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X Rays from Pionic ^{3}He[1]

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Abstract

Pionic X-ray energies, Lorentzian widths, and relative intensities have been measured f the transitions in liquid ^{3}He. The pion-nucleus interaction is found to result in an attractive shift of the 1s level of 27 ± 5 eV and in a Lorentzian width of 65 ± 12 eV. The measured K_β to K_α intensity ratio is 1.05 ± 0.07.

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Pionic X-rays provide the best information about the interaction between pions and nuclei at low relative momenta. Measurements for all but the lightest nuclei have been satisfactorily parameterised using an optical potential of Ericson and Ericson [1,2]. Recently, data have been obtained for lithium and beryllium [3], for ^{4}He [4], for ^{3}He [5], and for ^{2}H [6]. ^{3}He is particularly important because it is the only nucleus, except for hydrogen, with more protons than neutrons; it is unique in having an attractive s-wave interaction with the pion. Although the ratio of intensities of the pionic K_α and K_β transitions is normal for the gaseous states of ^{4}He and ^{3}He, this ratio has been found to be anomalous for liquid ^{4}He [4] and apparently also for liquid ^{3}He [10]. Thus, it was important to measure the pionic K transitions in liquid ^{3}He to confirm not only the strong interaction shift and width but also the intensity anomaly. An experiment to measure these quantities is reported herein.

The experiment was performed at TRIUMF using the M9 magnetic channel, which was tuned to accept 96 MeV/c (±5%) negative particles produced in a 10 cm long beryllium target bombarded by 10 μA of 500 MeV protons. Time-of-flight spectra showed that the relative abundance of particles in the collimated beam was 48% pions, 48% electrons and 4% muons.

The liquid ^{3}He target‡[1] [7] is seen in cross-section in fig. 1; the helium target volume is pill-shaped, 20 mm thick by 106 mm in diameter, and is cooled to 2°K by superfluid ^{4}He. The cylindrical lead collimator and borated gypsum blocks ensured that the pion beam was confined to the liquid helium volume and also served to shield the Si(Li) X-ray detector from the direct pion beam. Pions stopping in the ^{3}He target were signalled electronically by the usual $1.2.3.\bar{4}$. coincidence among the plastic scintillators constituting the telescope.

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‡[1] The ^{3}He target was loaned to the University of Victoria for use at TRIUMF by the National Aeronautics and Space Administration of the U.S.A. under contract NASW-2763.

Of the 5×10^4 pion stops per sec only about ten per cent were in the ^{3}He itself, with the remainder being in the mylar windows, target frame, and scintillators. X-rays emitted during the atomic cascade of the pions were detected with a Kevex Si(Li) detector (80 mm^2 × 5 mm thick) having an in-beam resolution of 181 eV FWHM at 6.4 keV. The data were stored in a Nuclear Data ND2400 4096 channel pulse height analyser, with half of the channels being used to record the pionic X-ray spectrum and the other half to record simultaneously a ^{57}Co source spectrum.

In fig. 2 is shown the pionic ^{3}He X-ray spectrum which was analysed for the strong-interaction shift and Lorentzian width of the 1s level, and for the relative intensities of the K transitions. The spectrum was obtained by combining the data from 22 separate runs over a total net acquisition time of 17.3 h. In order to correct small gain shifts the data were added after a quadratic correction was made on the basis of three source lines and two prominent lines from the X-ray spectrum; the energies (in eV) of these lines are: Fe^{57}K$_\alpha$ 6399 ± 1, Fe^{57}K$_\beta$ 7058 ± 2, πO M$_\alpha$ 11470 ± 1, ^{57}Fe γ 14412 ± 1, and πC L$_\alpha$ 18401 ± 1.

A background run with the ^{3}He removed from the target volume helped to identify the peaks shown in fig. 2; the πO 4-3 peak was used for normalization. The background run showed that there was (10 ± 1)% ^{4}He contamination in the ^{3}He spectrum from the superfluid ^{4}He in the cooling windows of the target volume. In addition a mass-spectrographic analysis showed a 1.0% ^{4}He contamination in the ^{3}He volume. In the final analysis, however, the amount of ^{4}He contamination in the spectrum was obtained by fixing the π ^{4}He energies and Lorentzian widths at the values determined by Backenstoss *et al.* [4] and then by varying the amount of ^{4}He in a simultaneous fit of lines in the ^{3}He spectrum. The ^{4}He contamination so determined was 9.3 ± 0.5%.

The summed spectrum was analysed using two independent line fitting programs. In one program [8] instrumental line shapes were assumed to be Gaussian; in a second program [9] the Fe^{57}K$_\alpha$ line in the source spectrum was used to define an empirical line shape, and each of the other lines was fitted to this shape. The two programs gave consistent results for the centroids, instrumental widths, and, in the case of the broadened lines, Lorentzian widths.

Because of possible instrumental shifts between lines in the source spectrum and those in the X-ray spectrum, only lines in the X-ray spectrum were used for energy calibration. It is seen in fig. 2 that the π ^{3}He K$_\alpha$, πO 4-3 and π ^{3}He K$_\beta$ lines are well separated from each other and stand out clearly above the background. Because the calculated πO 4-3 energy of 11470 eV has negligible strong interaction shift and has been verified experimentally [4], this line was used as an absolute energy calibration. The energy dispersion was then determined from the difference between the π ^{3}He K$_\beta$ and K$_\alpha$ energies. Each of these lines is shifted by essentially the same amount by the strong interaction (the effects on the 2p and 3p levels are negligible) so that the energy difference is purely electromagnetic and hence calculable. This method of energy calibration using an X-ray in the region of interest for absolute calibration and determining the dispersion locally is relatively insensitive to system nonlinearities. The widths, energies, and the 1s level strong interaction shift thus calculated are given in table 1. The statistical uncertainties were added in quadrature to the systematic uncertainties, which included the effects of instrumental resolution, fitting procedures, 1s level shift, width and intensity of ^{4}He interfering lines [4], Compton scattering in the target, spectrometer nonlinearity and the position of the πO 4-3 transition. An alternative calibration based on the three ^{57}Fe lines gave energies 10677 ± 6 eV and 12644 ± 6 eV for the K$_\alpha$ and K$_\beta$ lines respectively, in agreement with the values obtained from the oxygen calibration.

Our values for the 1s strong interaction shift and width are thus:

$$\Delta E_{1s} = 27 \pm 5 \text{ eV} \qquad \text{and} \qquad \Gamma_{1s} = 65 \pm 12 \text{ eV}.$$

These results may be compared with previous measurements by the Virginia group [10] of $\Delta E_{1s} = 50 {}^{+16}_{-20}$ eV and $\Gamma_{1s} = 89 \pm 67$ eV, and by Abela *et al.* [5] of $\Delta E_{1s} = 44 \pm 5$ eV and $\Gamma_{1s} = 42 \pm 14$ eV. The relative intensities of the pionic liquid ^{3}He K$_\alpha$, K$_\beta$, K$_\gamma$ and K$_\delta$ transitions were observed to be 100 ± 6, 105 ± 6, 22 ± 2, and 8 ± 1, respectively. The anomalously large ratio of K_β to K_α intensities agrees with the Virginia measurement of 1.19 ± 0.13 for liquid ^{3}He and may be compared to the ratio 1.24 ± 0.09 measured [4] for liquid ^{4}He. Liquid helium is the only known case where the pionic K_β intensity exceeds that of the K_α transition. In contrast, for gaseous ^{3}He and ^{4}He, the ratios of the K_β to K_α intensities are 0.40 ± 0.04 and 0.38 ± 0.04, respectively.[5] The intensity anomaly in liquid helium has been discussed previously [4], but remains unresolved.

We have attempted to predict the intensities using a standard cascade computer program which included the following processes: dipole radiative transitions, radioactive decay, nuclear absorption of the pion in ns and np states, and the internal Auger effect. The free parameters in the calculation were the distribution of pion states at the time of initial capture and the value of Γ_{2p} which was used in calculating the p-state absorptions. No reasonable variation in the free parameters gave the measured intensity ratios.

Our experimental values for the strong interaction shift and width of the π ^{3}He 1s level may be compared with the optical potential theory of Ericson and Ericson [1]. The π-atomic potential parameters have been discussed by Krell and Ericson [2], and we note that a strong dependence on the atomic number is expected for the strength parameter b_0 of the isoscalar local potential. Except for b_0 and C_0 we use the values of the potential parameters established for heavier elements by Tauscher [12] to calculate the strong interaction shift and width for the 1s state of π ^{3}He. The values used are:

$$b_0 = -0.015\ \mu^{-1}, \qquad c_0 = 0.21\ \mu^{-3}, \qquad B_0 = i\ 0.04\ \mu^{-4},$$
$$b_1 = -0.09\ \mu^{-1}, \qquad c_1 = 0.18\ \mu^{-3}, \qquad C = 0.$$

Using a Gaussian distribution with $\langle r^2\rangle^{\frac{1}{2}} = 1.88$ fm [13] for the ^{3}He nucleus, the result of the calculation is:

$$\Delta E_{1s} = 30.5\ \text{eV}; \qquad \Gamma_{1s} = 38.6\ \text{eV}.$$

We have put $C_0 = 0$ since the p-state absorption term, if included, reduces the s-state width by 24 eV, whereas from the physics point of view, no dramatic influence of the p-wave potential should be expected on the s states. To understand this, we refer to fig. 1 in Krell and Ericson [2]. The imaginary part of the p-wave (or non-local or gradient) potential has a dipole character similar to the real part shown in this figure. This form of the potential produces the unphysical negative p-wave absorption effect on the s state.

We believe that *the present experiment suggests that the simplification of including the absorptive p-wave potential part in the gradient structure is not correct for light nuclei* and that another form of absorption on the surface may be more appropriate for the p-wave interaction.

Our treatment of (two-nucleon) absorption does not properly account for charge exchange and radiative capture, which are the only channels for hydrogen. These reactions contribute very little to the width in heavier elements, but give a significant contribution in the case of ^{3}He [14]. According to a more recent evaluation by Phillips [15], it might just make up for the remaining differences between the result of the simple optical model calculations and our experimental results.

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Table 1

Summary of $\pi\ ^3$He X ray results (all energies in eV)

Transition	K_α	K_β
Instrumental resolution	221 ± 9	234 ± 9
Lorentzian width Γ	66	62
δΓ (statistical)	4.1	7.0
δΓ (total)	12.1	13.4
Calculated electromagnetic energy	10646	12613
Experimental energy	10673	12640
Strong interaction shift ΔE of the 1s level	27	
δΔE (statistical)	2.4	
δΔE (total)	5.0	

Figure Captions

1. Plan view of the $\pi\ ^3$He experiment
2. Summed spectrum of X rays from the $\pi\ ^3$He experiment

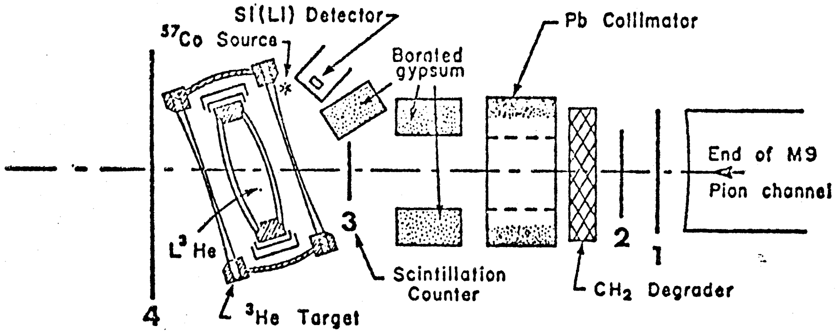

Fig. 1

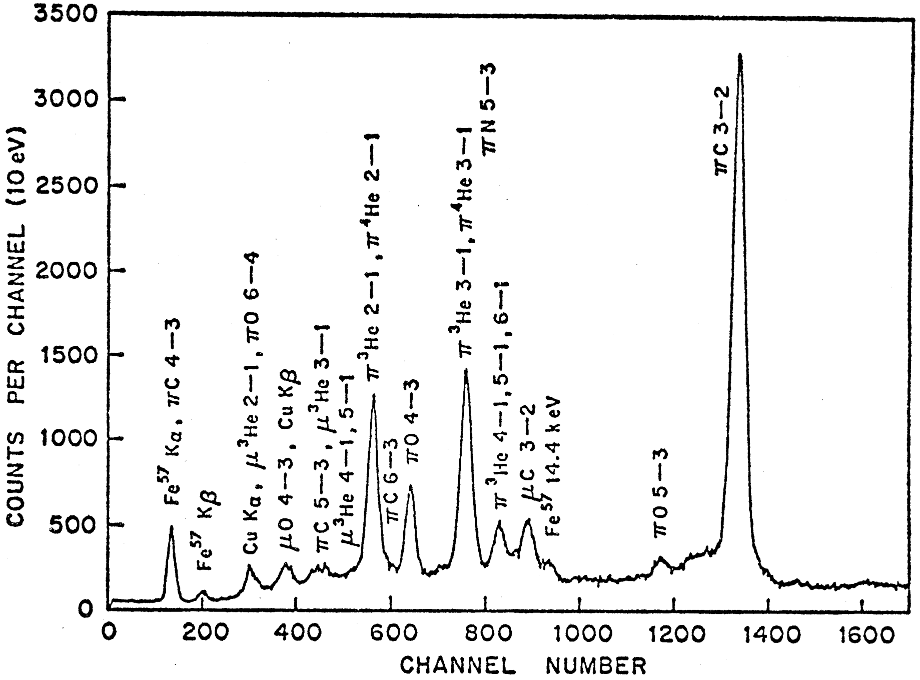

Fig. 2