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Peter Truöl, Helmut W. Baer, James A. Bistirlich,
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MEASUREMENT OF THE PANOFSKY RATIO IN ^{3}He[†]

Peter Truöl[*]

Physik-Institut der Universität Zürich
Zürich, Switzerland

and

Helmut W. Baer, James A. Bistirlich, Kenneth M. Crowe,
Nico de Botton,[‡] and Jerome A. Helland[§]

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

The photon spectrum from radiative and charge-exchange capture of pions in ^{3}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 $P_3 = 2.6$. 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 ± 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}He, where an earlier measurement by Zaǐmidoroga et al.,[2] yielded $P_3 = (\pi^- + {}^3\mathrm{He} \rightarrow \pi^0 + {}^3\mathrm{H})/(\pi^- + {}^3\mathrm{He} \rightarrow \gamma + {}^3\mathrm{H}) = 2.28 \pm 0.18$. 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}He to ^{1}H. By making this assumption it has been shown[5,6] that P_3 depends primarily one parameter, viz., the ^{3}He-^{3}H rms transition radius. The value $\langle r^2 \rangle^{1/2}_{^3\mathrm{He}} = 1.4 \pm 0.2$ F extracted from $P_3 = 2.28 \pm 0.18$ disagrees with the value 1.88 ± 0.05 F determined[7] 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 $\pi^- + {}^3\mathrm{He} \rightarrow d + n + \gamma$ 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}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 a 180° pair spectrometer employing three wire spark chambers. The energy resolution is 2 MeV (FWHM) at 130 MeV; the acceptance (Fig. 1a) (conversion efficiency $\times \Delta\Omega/4\pi$) was determined in a Monte Carlo calculation.[8] An independent calibration of the instrument was achieved with a hydrogen target. Since the relative efficiency at low energy was found to depend to some extent on the spark chamber performance and could vary by as much as 15-20%,[9] a total of 15 hydrogen runs were taken during the experiment. Despite the changes in the relative efficiency we find a constant value for the Panofsky ratio in ^{3}He when compared with hydrogen.

The ^{3}He (π^-, γ) spectrum (Fig. 1b) exhibits the expected four photon channels: $t\gamma$ with $E_\gamma = 135.8$ MeV; $dn\gamma$ and $pnn\gamma$ 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- to 15 MeV excitation in the ^{3}H system (Fig.1c), although the statistical evidence for the state proposed by Chang et al.[11] 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 ^{3}He events above 130 MeV. Separation of the small contribution (~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). Comparing (Table I) 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 ^{3}He, however, appears to be very nearly independent of 2p-state capture. Estimates[3] for the fraction (pions captured)/pions making 2p→ 1s x-ray transition) range up to 55%. However Ericson and Figureau[3] 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^- capture[12] by

$$\Lambda_\gamma(1s) = \frac{1}{4\pi}\,\frac{k}{m_\pi}\,C^2\left(1-\frac{k}{m_3+m_\pi}\right)\left(1+\frac{m_\pi}{m_n}\right)^2 |\phi_\pi(0)|^2\,|M|^2 \qquad \text{with}$$

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

and for charge-exchange[3] by

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

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

$[\hbar = c = 1;\ m_3 = \text{mass}(^3\text{He});\ m_n = \text{mass}(^1\text{H});\ (\omega_0, \vec{q}_0) = \pi_0$ 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 correction[3] for the extended charge distribution $|\phi_\pi(0)|^2 = (0.97/\pi)(Z\alpha m_\pi)^3(1+m_\pi/m_n)^{-3}$, where $\alpha = 1/137$. The value of C is determined by pion photoproduction cross sections at threshold and has the value[13] $C = 4\pi|E_{0+}^{(\pi^-)}| = 4\pi\,(3.15 \pm 0.06) \times 10^{-2}/m_\pi$. A is related to the πN isospin singlet and triplet scattering lengths[13] by $A = (4\pi\sqrt{2}/3)\,|a_1 - a_3|$.

For radiative capture, $|M|^2$ is related to the axial form factors of the mass-3 system and the nucleon and the Gamow-Teller matrix element $M_{GT} = \langle ^3\text{H} | \sum_{j=1}^{3} \tau_j^{(-)} \vec{\sigma}_j | ^3\text{He} \rangle$ by[14]

$$|M|^2 = \frac{2}{3}\,|M_{GT}|^2 \left(\frac{F_A^{^3\text{He}\to\,^3\text{H}}(q^2)}{F_A^{^3\text{He}\to\,^3\text{H}}(0)} \right)^2 \left(\frac{F_A^{n\to p}(0)}{F_A^{n\to p}(q^2)} \right)^2 .$$

The GT matrix element has the value $|M_{GT}|^2 = 3$ if ^{3}He and ^{3}H are exact mirror states with totally space-symmetric wave functions, whereas the experimental value is $|M_{GT}|^2 = 2.84 \pm 0.06$ measured[15] in β^- decay. A value of $F_A^{^3\text{He}\to\,^3\text{H}}(0.474)/F_A^{^3\text{He}\to\,^3\text{H}}(0) = 0.80$ [Ref. 3] is found from linear extrapolation of μ-capture (4-momentum transfer, $q^2 = 0.27\,F^{-2}$) to π-capture in good agreement with 0.776 ± 0.016 based on the assumption[14] $F_A(q^2)/F_A(0) = F_M(q^2)/F_M(0)$, where $F_M(q^2)$ is the ^{3}He → ^{3}H magnetic form factor determined using ^{3}He and ^{3}H electron scattering data.[7] For the nucleon[13] the latter procedure gives

$F_A^{n\to p}(0.474)/F_A^{n\to p}(0) = 0.948$. Combining the last two results with the experimental value for $|M_{GT}|^2$ gives $\lambda_\gamma(1s) = 3.41 \times 10^{15}\ \mathrm{sec}^{-1}$.

The charge-exchange matrix element $|M_o|^2$ is related to the vector-form factors and Fermi matrix element by[14]

$$|M_o|^2 = |M_F|^2 \times \left(\frac{F_V^{^3He\to {}^3H}(q^2)}{F_V^{^3He\to {}^3H}(0)}\right)^2 \left(\frac{F_V^{n\to p}(0)}{F_V^{n\to p}(q^2)}\right)^2 = 1 \times .974,$$

applying the CVC hypothesis to both nucleon and mass-3 form factors.

The Panofsky ratio for ^{3}He expressed in terms of the same quantity for hydrogen is

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

Inserting the experimental value[1] $P_1 = 1.533 \pm 0.021$ yields $P_3 (= 3.42|M_o|^2/|M|^2) = 2.63$, in good agreement with our measured value $P_3 = 2.68 \pm 0.13$.

Since P_1 appears in the evaluation of the experimental value for 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 <u>direct</u> test of the IA in s-wave pion-nucleus interactions. The good agreement with the IA calculation has to be contrasted with the poor agreement with recent values for P_3 obtained by current-algebra methods. Ericson and Figureau[3] 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] corrections for ρ-meson exchange, incoherent rescattering, and nuclear intermediate states are included. The corrections have the effect of increasing the radiative rate to 4.43×10^{15} sec^{-1} and thereby reducing P_3. It would appear therefore that these corrections are smaller than estimated. Other calculations along these lines,[13] where, however, terms first order in m_π/m_n are neglected, give values for the radiative rate around 2.3×10^{15} sec^{-1}.[18,19]

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Footnotes and References

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[‡] Permanent address: DPHN/HE, C.E.N. Saclay, BP n°2, 91-Gif sur Yvette, France.

[§] Present address: Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico.

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

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

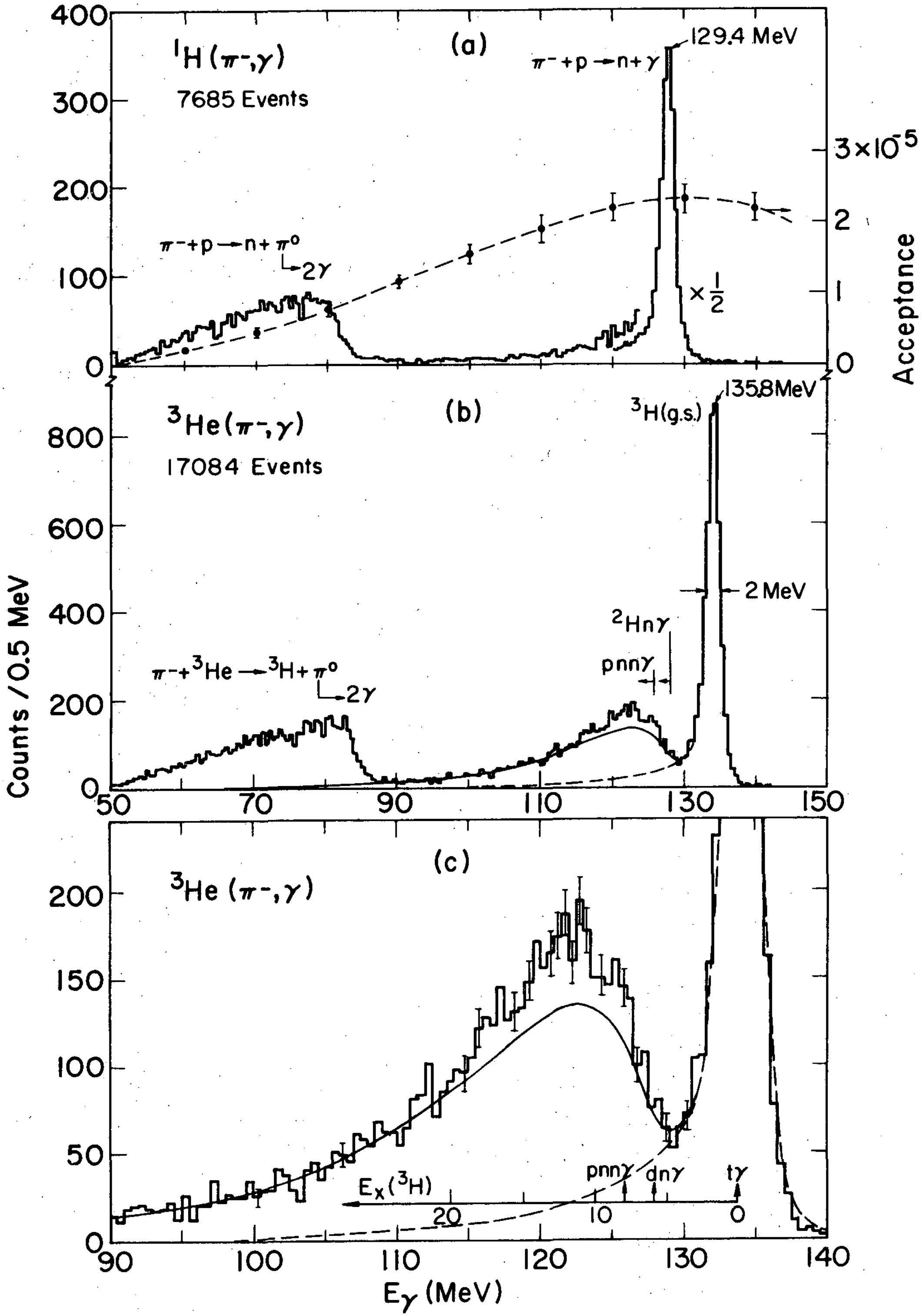
[a] Raw number of events in spectrum. [b] This experiment. [c] Previous experiment. [d] dnγ only. [e] Panofsky ratio. [f] $P_3 = P_1$ (= 1.533 ± 0.021) $\times \dfrac{N_\gamma(^3H\pi^0)}{N_\gamma(^3H\gamma)} \times \dfrac{N_\gamma(n\gamma)}{N_\gamma(n\pi^0)} \times (1-f)$, where $f = (5.3 \pm 2.0) \times 10^{-2}$ is small correction for difference in photon detection efficiency for ^{3}He and ^{1}H. [g] $\sigma[\pi^- + {}^3\text{He} \rightarrow (dn\gamma + pnn\gamma)] / \sigma[\pi^- + {}^3\text{He} \rightarrow {}^3\text{H} + \gamma]$. [h] Ratio of nucleon ejection modes to radiative absorption.

FIGURE CAPTION

Fig. 1. (a) Hydrogen spectrum and pair spectrometer acceptance.

(b) ^{3}He spectrum, 50-150 MeV.

(c) ^{3}He spectrum in region where the breakup channels dominate. The curve is a pole model calculation[8,10] (Δ = 6.8 MeV) with complete kinematics incorporated.



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