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We have measured the muon capture rate for the process $\mu^- + He^3 \rightarrow H^3 + \nu$ to an accuracy of a few percent, using high-pressure He^3 gas both as a target and as a scintillation detector for the recoil triton. The capture rate measured in this experiment agrees very well with the rate predicted on the basis of the Universal-Fermi-Interaction (UFI) theory.[1] To determine the capture rate, we have measured the ratio, F_c, of stopped muons giving a 1.9-MeV delayed triton recoil (T. R.) to the total number of stopped muons. In terms of the muon capture and decay rates, we have $F_c = \Lambda_c/\Lambda_T$, where Λ_c is the capture rate to a triton final state, and Λ_T is the sum of the muon decay rate, $\Lambda_D = 4.545 \times 10^5$ sec^{-1},[2] and the capture rate to all final states. Thus, from a measurement of F_c we can deduce Λ_c.

Figure 1 shows our apparatus. Helium-3 gas at a pressure of 445 psig and liquid-nitrogen temperature (-196 °C) was held in a cylindrical stainless steel vessel with lucite end windows. The gas served as a (a) target for the muon capture process, (b) scintillation detector for muons that came to rest in the gas, and (c) energy spectrometer for measuring the unique energy (1.9 MeV) of the delayed triton recoils. A plastic scintillation counter (No. 5) in the shape of a cup enclosed the gas, leaving only the beam direction free, and vetoed muons that passed through the gas without stopping. The inner wall of the cup was coated with a 0.1-μ-thick layer of aluminum, a 0.9-mg/cm^2-thick layer of MgO, and a 50-μg/cm^2-thick layer of p-p' diphenylstilbene (DPS) which shifted the short wavelength light emitted by the He^3 scintillator into the

visible region. The lucite window had a transparent coating of ~ 30 $\mu g/cm^2$ of DPS. Light from the gas scintillator was channeled through a hollow aluminized elbow into an RCA 7046 photomultiplier. Energy calibrations of the gas scintillator were obtained at 0.8 MeV by using the thermal-neutron-capture reaction (see Fig. 3b), at 1.9 MeV by using the triton-recoil peak itself, and at 5.47 MeV by using an Am^{241} alpha source, which could be inserted into different parts of the He^3 gas. The light output was found to be linear with energy loss in the gas, and to vary only 5% over the volume of the counter.

A beam of negatively charged particles was extracted from the Lawrence Radiation Laboratory's 184-in. synchrocyclotron. This beam was focused and momentum-analyzed so that the particles incident on the He target had a momentum of 110 ± 2 MeV/c. A fast coincidence (B_μ) between the time-of-flight counters, B1 and B2, identified the muon component of the beam (see Fig. 2). A stopped muon (S_μ) was electronically identified by a prompt coincidence of B_μ and the He^3 counter, with no signal from the cup counter (No. 5), i.e., $S_\mu = B_\mu$ He $\bar{5}$. Delayed pulses from the He counter, occurring in the interval 0.2 to 6.4 μsec after S_μ, triggered the coincidence circuit T.R. and were then sorted on the basis of pulse height and timing. Counters 3 and 5 which surrounded the gas were used to detect $\mu \rightarrow e$ decays (detection efficiency 86%), and any T.R. event that was associated with a pulse in counters 3 or 5 was vetoed. True T.R. events (1.9-MeV) had a range of only 1.5 mm in the gas and were not vetoed. Thus, a T.R. event was of the type T.R. = S_μ followed by a delayed He $\bar{3}\bar{5}$. Such events opened a linear gate and allowed the helium pulse height to be measured on a pulse-height analyzer. Decay electrons from $\mu \rightarrow e + \nu + \bar{\nu}$ were detected by the circuit μ-e, which looked at delayed events in counters 3 and 5 occurring 20 ns to 11 μs after a stopped μ. The time distributions of μ-e events and of T.R. events were measured and found to follow the expected 2.20-μsec lifetime to within 4%. During one part of the experiment, a logic requirement

(μ-e logic) was applied which cancelled any apparent T. R. events if a μ-e event was seen for the same stopped muon (the μ can only die once). This technique could cut down randoms in T. R. by 86%.

Data were taken in four main runs, in which the experimental conditions were varied to check for systematic errors. In addition, runs were made without the veto requirement from counter 5. This made it possible to see breakup events

$$\mu^- + He^3 \rightarrow p + n + n + \nu$$
$$\rightarrow d + n + \nu,$$

which might otherwise have been vetoed if the proton or deuteron had sufficient range to hit counter 5. Data of this type were taken with He^3, and later with He^4 in the target, and may yield total capture rates in He^3 and He^4. These runs also gave some insight into background problems. Runs with μ^- in He^4 and μ^+ in He^3 under normal operating conditions gave further insight into the backgrounds. Table I lists the conditions under which the various runs were taken.

The pulse-height spectrum for Run A at high gas pressure (445 psig) is plotted in Fig. 3a. The sharply rising background at low energy is from μ-to-e decays in which the electrons missed the veto counters. The shape of this "electron tail" was established from the runs on μ^+ He^3 and μ^- He^4. Figure 3b shows the energy spectrum for the run at reduced gas pressure (245 psig). At this pressure, electrons lose less energy in the gas, and thus there is a better separation between the 1.9-MeV T. R. peak and the electron tail. Only ~ 1/2% of the area of the triton gaussian is involved in the region of overlap, as compared with 4% in Run A. Random background accounts for an area of less than 1% in the energy region covered by the 1.9 MeV triton peak. Random events were known to an accuracy of 10% and thus contributed no significant error to the final result. The background which remains is due to muon capture resulting in many-body final states. This breakup background contributes 10 ± 4% to the area under the triton peak and represents the largest uncertainty in this experiment.

For the present report, we assumed that the breakup background varies linearly with energy. This background was extrapolated into the triton-peak region by fitting the data above the peak with a straight line. In Runs A and B we removed the "electron tail" by subtracting the appropriately normalized $\mu^- He^4$ spectra from the $\mu^- He^3$ spectra. The low-pressure and the μ-e logic runs had no accompanying $\mu^- He^4$ data, and the background contributions were determined by curve fitting. The energy spectra from these runs were fitted by an IBM 7090 using a program which assumed that the triton peak and the "electron tail" had a gaussian shape and that the breakup background varied linearly with energy. This computer program minimized the goodness-of-fit parameter χ^2, and gave the fitting constants and their rms errors. We quote a conservative error to allow for uncertainties in the shape of the breakup background. However, a more detailed investigation into the shape of this background is under way, and we feel that this will lead to a reduction of the errors.

A correction has been made for muons signalled as stopped, which in fact stopped in the "dead layer," i.e., which stopped in the cup coating materials, or did not penetrate deeply enough into the cup counter to give sufficient light to be vetoed. This correction was determined experimentally by replacing the He^3 with an equivalent stopping thickness of xenon. The number of muons stopped in the low-Z materials of the dead layer was recognized by $\mu \rightarrow e$ decays with a long lifetime. Stops in Xe show a very short $\mu \rightarrow e$ lifetime (90 nsec), which may be separated out by a time analysis. This correction to the measured number of stopped muons is $3.1 \pm 0.9\%$ at 445 psig, and $7.0 \pm 2.0\%$ at 245 psig. The number of triton recoils are corrected for an edge effect in which the triton hits the counter walls, $1.1 \pm 0.3\%$ at 445 psig and $2.1 \pm 0.5\%$ at 245 psig. The T.R. events must also be multiplied by 1.175 ± 0.007 to correct for the finite width of the time gate.

The corrected results are listed in Table II. The four runs are in good statistical agreement, and the weighted mean is

$$\Lambda_c = 1520 \pm 50 \text{ sec}^{-1}.$$

The rate measured by Falomkin et al. using a He^3 diffusion chamber[3] ($\Lambda_c = 1410 \pm 140 \text{ sec}^{-1}$) is consistent with our results. On the basis of the Universal Fermi Interaction, and using the most recent values of the He^3 rms radius obtained from electron-scattering experiments,[4] L. Wolfenstein predicted a rate of[5]

$$\Lambda_c = 1450 \text{ sec}^{-1}.$$

The error in the theory is difficult to estimate, but including the uncertainties in the triton ft value, the He^3 radius, and the magnitude of the induced pseudoscalar coupling, it may be as high as 10%.[1] The result of our experiment agrees well with the prediction of the Universal Fermi Interaction.

We are pleased to acknowledge the support and interest of Professor Emilio Segrè, the advice of Professor Norman E. Booth, and the sustained effort of the target group--in particular Messrs. William Pope, Richard Schafer, and Raymond Fuzesy, who engineered and tested the high-pressure gas target. The crew of the 184-in. cyclotron under Mr. James Vale maintained a steady and reliable beam throughout the experiment.

FOOTNOTES AND REFERENCES

*Work done under the auspices of the U. S. Atomic Energy Commission.

1. L. Wolfenstein, in Proceedings of the 1962 International Conference on High-Energy Physics at CERN (CERN, Geneva, 1962), p. 821. The theoretical Λ_c is given here as 1400 ± 140 sec^{-1}.

2. F. J. M. Farley, T. Massam, T. Muller, and A. Zichichi, in Proceedings of the 1962 International Conference on High-Energy Physics at CERN (CERN, Geneva, 1962), p. 415.

3. I. V. Falomkin, A. I. Filippov, M. M. Kulyukin, B. Pontecorvo, Yu. A. Scherbakov, R. M. Sulyaev, V. M. Tsupko-Sitnikov, and O. A. Zaimidoroga, Phys. Letters 3, 229 (1963).

4. H. Collard and R. Hofstadter, The Structure of the He^3 Nucleus, Stanford Internal Report HEPL-285 January 1963.

5. L. Wolfenstein, Carnegie Institute of Technology, Pittsburg, Pa., private communication, May 1963.

Table I. Summary of the runs made during the experiment

Designation	Purpose	Pressure (psig)	Number of events
$\mu^- He^3$ A	μ capture by He^3 giving 1.9-MeV triton	445	12 000
$\mu^- He^3$ B		445	14 000
$\mu^- He^3$ (μ-e logic)		445	6 000
$\mu^- He^3$ low-pressure		245	11 000
$\mu^- He^3$ breakups	μ capture by $\begin{pmatrix} He^3 \\ He^4 \end{pmatrix}$ into all channels	445	7 000
$\mu^- He^4$ breakups		445	2 000
$\mu^- He^4$	Study of backgrounds	445	-
$\mu^+ He^3$		445	-
$\mu^- Xe$	Study of "dead layer"	100	-

Table II. Results

Run	Corrected number of triton recoils	Corrected number of stopped muons ($\times 10^3$)	$\frac{TR}{S_\mu} = F_c$ ($\times 10^{-3}$)	$\Lambda_c^{He^3}$ (sec^{-1})
A(445 psig)	13 760 ± 710	4 130 ± 40	3.33	1 520 ± 85
B(445 psig)	16 360 ± 710	4 970 ± 45	3.29	1 500 ± 75
Low pressure	12 660 ± 370	3 730 ± 80	3.39	1 550 ± 60
μ-e Logic	7 200 ± 530	2 190 ± 20	3.28	1 500 ± 120

FIGURE CAPTIONS

Fig. 1. The target assembly.

Fig. 2. (a) Composition of the beam, as measured by time-of-flight analysis with counters over a flight path of 18.5 ft: 60% muons, 38% electrons, and 2% pions. (b) The same spectrum when the time sorter is gated only on the fast coincidence, B_μ.

Fig. 3. (a) Pulse-height spectrum of Run A (445 psig) showing the triton recoil peak, the "electron tail," and the background due to breakup reactions. (b) Pulse height spectrum of the low-pressure (245-psig) data. The dashed curve shows the relative amount of random background due mostly to the neutron absorption reaction ($n + He^3 \rightarrow H^3 + p$), in which 0.8 MeV is released.

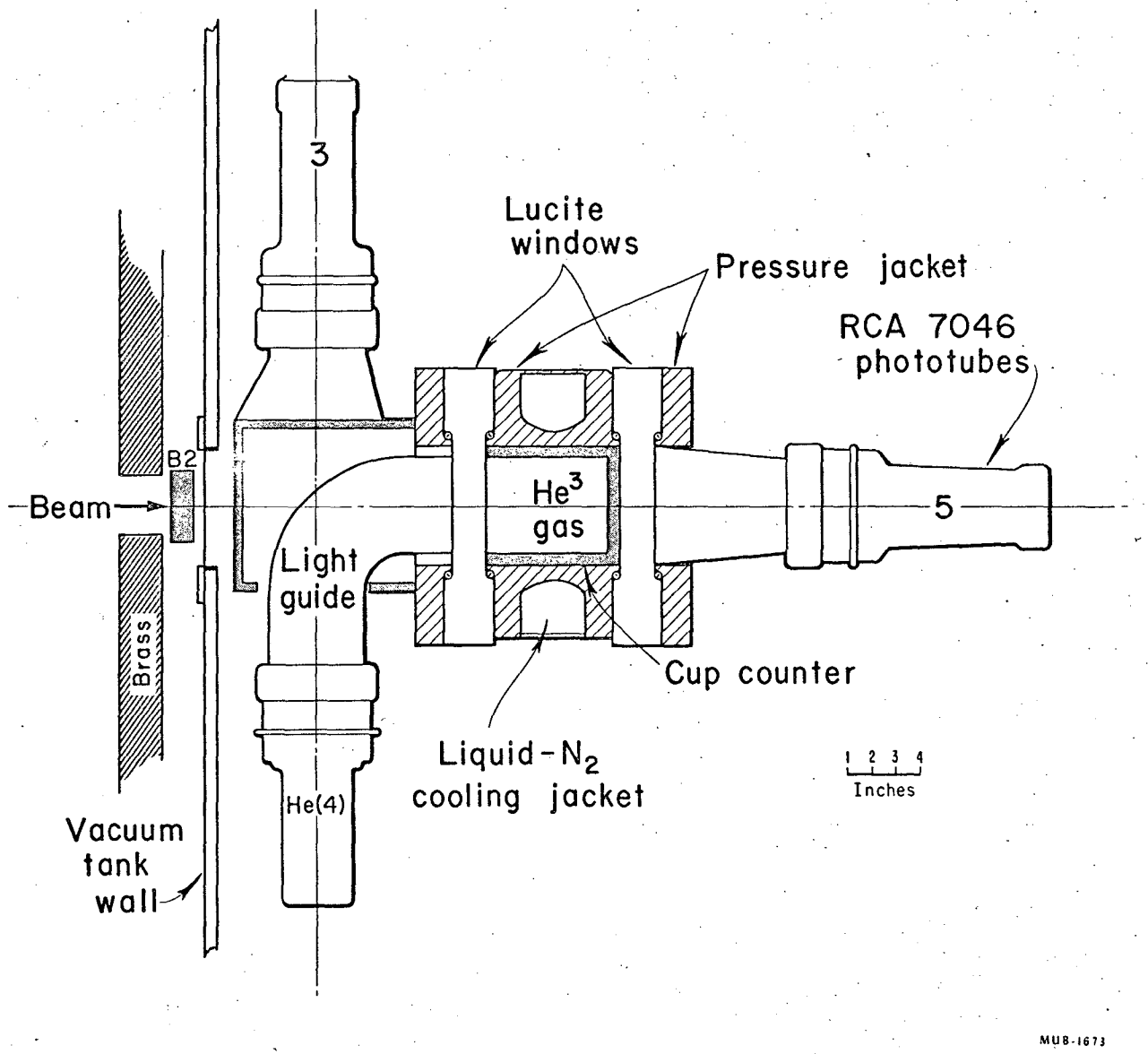
3
Lucite windows
Pressure jacket
RCA 7046 phototubes
B2
Beam
He3 gas
5
Light guide
Brass
Cup counter
Liquid-N2 cooling jacket
1 2 3 4
Inches
He(4)
Vacuum tank wall
MUB-1673

Fig. 1

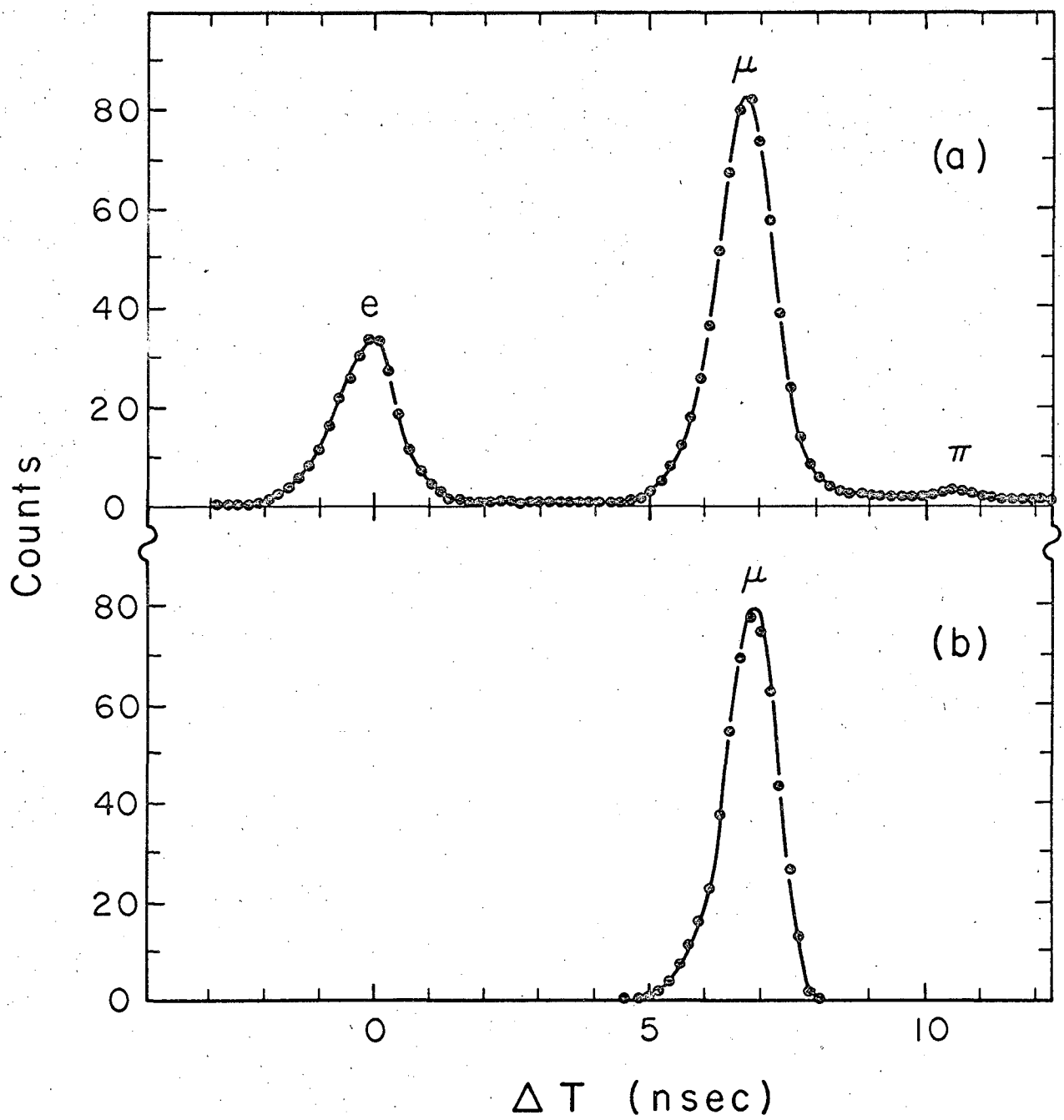

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Fig. 2

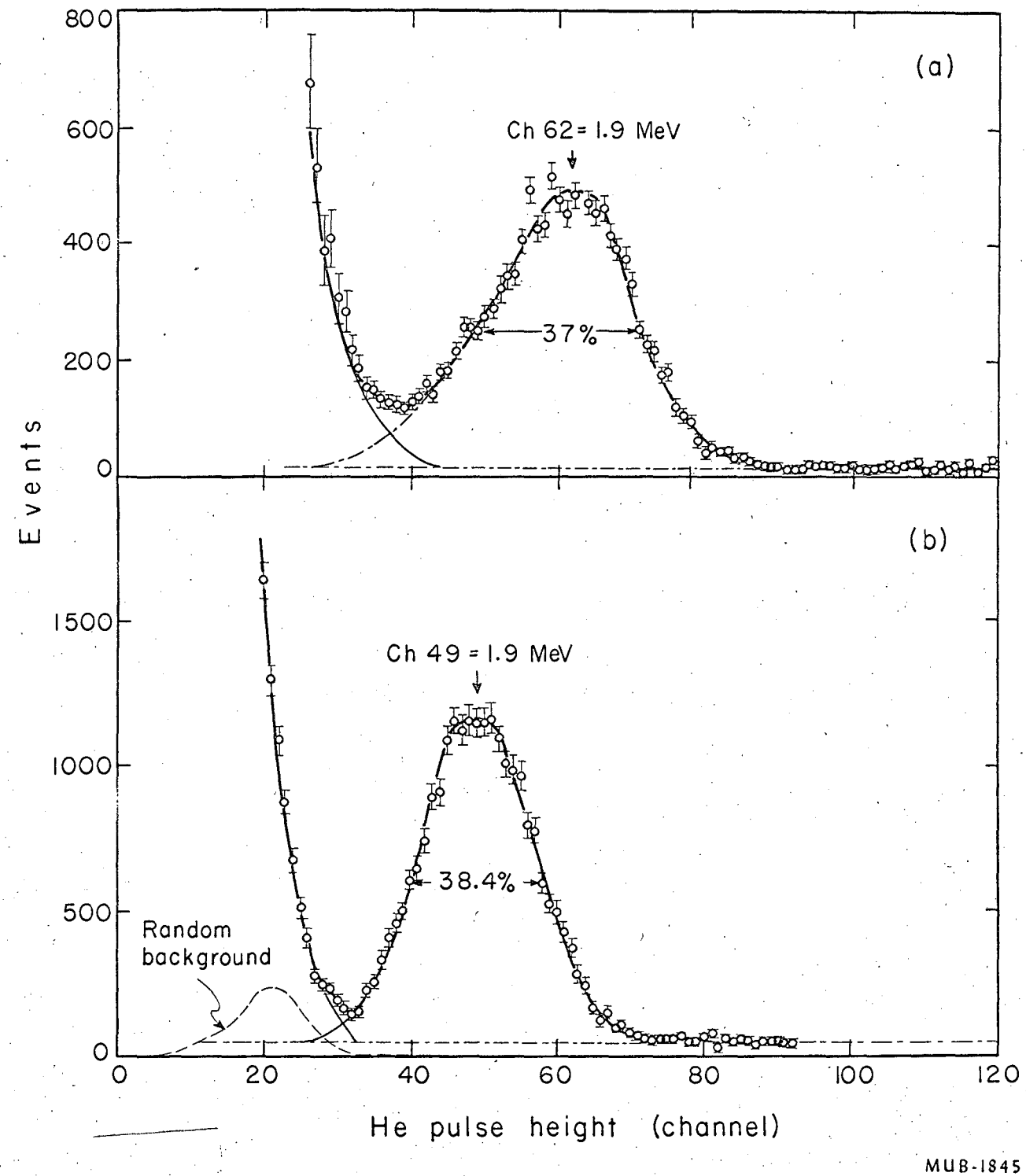
(a)
Ch 62 = 1.9 MeV
37%
(b)
Ch 49 = 1.9 MeV
38.4%
Random background
Events
He pulse height (channel)
MUB-1845

Fig. 3