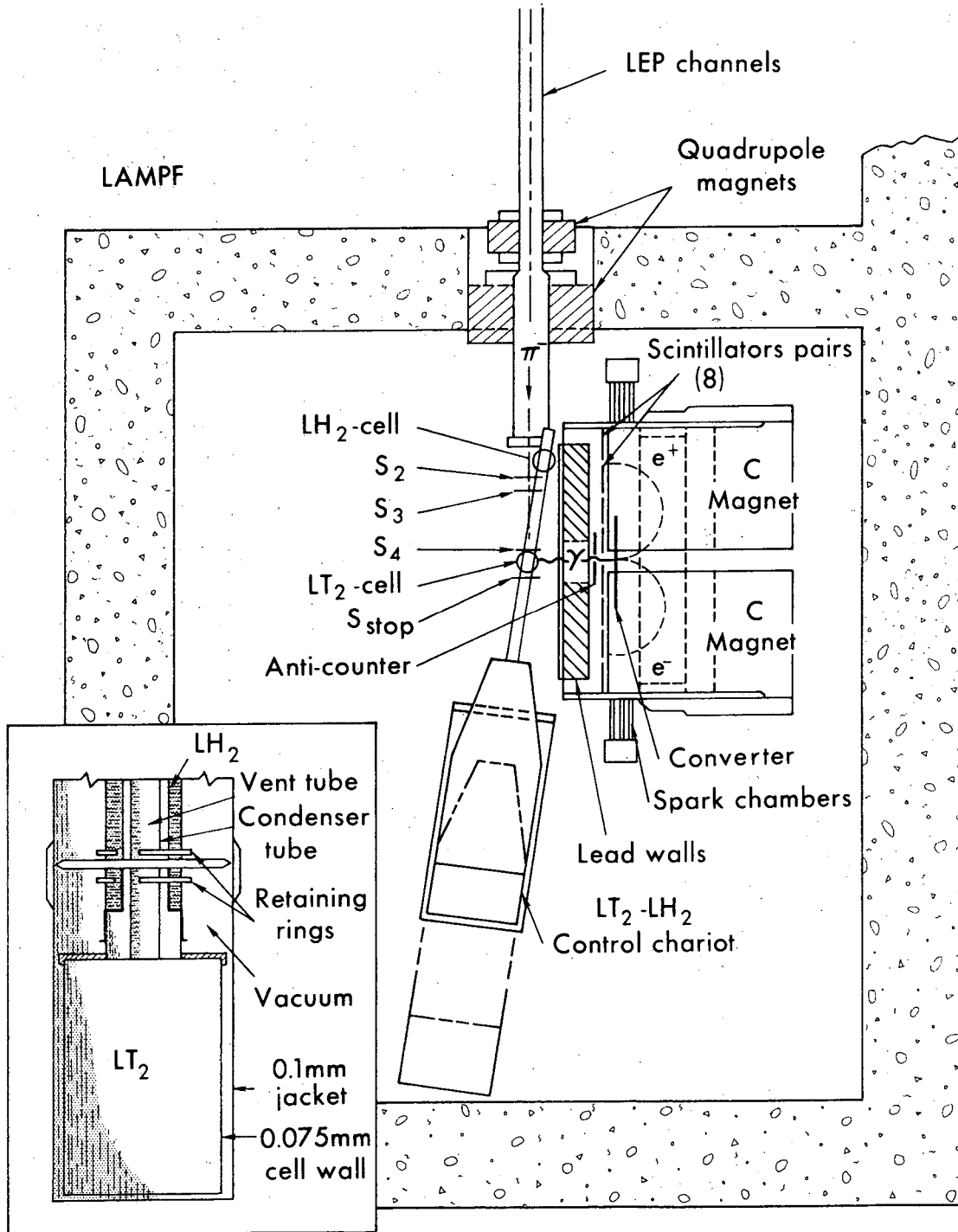
^hReference 3

ⁱReference 4.

FIGURE CAPTIONS

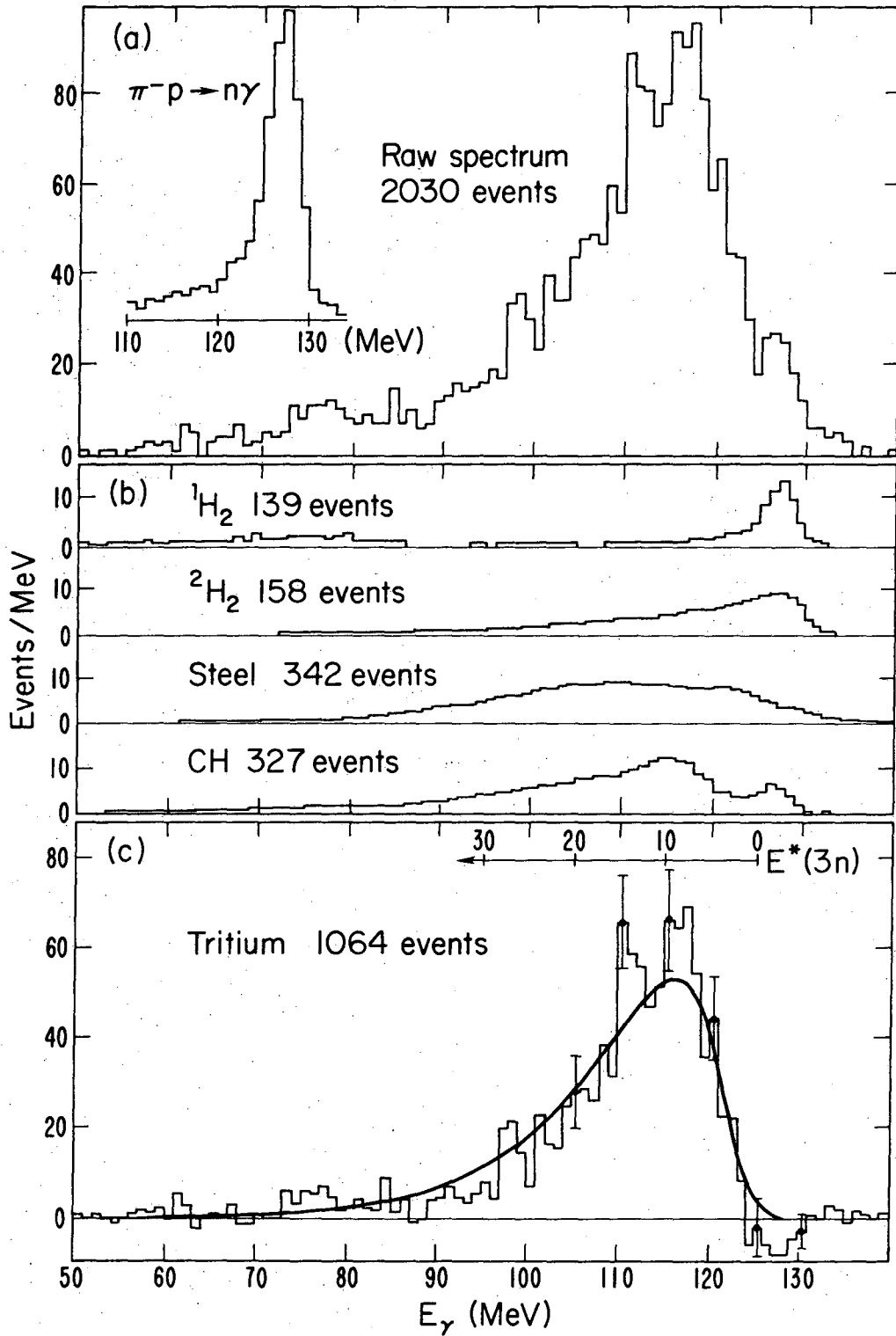
Fig. 1. The experimental set-up at LAMPF showing the pair-spectrometer and liquid tritium target. The insert shows a cross section of the target cell obtained from an x-ray radiograph.

Fig. 2. a) Raw photon spectrum obtained from the tritium target. The insert shows our resolution obtained at 129.4 MeV.
b) Background spectra for hydrogen, deuterium, steel and CH.
c) Spectrum from reaction $\pi^- t \rightarrow n n \gamma$ after subtraction of ^1H , ^2H , and steel and scintillator contribution. Solid curve is the theoretical spectrum of Phillips and Roig¹⁶ (see text), folded with acceptance and instrumental line shape and normalized to the total number of photons.



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Fig. 1



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Fig. 2

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