PIONIC X-RAY TRANSITIONS IN $^3\text{He}^*$

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ABSTRACT

Pionic ^3He atoms have been produced in a gaseous target. Energies and strong absorption broadening of the $2 \rightarrow 1$ and the $3 \rightarrow 1$ transition lines have been measured. The $1s$ level is shifted by 44 ± 5 eV by the (attractive) strong interaction, and the natural $1s$ level width is 42 ± 14 eV.

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The strong interaction effects in pionic atoms have been satisfactorily described by an optical potential for all nuclei with the exception of the very lightest ones [1]. The precise data available for ${}^6\text{Li}$, ${}^7\text{Li}$, and ${}^9\text{Be}$ [2] and particularly ${}^4\text{He}$ [3] necessitate more detailed microscopic treatments, which so far have not fully succeeded in explaining the data.

We report here on the strong interaction shift and width of the $1s$ level in ${}^3\text{He}$. The three-nucleon target has been chosen because it is a testing ground for the two-nucleon-absorption hypothesis, while the properties of the three-nucleon system are still understood well enough to make the absorption process accessible to microscopic theories. Such theories also have an impact on the calculation of the atomic properties of pionic ${}^3\text{He}$. Furthermore, the final state after pion capture in ${}^3\text{He}$ consists of no more than three nucleons and hence can be fully determined with reasonable experimental effort.

Pionic ${}^3\text{He}$ X-ray spectra have been investigated some time ago [4] but have never been published.

The measurement has been carried out at the $\pi\text{E}1$ -channel [5] of the SIN ring-accelerator. The channel was tuned to 200 MeV/c and delivered $\sim 3 \times 10^6$ pions per second. The relative abundance of e^- , π^- , and μ^- in the beam was 1.6:1.0:0.1, respectively. A scintillator telescope especially tuned for high counting rates served to detect pions which stopped in the target. Pions and electrons were identified by measuring the time-of-flight with respect to the 50 MHz frequency of the ring-accelerator. The rejection of electrons led to a considerable reduction of background caused by bremsstrahlung. The FWHM of the distribution of stopped π^- perpendicular to the beam axis was 44 mm in the horizontal direction and 36 mm in the vertical direction. The target consisted of a self-supporting mylar (14 mg/cm^2) cylinder, 12 cm long with a diameter of 6 cm. The ${}^3\text{He}$ gas which was contained in this volume was cooled to $\sim 5 \text{ K}$ by thermal contact with a copper plate which was at the lower end of a liquid ${}^4\text{He}$ container. The resulting target thickness was

$\sim 90 \text{ mg/cm}^2$. Typically, we registered a rate of $\sim 1 \times 10^5$ pion stops per second in the ^3He target. Cryostat and target were enclosed in a vacuum container with mylar windows (14 mg/cm^2) for beam entrance and exit and outgoing X-rays. Thermal radiation losses were prevented by 15 layers of superinsulation (1 mg/cm^2 each) surrounding the whole target assembly. The X-rays from the target were detected in coincidence with signals produced by stopped mesons. We used a Si(Li) detector with a $25 \text{ }\mu\text{m}$ Be window, an area of 80 mm^2 , and a thickness of 5 mm . The X-ray spectrum from stopped pions in ^3He was accumulated for ~ 16 hours, corresponding to 46×10^3 events in the $\pi^3\text{He } 2 \rightarrow 1$ line. In addition, spectra were measured for muons stopping in a ^3He target (6 h) and for stopped pions with the target containing ^4He (2 h) and being empty (4 h).

Figure 1 shows the pionic ^3He spectrum. The peaks in the spectrum were fitted using an expression consisting of a Gaussian with a one-parameter tail towards lower energies. The background was assumed to be linear. The built-in calibration lines of $\pi\text{C}3 \rightarrow 2$ and $\pi\text{O}3 \rightarrow 2$ served to adjust for small gain shifts. The analysis of the peaks of interest was sometimes influenced by contributions of muonic and weak pionic lines from the materials of the target container (see Fig. 1). These impurity peaks were taken into account making use of the knowledge of their separation in energy and their relative intensities as deduced from the empty target and the muonic ^3He runs.

The energy calibration of the spectrum in Fig. 1 was obtained from the known energies of the transitions $\pi\text{C}4 \rightarrow 3$, $\pi\text{O}4 \rightarrow 3$, $\pi\text{C}3 \rightarrow 2$, and $\pi\text{O}3 \rightarrow 2$, taking place in the mylar walls of the target container. Calculated values were taken for these transition energies [6], except for the $\pi\text{O}3 \rightarrow 2$ line for which a measured energy was used [6] because of the presence of a small strong interaction shift. A linear relationship between the fitted peak positions and the corresponding transition energies proved to be sufficient. The fact that built-in calibration lines are used, which are accumulated under conditions identical to those of the ^3He lines, leads to the small error of 1.2 eV of the energy calibration.

As a result, we obtained transition energies E_{exp} in pionic ${}^3\text{He}$ as listed in Table 1. The quoted uncertainty δE_{tot} is composed of a statistical error from the fitting procedure, an uncertainty of the energy calibration, and of estimated systematic contributions caused by impurity peaks, low-energy tails, and the particular choice of the region of the spectrum included in the fit. The systematic uncertainty was about twice the statistical error. Also listed is the purely electromagnetic transition energy E_{em} obtained by calculating the eigenvalue of the Klein-Gordon equation for an extended nucleus. An harmonic well distribution was used with an r.m.s. radius of 1.88 fm [7]. The corrections amount to -6.4 eV (finite size), 29.8 eV and 30.5 eV (vacuum polarization for the $2 \rightarrow 1$ and $3 \rightarrow 1$ transition, respectively), and -2.6 eV for the pion form factor [8,9]. As a check, we have determined the energies of the same transitions in muonic ${}^3\text{He}$ and found agreement within the experimental uncertainties (~ 10 eV) with the corresponding electromagnetic transition energies.

A similar treatment was followed to extract the broadening of the pionic ${}^3\text{He}$ lines due to the strong interaction. The energy-dependent instrumental resolution was determined by fitting a linear function of the energy to the Gaussian widths of the calibration transitions $\pi C4 \rightarrow 3$, $\pi O4 \rightarrow 3$, $\pi C3 \rightarrow 2$ and $\pi O3 \rightarrow 2$. The pionic ${}^3\text{He}$ lines were then fitted with a Gaussian for the instrumental peak width, folded with a Lorentzian, representing the strong interaction broadening. The resulting Lorentzian widths for the $\pi^3\text{He}2 \rightarrow 1$ and $\pi^3\text{He}3 \rightarrow 1$ transitions are given in Table 1. The corresponding instrumental (Gaussian) widths for the two transitions are 336 ± 10 eV and 346 ± 10 eV, respectively. The quoted uncertainties have contributions, stemming from the same sources as already mentioned for δE . Again, the systematic uncertainties amounted to about twice the statistical error.

Attributing shift and broadening of the $\pi^3\text{He}3 \rightarrow 1$ and $\pi^3\text{He}2 \rightarrow 1$ transition lines to effects of the strong interaction in the $1s$ level only, the energy shift and the width of the $1s$ level are obtained by averaging the respective results for the two transitions listed in Table 1:

$$\begin{aligned}\Delta E_{1s} &= 44 \pm 5 \text{ eV} \\ \Gamma_{1s} &= 42 \pm 14 \text{ eV} .\end{aligned}\tag{1}$$

This result represents an improvement of the previously determined [4] values

$\Delta E_{1s} = 50_{-20}^{+16}$ eV *) and $\Gamma_{1s} = 89 \pm 67$ eV but are consistent with these. The complex s-wave scattering length $a_{\pi^3\text{He}}$ is obtained as described by Hüfner et al. [10]. It is $a_{\pi^3\text{He}} = 0.050 \pm 0.005 + i(0.034 \pm 0.012) m_{\pi}^{-1}$.

It should be pointed out that $\pi^3\text{He}$ is the only known case with $\Delta E_{1s} > 0$, corresponding to an attractive s-wave π -nuclear interaction. This may be qualitatively understood as follows. The strong interaction shift can be estimated assuming that the π^- -nucleus scattering length is a coherent superposition of the elementary $\pi^- + n$ and $\pi^- + p$ scattering lengths [11]. Since the latter two are comparable in magnitude but opposite in sign, the energy shift can be expected to have the sign of the scattering length of the unpaired p in ^3He , as is actually the case.

Following the same argument, it has been suggested [12] that isotopic differences of the real part of the $\ell = 0$ pion scattering length for light nuclei are directly related to the $\pi^- + n$ scattering length $a_{\pi n}$. Figure 2 shows the isotopic difference $\text{Re}(a_{\pi, A+1} - a_{\pi, A})$ versus A for the isotope pairs $^3, ^4\text{He}$ (this work and [10]), $^6, ^7\text{Li}$ [10], $^{10}, ^{11}\text{B}$ [10], and $^{16}, ^{18}\text{O}$ [10] (normalized to a difference of one neutron, as quoted in Ref. 12). For comparison, the $\pi^- + n$ scattering length $a_{\pi n}$ [13] is also marked. It can be seen that, although isotopic differences are comparable in size to the elementary $a_{\pi n}$, there is a definite and so far unexplained A-dependence.

Recently, it has been pointed out that the relative intensity $R_{3 \rightarrow 1/2 \rightarrow 1}$ of the pionic K_{β} line as compared to the K_{α} line shows an anomalously large value of $R_{3 \rightarrow 1/2 \rightarrow 1} = 1.24 \pm 0.09$ in liquid ^4He [3]. The same parameter has also been determined in liquid ^3He [4]: $R_{3 \rightarrow 1/2 \rightarrow 1} = 1.19 \pm 0.13$. It has been suggested that this large $R_{3 \rightarrow 1/2 \rightarrow 1}$ is caused by effects occurring during interatomic collisions. This is consistent with our observation that $R_{3 \rightarrow 1/2 \rightarrow 1}$ is significantly smaller in gaseous targets, where the interatomic distances are large compared to the liquid phase. We determined a $R_{3 \rightarrow 1/2 \rightarrow 1}$ of 0.38 ± 0.04 and 0.40 ± 0.04 for gaseous ^4He and ^3He , respectively.

*) Based on our electromagnetic values.

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Table 1

Pionic ^3He

Transition	E_{exp} (keV)	$\delta E_{\text{stat.}}$ (eV)	δE_{tot} (eV)	E_{em} (keV)	Shift (eV)	Lorentzian width (eV)
$2 \rightarrow 1$	10.691	2	5	10.646	45	37 ± 14
$3 \rightarrow 1$	12.653	4	6	12.613	40	62 ± 23

Figure captions

Fig. 1 : Pionic ^3He . The peak labels concern the calibration lines (top row), pionic and muonic ^3He lines (second row), and impurity lines taken into account (bottom row).

Fig. 2 : Isotopic difference between the real parts of the $\ell = 0$ scattering lengths for several light nuclei. The hatched region marks the value of the elementary (π^-n) scattering length.

Fig. 1

Fig. 2