Measurement of the Panofsky Ratio in ^{3}He†

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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 $P_3 = (\pi^- + {}^3\text{He} \to {}^3\text{H} + \pi^0)/(\pi^- + {}^3\text{He} \to {}^3\text{H} + \gamma) = 2.68 \pm 0.13$. 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 the combined $^2\text{H} + n + \gamma$ 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 $\pi^- + p \to n + \pi^0$ and the radiative capture reaction $\pi^- + p \to \gamma + n$. 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 Zaimidoraga *et al.*[2] yielded $P_3 = (\pi^- + {}^3\text{He} \to \pi^0 + {}^3\text{H})/(\pi^- + {}^3\text{He} \to \gamma + {}^3\text{H}) = 2.28 \pm 0.18$. Some authors[3,4] have regarded this quantity as a test case in the application of the hypothesis of partial conservation of axial-vector current to soft-pion problems involving complex nuclei. Other authors employ the impulse approximation (IA) directly and relate the Panofsky ratio for ^{3}He to that for ^{1}H. By making this assumption it has been shown[5,6] that P_3 depends primarily on one parameter, viz., the ^{3}He-^{3}H rms transition radius. The value $\langle r^2 \rangle_{^3\text{He}}^{1/2} = 1.4 \pm 0.2$ fm extracted from $P_3 = 2.28 \pm 0.18$ disagrees with the value 1.88 ± 0.05 fm determined[7] by electron scattering. In view of the importance of this quantity to the study both of the elementary-particle approach to nuclei and of the structure of the mass-3 system and possible three-body forces, it was thought desirable to remeasure this quantity and to study directly the radiative breakup reactions $\pi^- + {}^3\text{He} \to d + n + \gamma$ and $p + n + n + \gamma$.

The experiment was performed in the stopped-π beam of the Lawrence Berkeley Laboratory 184-in. cyclotron. Details of the experimental setup are given by Baer.[8] A π^- beam is brought to rest in a 9.5-cm-diam, 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. In a calibration experiment with a hydrogen target we

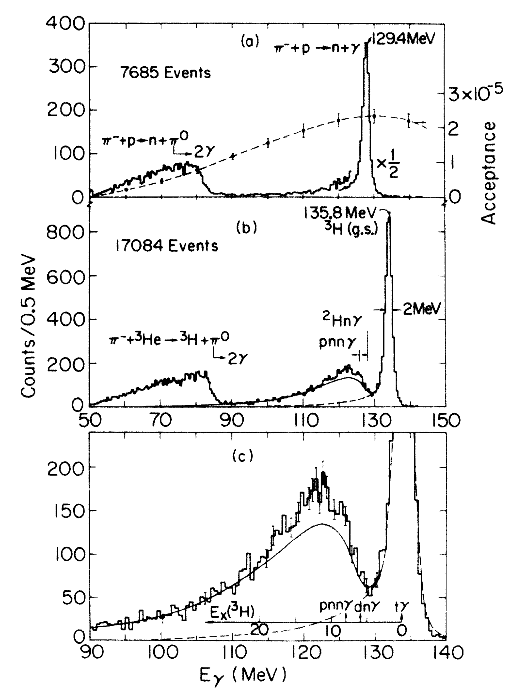

FIG. 1. (a) Hydrogen spectrum and pair spectrometer acceptance. (b) ^{3}He spectrum, 50–150 MeV. (c) ^{3}He spectrum in region where the breakup channels dominate. The curve is a pole-model calculation (Refs. 8 and 10) ($\Delta = 6.8$ MeV) with complete kinematics incorporated.

determine the energy resolution of the spectrometer to be 2 MeV (full width at half-maximum) at 129.4 MeV [Fig. 1(a)]; the acceptance (conversion efficiency times detection efficiency times $\Delta\Omega/4\pi$) is given in Fig. 1(a) 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}He(π^-,γ) spectrum [Fig. 1(b)] exhibits the expected four photon channels: $t\gamma$ (t represents ^{3}H) with $E_\gamma = 135.8$ MeV; $dn\gamma$ and $pnn\gamma$ with endpoint energies of 129.8 and 127.7 MeV, respectively; and $t\pi^0$, $\pi^0 \to 2\gamma$, with a uniform distribution between 53.1 and 85.7 MeV. There is a suggestion of a broad peak corresponding to a 10–15-MeV excitation in the ^{3}H system [Fig. 1(c)], 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 ^{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. 1(c)]. 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., with their sum not constrained to 100%, but agreeing with it), and their ratio P_1, agree with previous measurements.[1] P_3 is determined from

$$P_3 = P_1(1.533 \pm 0.021)[N_\gamma(^3\mathrm{H}\pi^0)/N_\gamma(^3\mathrm{H}_\gamma)][N_\gamma(n\gamma)/N_\gamma(n\pi^0)](1-f),$$

where N_γ 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 ^{3}He and ^{3}H, since the photon energies differ slightly. The uncertainties in the acceptance cancel out and the pion normalization does not enter.

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

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

[a] Raw number of events in spectrum.
[b] This experiment.
[c] Previous experiments.
[d] Ref. 2.
[e] $dn\gamma$ only.
[f] Ref. 1.
[g] Panofsky ratio.
[h] See text.
[i] $\sigma(\pi^- + {}^3\mathrm{He} \to (dn\gamma + pnn\gamma))/\sigma(\pi^- + {}^3\mathrm{He} \to {}^3\mathrm{H} + \gamma)$.
[j] Ratio of nucleon ejection modes to radiative absorption.

The errors for N_γ and the small error of P_1 from previous experiments yield an error for P_3 of 4.8%. We bracketed the ^{3}He runs with fifteen ^{1}H runs[11] (both targets were mounted interchangeably 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 it 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 $2p \to 1s$ 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

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

with

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

and for charge exchange[3] by

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

with

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

where $\hbar=c=1$; m_3 = mass of ^{3}He; m_n = mass of ^{1}H; $(\omega_0, \vec{q}_0)=\pi_0$ four-momentum; and $\vec{k}$ and $\hat{\epsilon}$ are the photon momentum and polarization, respectively. 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: $|\varphi_\pi(0)|^2=(0.97/\pi)(Z\alpha m_\pi)^3(1+m_\pi/m_3)^{-3}$, where $\omega=1/137$. The value of C is determined by pion photoproduction cross sections at threshold and has the value[13] $C=4\pi|E_{0+}^{(\pi^-)}| =4\pi(3.15\pm0.06)\times10^{-2}/m_\pi$. A is related to the πN isospin singlet and triplet scattering lengths[13] by $A =(4\pi\sqrt{\frac{2}{3}})|a_1-a_3|$.

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

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

For radiative capture, $|M|^2$ is related[14] to the axial form factors of the mass-3 system and the nucleon and the Gamow-Teller matrix element[15]

$$M_{GT}=\langle^3\mathrm{H}|\sum_{j=1}^{3}\tau_j^{(-)}\vec{\sigma}_j|^3\mathrm{He}\rangle.$$

The charge-exchange matrix element $|M_0|^2$ is related[14] to the vector form factors and Fermi matrix element. Inserting $|M_0|^2/|M|^2=0.73$[16] and $P_1 =1.531$, we obtain $P_3=2.49$, in good agreement with our measured value. The radiative rate from this calculation is 3.60×10^{15} 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 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 $(\alpha/4\pi)^{1/2}(1/f_\pi)\times(g_A/g_V)$. 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 4.43×10^{15} sec^{-1} (4.1×10^{15} 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 2.3×10^{15} sec^{-1}.[18,19]

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[11]This procedure was not followed in the early part of the run. This is the reason that our preliminary analysis based on 25% of our data was influenced by a 15–20% variation in relative efficiency and yielded the higher value $P_3=3.5\pm0.4$ [H. Baer *et al.*, in *Proceedings of the International Conference on Few Particle Problems in the Nuclear Interaction, Los Angeles, California, 1972,* edited by I. Slaus, S. A. Moszkowski, R. P. Haddock, and W. T. H. Van Oers (North-Holland, Amsterdam, 1973), p. 877].

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[15]$|M_{\rm GT}|^2=3$, if ^{3}He and ^{3}H are exact mirror states; β-decay [R. Salgo and H. Staub, Nucl. Phys. A138, 417 (1969)] yields $|M_{\rm GT}|^2=2.84\pm0.06$.

[16]We have

$$|M|^2=\tfrac{2}{3}|M_{\rm GT}|^2\left(\frac{F_A(q^2)}{F_A(0)}\right)^2\left(\frac{f_A(0)}{f_A(q^2)}\right)^2\approx 2\left(\frac{F_M(q^2)}{F_M(0)}\right)^2\times0.95$$

$$=1.9(0.78\pm0.02),\quad q^2=0.474\ {\rm fm}^{-2},$$

$$|M_0|^2=|M_{\rm F}|^2\left(\frac{F_V(q^2)}{F_V(0)}\right)^2\left(\frac{f_V(0)}{f_V(q^2)}\right)^2\approx 1\times0.97,$$

$$q^2=0.027\ {\rm fm}^{-2}$$

where the F's are the transition form factors for ^{3}He $\rightarrow{}^3$H, the f's those for $p\rightarrow n$ (see Ref. 14); data are from Ref. 7.

[17]Previous calculations yielded the values 8.32×10^{15} sec^{-1} (Ref. 5) and 0.97×10^{15} sec^{-1} [P. Divakaran, Phys. Rev. 139, B387 (1965)]. Differences with our value are due to missing factors of $m_\pi/2k$ in Ref. 5 and of 4 in the work of Divakaran, and the use of the older value $r_{\rm rms}(^3{\rm He})=1.55$ fm.

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