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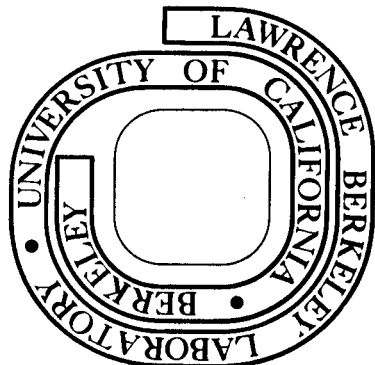
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MEASUREMENT OF THE PANOFSKY RATIO IN ${}^3\text{He}^+$

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ABSTRACT

The photon spectrum from radiative and charge-exchange capture of pions in ${}^3\text{He}$ was measured in a high-resolution pair-spectrometer yielding the new value of the Panofsky ratio $P_3 = (\pi^- + {}^3\text{He} \rightarrow {}^3\text{H} + \pi^0) / (\pi^- + {}^3\text{He} \rightarrow {}^3\text{H} + \gamma) = 2.68 \pm 0.13$. An impulse approximation analysis is presented which gives a value $P_3 = 2.5$. In addition, the branching ratios for the ${}^3\text{He} + \pi^0$, ${}^3\text{H} + \gamma$, and $({}^2\text{H} + n + \gamma$ and $p + n + n + \gamma)$ channels are measured to be 17.8 ± 2.3 , 6.6 ± 0.8 , and $7.4 \pm 1.0\%$, respectively.

The absorption of negative pions from atomic orbits around free protons proceeds almost exclusively via the charge-exchange reaction $\pi^- + p \rightarrow n + \pi^0$ and the radiative capture reaction $\pi^- + p \rightarrow \gamma + n$. The ratio of the transition rates for these two processes, the so-called Panofsky ratio,¹ links pion-photoproduction at threshold to pion-nucleon scattering and provides a determination of the pion-nucleon coupling strength. The equivalent ratio for protons bound in nuclei has been observed only in ${}^3\text{He}$, where an earlier measurement by Zaimidoroga *et al.*,² yielded $P_3 = (\pi^- + {}^3\text{He} \rightarrow \pi^0 + {}^3\text{H}) / (\pi^- + {}^3\text{He} \rightarrow \gamma + {}^3\text{H}) = 2.28 \pm 0.18$. Some authors^{3,4} have regarded this quantity as a test case in the application of the PCAC hypothesis to soft-pion problems involving complex nuclei. Other authors employ the impulse approximation (IA) directly and relate the Panofsky ratio for ${}^3\text{He}$ to ${}^1\text{H}$. By making this assumption it has been shown^{5,6} that P_3 depends primarily on one parameter, *viz.*, the ${}^3\text{He}$ - ${}^3\text{H}$ rms transition radius. The value $\langle r^2 \rangle_{3\text{He}}^{1/2} = 1.4 \pm 0.2F$ extracted from $P_3 = 2.28 \pm 0.18$ disagrees with the value $1.88 \pm 0.05F$ determined⁷ by electron scattering. In view of the importance of this quantity both to the study of the elementary particle approach to nuclei as well as the structure of the mass-3 system and possible 3-body forces it was thought desirable to remeasure this quantity and to study directly the radiative breakup reactions $\pi^- + {}^3\text{He} \rightarrow d + n + \gamma$ and $p + n + n + \gamma$.

The experiment was performed in the stopped- π beam of the Lawrence Berkeley Laboratory 184-inch cyclotron. Details of the experimental setup are given in Ref. 8. A π^- beam is brought to rest in a 9.5-cm-diameter, 12.7-cm-long Mylar flask (0.02 cm wall thickness) filled with liquid ${}^3\text{He}$ at 1.9°K. A typical rate was 3×10^4 π /sec stopping in the

helium content of the target. The photons were detected in 180° pair spectrometer employing three wire spark chambers. In a calibration experiment with a hydrogen target we determine the energy resolution of the spectrometer to be 2 MeV (FWHM) at 129.4 MeV (Fig. 1a); the acceptance (conversion efficiency \times detection efficiency $\times \Delta\Omega/4\pi$) is given in Fig. 1a and was determined in a Monte Carlo calculation.⁸ The detection efficiency includes the efficiency of our off-line pattern recognition programs for finding the 10-20% good events among all triggers as described in Ref. 8. It was determined by visual inspection of a total of 50 000 triggers.

The $^3\text{He} (\pi^-, \gamma)$ spectrum (Fig. 1b) exhibits the expected four photon channels; $t\gamma$ with $E_\gamma = 135.8$ MeV; dny and pny with end-point energies of 129.8 and 127.7 MeV respectively; and $t\pi^0$, $\pi^0 \rightarrow 2\gamma$ with a uniform distribution between 53.1 and 85.7 MeV. There is a suggestion of a broad peak corresponding to 10-15 MeV excitation in the ^3H system (Fig. 1c), although the statistical evidence for the state proposed by Chang *et al.*⁹ is inconclusive. The two breakup channels cannot be separated from each other, but their separation from the $t\gamma$ reaction can be achieved reliably by shifting the hydrogen line by 6.35 MeV and normalizing to ^3He events above 130 MeV. Separation of the small contribution ($\sim 4\%$) which the breakup reactions make to the charge-exchange peak ($E_\gamma < 90$ MeV) was performed with a pole model^{8,10} calculation (Fig. 1c). This procedure yields the number of events for each process in the spectrum given in Table I. We divide by the acceptance and the number of pions stopped in the target to obtain the absolute rates, after a correction for photon conversion between the target and the converter.

The 15% errors in the absolute rates reflect the uncertainties of the spectrometer acceptance as well as of the beam divergence and the effective target thickness needed to determine the stop rate. For calibration, the hydrogen results are also given in Table I. Here the mesonic and radiative capture rates independently (i.e., their sum is not constrained to 100%, but agrees with it) and their ratio P_1 agree with previous measurements.¹ P_3 is determined from:

$$P_3 = P_1 (1.533 \pm 0.021) \times [N_Y(^3\text{He}\pi^0)/N_Y(^3\text{H}\gamma)] \times [N_Y(n\gamma)/N_Y(n\pi^0)] \times (1 - f).$$

where N_Y are the numbers of events in the spectra for the respective channels, and $f = (5.3 \pm 2.0)\%$ is a small correction for the difference in relative efficiency for ^3He and ^3H , since the photon energies differ slightly. The uncertainties in the acceptance cancel out and the pion normalization does not enter. The errors for N_Y and the small error of P_1 from previous experiments yield an error for P_3 of 4.8%. We bracketed the ^3He runs with 15 ^1H runs¹¹ (both targets were mounted interchangeable on rails) since it was found that the acceptance for lower energies was sensitive to spark-chamber performance. P_3 determined for each sequence of runs agrees with the value taken from the total spectrum quoted in Table I. Comparing our results with ones obtained in Ref. 2, we find that the difference in the Panofsky ratio stems mainly from difference in the charge-exchange yields, since the radiative yields agree very well. This seems understandable, since the small kinetic energy of the recoil triton (190 keV) may cause difficulties in observing them in diffusion chambers. This point is discussed by the authors in Ref. 2.

Analyses of radiative π^- capture in light nuclei are in general complicated by the fact that a large fraction of pions gets captured from the 2p Bohr orbit. The Panofsky ratio in ^3He , however, appears to be very nearly independent of 2p-state capture. Estimates³ for the fraction (pions captured)/(pions making 2p \rightarrow 1s x-ray transition) range up to 55%. However Ericson and Figureau³ estimate that only 0.1% and 0.03% of pions captured from the 2p orbit undergo charge exchange (CEX) and radiative (REX) capture, respectively. Thus the measured Panofsky ratio should be given quite accurately by the relative 1s-capture CEX/REX matrix elements.

The transition rates in the IA are given for radiative π^- capture¹² by

$$\Lambda_Y(1s) = \frac{1}{4\pi} \frac{k}{m_\pi} C^2 \left(1 - \frac{k}{m_3 + m_\pi}\right) \left(1 + \frac{m_\pi}{m_n}\right)^2 |\phi_\pi(0)|^2 |M|^2 \quad (1)$$

with

$$|M|^2 = \frac{1}{2J_i + 1} \sum_{m_i, m_f, \lambda} \int \frac{d\Omega_{\hat{k}}}{4\pi} |\langle J_f M_f | \sum_{j=1}^3 (\hat{\epsilon}_\lambda \cdot \vec{\sigma}_j) \tau_j^{(-)} e^{-i\vec{k} \cdot \vec{r}_j} | J_i M_i \rangle|^2$$

and for charge-exchange³ by

$$\Lambda_{\pi^0}(1s) = \frac{1}{4\pi} \frac{q_0}{m_\pi} A^2 \left(1 - \frac{\omega_0}{m_3 + m_\pi}\right) \left(1 + \frac{m_\pi}{m_n}\right)^2 |\phi_\pi(0)|^2 |M_0|^2$$

with

$$|M_0|^2 = \frac{1}{2J_i + 1} \sum_{m_i, m_f} \int \frac{d\Omega_{\hat{q}}}{4\pi} |\langle J_f M_f | \sum_{j=1}^3 \tau_j^{(-)} e^{-i\vec{q}_0 \cdot \vec{r}_j} | J_i M_i \rangle|^2 \quad (2)$$

[$\hbar = c = 1$; $m_3 = \text{mass}(^3\text{He})$; $m_n = \text{mass}(^1\text{H})$; (ω_0, \vec{q}_0) - π_0 four momentum; $\vec{k}, \hat{\epsilon}$ = photon momentum, polarization]. It is assumed that the pion wave

function may be taken out of the matrix element and replaced by its value at the origin with a small correction³ for the extended charge distribution $|\phi_\pi(0)|^2 = (0.97/\pi)(Z \alpha m_\pi)^3 (1 + m_\pi/m_3)^{-3}$, where $\alpha = 1/137$. The value of C is determined by pion photoproduction cross sections at threshold and has the value¹³ $C = 4\pi |E_{0+}(\pi^-)| = 4\pi (3.15 \pm 0.06) \times 10^{-2}/m_\pi$. A is related to the πN isospin singlet and triplet scattering lengths¹³ by $A = (4\pi \sqrt{2/3}) |a_1 - a_3|$.

With (1) and (2) the Panofsky ratio for ${}^3\text{He}$ expressed in terms of the same quantity for hydrogen becomes

$$P_3 = 2P_1 \frac{q_{03}}{k_3} \frac{k_1}{q_{01}} \frac{m_3 + m_\pi - \omega_{03}}{m_3 + m_\pi - k_3} \frac{m_n + m_\pi - k_1}{m_n + m_\pi - \omega_{01}} \frac{|M_0|^2}{|M|^2}. \quad (3)$$

For radiative capture, $|M|^2$ is related¹⁴ to the axial form factors of the mass-3 system and the nucleon and the Gamow-Teller matrix element

$$M_{GT} = \langle {}^3\text{H} | \sum_{j=1}^3 \tau_j^{(-)} \sigma_j | {}^3\text{He} \rangle. \quad (15)$$

The charge-exchange matrix element.

$|M_0|^2$ is related¹⁴ to the vector-form factors and Fermi matrix element.

Inserting $|M_0|^2 / |M|^2 = 0.73$ (Ref. 16) and $P_1 = 1.531$, we obtain

$P_3 = 2.49$, in good agreement with our measured value. The radiative rate from this calculations is $3.60 \times 10^{15} \text{ sec}^{-1}$.¹⁷ Since P_1 appears in the evaluation of the experimental value of P_3 as well as in the theoretical expression, our result is independent of the particular value for P_1 chosen, and can therefore be considered a *direct* test of the IA in s-wave pion-nucleus interactions. The agreement of our experimental value with recent values for P_3 obtained by current-algebra methods is not quite as satisfactory. Ericson and Figureau³ obtain values between 1.9 and 2.1, depending on whether the CEX cross section is calculated

in IA or in the soft-pion technique. In this calculation the electric-dipole amplitude $|E_{0+}^{(\pi^+)})|$ in the nucleon case gets replaced by the soft-pion value $\sqrt{\alpha/4\pi} (1/f_\pi) (g_A/g_V)$. When the elementary amplitude is applied to the nuclear case,⁴ a 22% correction for ρ -meson exchange, incoherent rescattering, and nuclear intermediate states is included. The correction has the effect of increasing the radiative rate to $4.43 \times 10^{15} \text{ sec}^{-1}$ ($4.1 \times 10^{15} \text{ sec}^{-1}$, Ref. 4) and thereby reduces P_3 . It would appear therefore that these corrections are smaller than estimated. Other calculations along these lines, where, however, terms first order in m_π/m_n are neglected, give values for the radiative rate around $2.3 \times 10^{15} \text{ sec}^{-1}$.^{19,20}

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Footnotes and References

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

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15. $|M_{GT}|^2 = 3$, if ${}^3\text{He}$ and ${}^3\text{H}$ are exact mirror states; β -decay R. Salgo and H. Staub, Nucl. Phys. A138, 417 (1969) yields $|M_{GT}|^2 = 2.84 \pm 0.06$.

$$16. \quad |M|^2 = \frac{2}{3} |M_{GT}|^2 \times \left(\frac{F_A(q^2)}{F_A(0)} \right)^2 \left(\frac{F_A(0)}{F_A(q^2)} \right)^2 \approx 2 \times \left(\frac{F_M(q^2)}{F_M(0)} \right)^2 \times 0.95$$

$$= 1.9 \times (0.78 \pm 0.02), \quad q^2 = 0.474 F^{-2} \quad (\text{Ref. 7,14}),$$

$$|M_o|^2 = |M_F|^2 \cdot \left(\frac{F_V(q^2)}{F_V(0)} \right)^2 \cdot \left(\frac{F_V(0)}{F_V(q^2)} \right)^2 \approx 1 \times 0.97, \quad q^2 = 0.027 F^{-2},$$

$F(f) = ({}^3\text{He}; {}^3\text{H}) [(p;n)]$ - form factors.

17. Previous calculations yielded values $8.32 \times 10^{15} \text{ sec}^{-1}$ (Ref. 5) and $0.97 \times 10^{15} \text{ sec}^{-1}$ (Ref. 17). Differences with our value are due to missing factors of $m_\pi/2k$ in Ref. 5, 4 in Ref. 18, and the older value $r_{\text{rms}}({}^3\text{He}) = 1.55 F$.

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these authors obtain $\lambda_\gamma(1s) = 3.37 \times 10^{15} \text{ sec}^{-1}$ and $P_3 = 2.2$.

After introducing a missing factor of 2/3 in the expression

for $\lambda_\gamma(1s)$, one obtains $\lambda_\gamma(1s) = 2.25 \times 10^{15} \text{ sec}^{-1}$ and $P_3 = 3.3$.

TABLE I. Results for stopped- π^- absorption on ^3He and ^1H .

Final state	N_{γ}^a	R^b (%)	R^c (%)
$^3\text{H } \pi^0$	6273 ± 82	17.8 ± 2.3	15.8 ± 0.8^2
$^3\text{H } \gamma$	5580 ± 157	6.6 ± 0.8	6.9 ± 0.5^2
$\text{dn}\gamma + \text{pn}\gamma$	5331 ± 137	7.4 ± 1.0	$[3.6 \pm 1.2]^{d,2}$
$\text{n } \pi^0$ (^1H)	2355 ± 49	65.6 ± 11.1	60.5 ± 0.3^1
$\text{n } \gamma$ (^1H)	3860 ± 62	42.4 ± 4.4	39.5 ± 0.3^1
dn		$[68.2 \pm 2.6]$	15.9 ± 2.3^2
pnn			57.8 ± 5.4^2
P_3 (^3He) ^e		2.68 ± 0.13^f	2.28 ± 0.18^2
P_1 (^1H) ^e		1.54 ± 0.26	1.533 ± 0.021^1
B_3^g		1.12 ± 0.05	
C_3^h		10.3 ± 1.3	10.7 ± 1.2^2

^aRaw number of events in spectrum. ^bThis experiment

^cPrevious experiments. ^d $\text{dn}\gamma$ only. ^ePanofsky ratio ^fSee text.

^g $\sigma[\pi^- + ^3\text{He} \rightarrow (\text{dn}\gamma + \text{pn}\gamma)]/\sigma[\pi^- + ^3\text{He} \rightarrow ^3\text{H} + \gamma]$. ^hRatio of nucleon ejection modes to radiative absorption.

FIGURE CAPTION

- Fig. 1. (a) Hydrogen spectrum and pair spectrometer acceptance.
(b) ${}^3\text{He}$ spectrum, 50-150 MeV.
(c) ${}^3\text{He}$ spectrum in region where the breakup channels dominate. The curve is a pole model calculation^{8,10} ($\Delta = 6.8$ MeV) with complete kinematics incorporated.

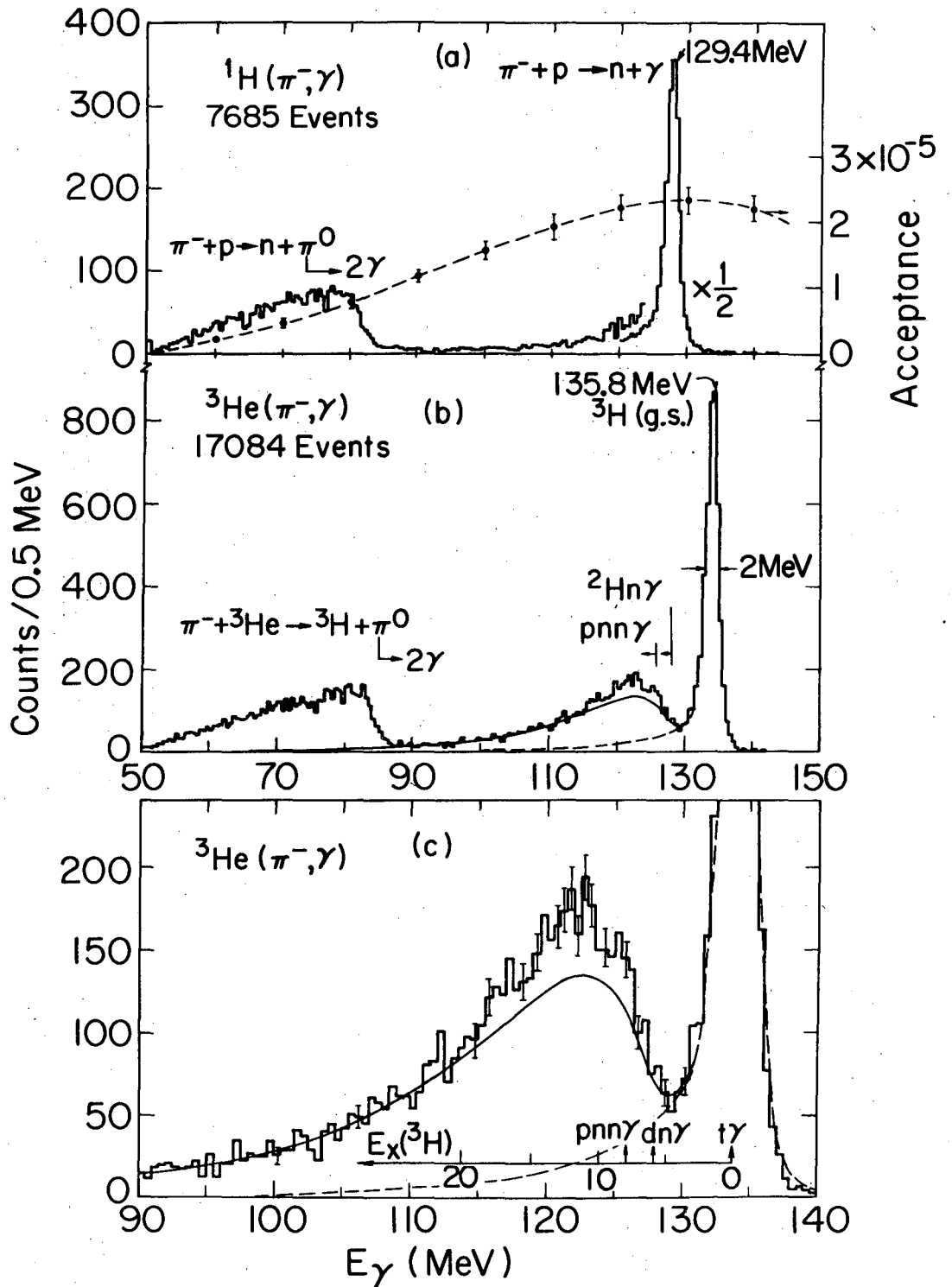


Fig. 1.

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