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PRECISE MEASUREMENT OF PIONIC K X RAYS IN LIQUID ^{3}He*

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Abstract

We have remeasured energies and Lorentzian widths of pionic K X-ray transitions in liquid ^{3}He with improved accuracy. The strong interaction shift of the π^3He 1s level is found to be attractive and to produce an increase in the K transition energies of 34 ± 4 eV; the Lorentzian width is 36 ± 7 eV. The results are compared with recent theoretical calculations. We have also measured K X-ray energies in π^4He and μ^4He, the Lorentzian width of the 1s level in π^4He, and relative intensities of K X-ray transitions in π^3He, π^4He and μ^4He.

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The π ^{3}He system provides a stringent test of our understanding of pion-nuclear interactions. Two recent measurements [1,2] of the ^{3}He pionic K X rays yielded results inconsistent with each other but each in partial agreement with new calculations (within a multiple scattering framework) of the hadronic contribution to X-ray energies and widths [3,4]. We have repeated our measurement, incorporating technical improvements in order to better determine the calibration and detector lineshape under beam conditions. Data on π ^{4}He and μ ^{4}He were also acquired as tests of possible systematic errors.

Experimental Procedure and Analysis

The experimental setup was similar to that described in reference 1. An 0.4 cm^3 Si(Li) detector was used having an in-beam energy resolution of 250 eV for the 14.4 keV ^{57}Fe gamma ray; the singles rate in the detector was about 500 counts/sec. Pile-up rejection ensured that only those events were accepted which did not have a pulse in the preceding 50 μ's nor in the subsequent 10 μ's. Digital stabilization against zero and gain shifts using the 6.4 keV ^{57}Fe K_α line and the 28.6 keV ^{125}Te K_α line maintained the peak positions constant to within ± 1 eV during the entire data collection period. Thus, final spectra were obtained by simply summing corresponding channels from individual runs. Prompt X rays, their energy-dependent timing spectra, and calibration spectra were acquired concurrently.

Considerable care was taken to accept source calibration events under rate conditions similar to those for the mesonic X rays. Only those source calibration events were accepted which occurred within a 100 ns gate opened by a scintillator placed just to the side of the beam telescope and registering a fraction of the beam scattered out of the telescope direction. The energy calibration lines listed in Table 1 were fitted, using the computer program JAGSPOT [5], to Gaussian lineshapes with two-parameter low energy tails and a linear background;

this seven-parameter fit gave acceptable χ^2's even for high-statistics lines. For broadened peaks this line shape was analytically convoluted with a Lorentzian. The consistency of the analysis was tested using another program in which the highest-statistics lines (^{57}Fe K_α) was used to define an empirical line shape which then was shifted and stretched to fit other lines. The two programs gave consistent results. The instrumental resolutions for the calibration lines were fitted to a quadratic function which was used to determine the instrumental resolutions for broadened lines.

The cryogenic target [7] was disc-shaped with a diameter of 10.6 cm and an effective liquid ^{3}He thickness at 2° K of 200 mg/cm^2; each target face was cooled by a thin layer of superfluid ^{4}He. It was found that there was a (12 ± 1%) ^{4}He contribution in the ^{3}He spectrum from the superfluid ^{4}He in the cooling windows of the target volume and from a 1% ^{4}He contamination in the ^{3}He itself (as determined from a mass-spectrographic analysis). A target-empty X-ray spectrum, obtained with the target volume itself evacuated but with ^{4}He in the cooling windows, helped to identify impurity lines originating in various target structural materials.

μ ^{4}He

Preliminary to the main π^3He experiment, muons were stopped with ^{4}He in the central target volume in order to measure muonic K transition energies. This was a valuable test of the in-beam energy calibration method since these energies are accurately calculable. The values of the muonic ^{4}He K_α and K_β energies were found to be 8223 ± 5 eV and 9740 ± 6 eV respectively. These energies agree within the statistical uncertainties with the Dirac values (8224 eV and 9744 eV respectively) for the muonic ^{4}He K_α and K_β energies corrected for nuclear size and vacuum polarization.

π ^{4}He

π ^{4}He X-ray data were also taken, mainly as a check of the system. The π ^{4}He X-ray lines were analyzed in the same way as the π ^{3}He X-ray lines in order to extract their energies and widths in a consistent manner. The shift and width determined from each of the K_α and K_β transitions are in good agreement with each other. The weighted average of the 1s state strong interaction shifts determined from the K_α and K_β transition energies is repulsive, with a value ΔE_{1s} = 71 ± 5 eV; the average 1s state width is $\Gamma_{1s} = 51 \pm 9$ eV. Our results for π ^{4}He are consistent with those ($\epsilon_{1s} = 76 \pm 2$ eV, $\Gamma_{1s} = 45 \pm 3$ eV) obtained by Backenstoss *et al.* [9], which were used to correct for π ^{4}He lines in the π ^{3}He spectrum.

π ^{3}He

Fig. 1 shows the summed pionic ^{3}He X-ray spectrum which was obtained by adding twenty separate runs over a total net acquisition time of about 24 hours. The positions, Lorentzian widths and intensity parameters of the π ^{3}He K_α and K_β peaks were found by fitting several closely-spaced peaks simultaneously, with the energies and widths of interfering lines fixed at the values obtained from the analysis of the π ^{4}He X-ray and target-empty X-ray spectra. Our values for the energies and Lorentzian widths of the π ^{3}He K_α and K_β lines are listed in Table 2, with the strong interaction energy shift of the 1s level being the difference between the measured energy and the calculated electromagnetic energy for each line. The electromagnetic energies are the Klein-Gordon values, corrected for nuclear finite size, vacuum polarization, and finite size of the pion [10,11]. The nuclear finite size effect was calculated using a Gaussian charge distribution with $\langle r^2 \rangle^{\frac{1}{2}} = 1.88$ fm [12] for ^{3}He. The quoted total uncertainties were obtained by combining the statistical uncertainties in quadrature with the systematic uncertainties, which included effects of instrumental resolution, fitting procedures, position and intensity parameters of interfering lines, Compton scattering in the target, and spectrometer nonlinearity.

The average values for the $\pi\ ^3He$ 1s level strong interaction shift and width are thus:

$$\varepsilon_{1s} = -34 \pm 4 \text{ eV} \quad \text{and} \quad \Gamma_{1s} = 36 \pm 7 \text{ eV}.$$

The strong interaction shift agrees with our previous measurement [1] but differs by two standard deviations from the value of Abela *et al.* [2]. On the other hand, our new measured width agrees with Abela *et al.* [2] but differs by two standard deviations from our previous value [1]. The major difference between the present run and our 1978 run is in the way that the calibration spectra were collected. In the present run much better long-term gain stability was achieved, and special care was taken to ensure that beam rate effects were similar for X rays and for calibration sources. The rather small in-beam resolution determined for the sources during the experiment reported in 1978 may not have been sufficiently beam dependent and may be the origin of the large Lorentzian width reported at that time.

The hadronic isotope shift is much less sensitive to systematic uncertainties than are the absolute energies. We obtain $\varepsilon_{1s}(^3He) - \varepsilon_{1s}(^4He) = -105 \pm 3$ eV.

Table 3 shows experimental and theoretical values for the strong interaction shift and width for $\pi\ ^3He$. Both Lohs [4] and Thomas [3] consider the effects of a possible dispersive contribution to the scattering length, $\Delta a = -\mathrm{Im}(a)$. Weak evidence for such a term has been reported from an optical model analysis by Tauscher [14]. Lohs' calculation incorporates s- and p-wave double scattering, s-wave triple scattering, and double spin flip. (The phase shift analysis of Bugg *et al.* is used.) The width calculated by Lohs is based upon a multiple scattering calculation of the charge exchange cross-sections, together with the measured Panofsky ratio [19].

Thomas performed a similar multiple scattering calculation in which the sensitivity of the results to the choice of pion-nucleon phase shifts is explored. We quote his newly-revised values which are in good agreement with Lohs. The uncertainty in this calculation, which comes 90% from the experimental uncertainty in the isoscalar scattering length a_1 precludes us from distinguishing the presence of the dispersive term. An improvement of the accuracy of a_1, measured with πd X rays, would clarify this situation.

Phillips and Roig [15] have calculated the 1s absorptive width $\Gamma_{abs}^{1s} = 27 \pm 8$ eV using a phenomenological two nucleon absorption model. Allowing for the charge-exchange cross sections, this results in $\Gamma_{tot}^{1s} = 37 \pm 11$ eV, in good agreement with experiment.

X-Ray Intensities

In order to determine the intensities of the $\pi\ ^3He$ K_γ and K_δ lines in the presence of interfering lines, the positions and widths were fixed and other parameters were allowed to vary in order to determine only the areas under the peaks. The Lorentzian widths were fixed at the average value already determined from the $\pi\ ^3He$ K_α and K_β lines. The positions of the $\pi\ ^3He$ K_γ and K_δ lines were fixed at the calculated electromagnetic energies corrected by the measured strong interaction energy shift of the 1s level. The measured intensities of the pionic K_β, K_γ and K_δ transitions in liquid ^3He relative to 100 for the K_α transition were 107 ± 6, 24 ± 2 and 8 ± 1, respectively, in agreement with our previous measurements [1].

Table 4 shows the measured relative intensities of K X rays for π and μ, ^3He and ^4He, liquid and gas phases. There has been no satisfactory theoretical explanation of these intensities, particularly of the anomalously large K_β intensity in pionic liquid helium. However, some agreement has been achieved [9] in cascade models using adjustable parameters in those areas of the cascade which are not yet properly understood: the initial distribution of pion atomic states, the strength of the external Auger effect, and the strength of the Stark mixing.

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Table 1

Energies of the Calibration Lines

Calibration Line	Energy (keV)
Fe^{57} $K\alpha$	6.399 ± .001
Fe^{57} $K\beta$	7.058 ± .002
πO 4-3	11.470 ± .001
Fe^{57} γ	14.412 ± .001
πC 3-2	18.401 ± .001
πO 3-2	32.843 ± .002
I^{125} γ	35.492 ± .001

Table 2

$\pi\ ^3He$ Results

(energies in eV)

Transition	K_α	K_β
Measured Energy	10679.0	12647.5
Statistical Uncertainty	1.5	1.5
Total Uncertainty	4.3	4.3
Electromagnetic Energy	10646	12613
Strong Interaction Shift	33	34.5
Gaussian Width	229 ± 6	238 ± 6
Lorentzian Width	34.8 ± 7	37.5 ± 7

Table 3

Experimental and Theoretical Values (in eV) for the Strong Interaction Shift and Width for π ^{3}He

	Shift	Width	Reference
Experimental Values	50^{+16}_{-20}	89 ± 67	Sapp [13]
	44 ± 5	42 ± 14	Abela *et al.* [2]
	27 ± 5	65 ± 12	Mason *et al.* [1]
	34 ± 4	36 ± 7	Present results
Theoretical Values	39 ± 14	24 ± 8	Lohs [4], notes a and d
	25 ± 14	-	Lohs [4], notes a and e
	36 ± 11	-	Thomas [3], notes b and d
	38 ± 5	-	Thomas [3], notes a and d
	53 ± 9	-	Thomas [3], notes c and d
	23 ± 11	-	Thomas [3], notes b and f
	25 ± 4	-	Thomas [3], notes a and f
	40 ± 9	-	Thomas [3], notes c and f
	-	37 ± 11	Phillips and Roig [15]

Notes
a) The phase shifts of Bugg *et al.* [16] were used.
b) The phase shifts of M. Salomon [17] were used.
c) The phase shifts of Samaranayake and Woodstock [18] were used.
d) No dispersion.
e) A dispersive correction $\Delta a = -\mathrm{Im}(a)$ is included, with $\Gamma = 42$ eV.
f) A dispersive correction $\Delta a = -\mathrm{Im}(a)$ is included, with $\Gamma = 37$ eV.

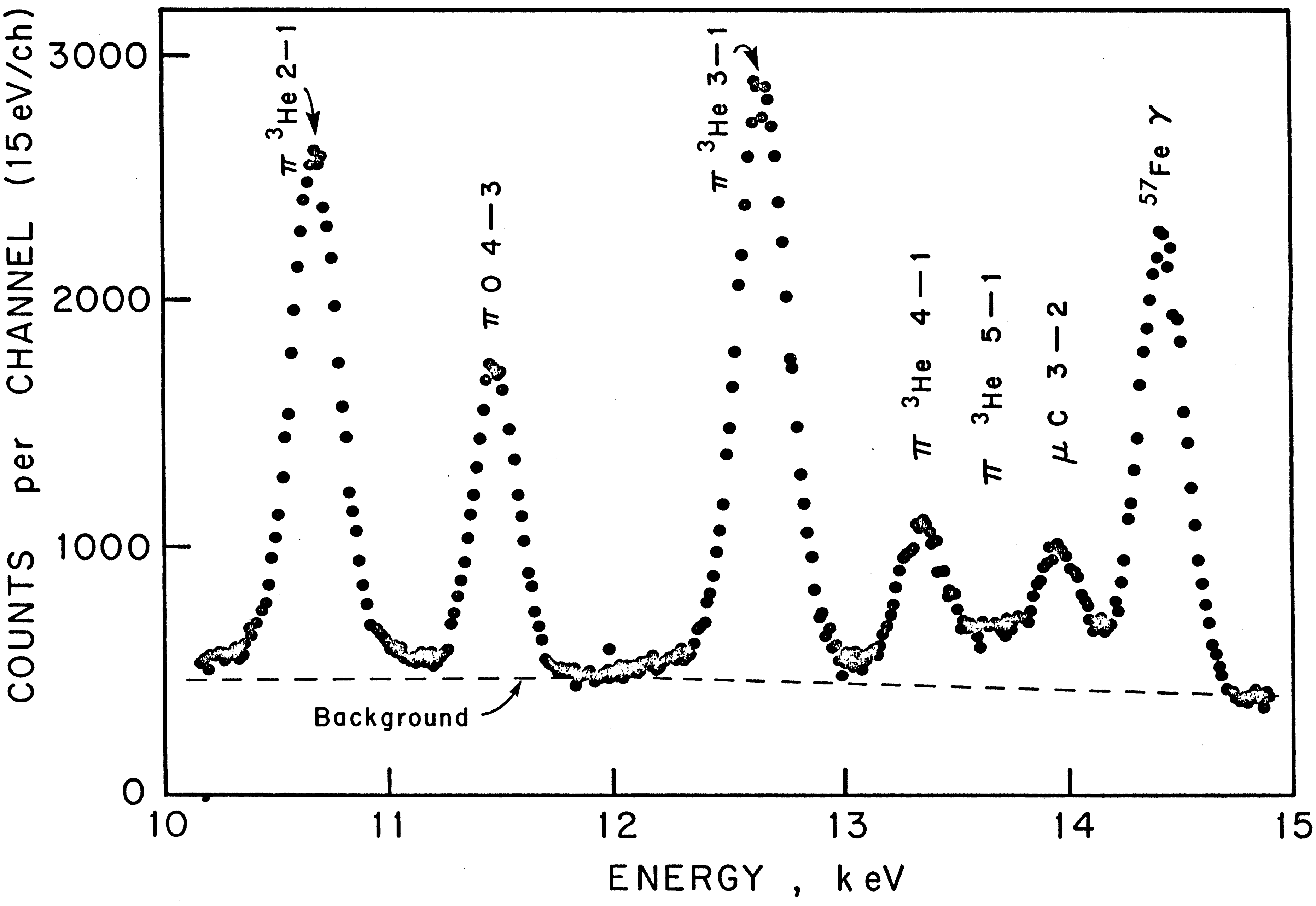
Table 4

X Ray Intensities Relative to 100 for K_α

($\ell \equiv$ liquid; g $\equiv$ gas)

Type	K_β	K_γ	K_δ	Reference
π ^{4}He (ℓ)	124 ± 9	42 ± 3	9.6 ± .8	Backenstoss *et al.* [9]
	120	34	7	Present Experiment
π ^{3}He (ℓ)	119 ± 13	-	-	Sapp *et al.* [13]
	105 ± 6	22 ± 2	8 ± 1	Mason *et al.* [1]
	107 ± 6	24 ± 2	8 ± 1	Present Experiment
π ^{4}He (g)	38 ± 4	-	-	Abela *et al.* [2]
π ^{3}He (g)	40 ± 4	-	-	Abela *et al.* [2]
π ^{4}He Theory	98.5	44	9.5	Backenstoss [9]
μ ^{4}He (ℓ)	54 ± 4	11 ± 2	2.6 ± 1.6	Backenstoss [9]
	45	7	-	Present Experiment
μ ^{4}He Theory	54.6	10.5	1.5	Backenstoss [9]

Fig. 1 π ^{3}He X-ray Spectrum


COUNTS per CHANNEL (15 eV/ch)
3000
2000
1000
0
10
11
12
13
14
15
ENERGY , keV
π ³He 2—1
π O 4—3
π ³He 3—1
π ³He 4—1
π ³He 5—1
μ C 3—2
⁵⁷Fe γ
Background