Search for $^{10}$He in the stopped pion absorption $^{14}$C$(\pi^-,p^3$He)X

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Abstract. The formation of the $^{10}$He states was studied in the reaction of stopped pion absorption $^{14}$C$(\pi^-,p^3$He)X. Measurements were carried out using two-arm multilayer semiconductor spectrometer and “radioactive” target consisting of 76% $^{12}$C and 23% $^{13}$C. The contribution of uncontrolled impurities in the target was ≤ 1%. In order to determine the contribution of the $^{12}$C impurity measurements were performed on an isotopic pure carbon $^{12}$C target. An indication on the excitation state with missing mass spectrum of $^{14}$C$(\pi^-,p^3$He)X reaction. Comparison with theoretical and experimental results obtained by other authors was performed.

1. Introduction

For $Z \geq 2$ the two-neutron unbound superheavy helium isotope $^{10}$He has the largest ratio N/Z of any nucleus (nucleon stable or nonstable). Therefore, the study of a level structure of $^{10}$He is of increased interest. However, this isotope is very difficult to study, since there are a limited number of reactions in which it is possible to form states with such an enormous large neutron excess.

For the first time, the $^{10}$He nucleus was observed in the knockout reaction in an experiment performed on the RIKEN [1, 2]. In reaction CD$_2$(11$\text{Li}$, mn$^3$He)X, a resonant state was found in the effective mass spectrum of the system $(n+n^3$He) with the following parameters $E_r = 1.2(3)$ MeV (energy with respect to the $^{10}$He→ $n+n^3$He threshold) and $\Gamma \leq 1.2$ MeV [2]. In this experiment, no evidence of the existence of excited states of $^{10}$He was found. It should be noted that the phase volume distributions make a significant contribution to the measured spectrum.

All other experiments with the $^{10}$He production were also carried out on beams of radioactive ions (see table 1). In an experiment performed at IHM, the $^{10}$Be ($^{12}$C, $^{14}$O)$^{10}$He reaction was studied at an energy 334 MeV [3]. The reaction mechanism corresponds to a two-proton pick-up plus a two-neutron stripping reaction. Despite the large background in the measurements, the authors were able to distinguish the ground and two excited states, the parameters of which are shown in the table. The spin-parity values of the states were determined by comparing experimental and theoretical resonance widths in the framework of the R-matrix theory. It should be pointed out that the resonant formation cross-section has the strong angular dependence. The states shown in the table were observed in the range of scattering angles $1.7^\circ \leq \theta \leq 3.0^\circ$, while in the range $2.7^\circ \leq \theta \leq 3.9^\circ$ only one state with $E_r = 7.87(6)$ MeV was found.

More recently experiments were performed on the radioactive beams of $^{11}$Li [4-7], $^8$He [8-9], and $^{14}$Be [11]. It should be noted that in all these experiments, the statistics is poor. A distinctive feature of the results is the difference in the energy of the ground state obtained in experiments on $^3$He beams.
and in other experiments. This discrepancy is \( \sim 1\text{–}2 \text{ MeV} \) (see table 1). Grigorenko and Zhukov [12] suggested that the discrepancy between results obtained on the \(^{9}\text{He}\) and \(^{11}\text{Li}\) beams are due to the different source size of the reactions. The calculations showed that the extended wave function size of \(^{11}\text{Li}\) in comparison to \(^{8}\text{He}\) would produce a shift from \( \sim 2 \text{ MeV} \) to \( \sim 1 \text{ MeV} \) in the energy of \(^{10}\text{He}\) [12]. However, the same discrepancy with the data for the \(^{8}\text{He}\) beam exists for the results of experiments on the \(^{13}\text{C}\) [3] and \(^{14}\text{Be}\) beams [10, 11]. These results cast some doubt on the assumption made in work [12].

| \(E_r, \text{ MeV}\) | \(J^\pi\) | Reaction | Work |
|---|---|---|---|
| 1.2(3) | \(\leq1.2\) | \(^{12}\text{Li}, \text{nnHe})X\) | [1, 2] |
| 1.07(7) | 0.3(2) | \(^{10}\text{Be}(^{12}\text{C}, ^{14}\text{O})^{10}\text{He}\) | [3] |
| 4.31(20) | 1.0(3) | \(^{10}\text{Be}(^{12}\text{C}, ^{14}\text{O})^{10}\text{He}\) | [3] |
| 7.87(6) | 0.6(3) | \(^{10}\text{Be}(^{12}\text{C}, ^{14}\text{O})^{10}\text{He}\) | [3] |
| 1.7(3)(3) | 1.91(41) | \(^{10}\text{Be}(^{12}\text{C}, ^{14}\text{O})^{10}\text{He}\) | [3] |
| 3.99(26) | 1.64(89) | \(^{10}\text{Be}(^{12}\text{C}, ^{14}\text{O})^{10}\text{He}\) | [3] |
| \(\leq3\) | \(\geq6\) | \(^{12}\text{C} (\pi^-, \text{p}^{3}\text{He})X\) | this work |

Experimental information about excited states of \(^{8}\text{He}\) is even more limited and contradictory (see table 1). In ref. [9], estimates of the excitation energies were obtained from the analysis of angular distributions of the \(^{8}\text{He}\) from \(^{10}\text{He}\rightarrow n^+n^{+}\text{He}\) decay. However, due to poor statistics, the authors provided only the lower limits of resonance energies. Two regions of resonant energies can be distinguished, in which the excited states of \(^{10}\text{He}\) lie: \(4 \div 5 \text{ MeV} \) and \(6 \div 8 \text{ MeV} \). In most papers, the spin-parity of the ground state and the two excited states was defined as: \(0^+, 2^+\) and \(3^-\). Only in ref. [9] other values \(J^\pi\) are proposed: \(0^+, 1^-\) and \(2^-\). It should be noted that due to insufficient statistics, it is impossible to exclude the possibility that the peaks observed in experiments are a superposition of two or three resonance states [13].

Theoretical results for \(^{10}\text{He}\) are also sparse. Using the method of analytic continuation in the coupling constant with the \(^{8}\text{He}+n+n\) model, the ground state of \(^{10}\text{He}\) was investigated in ref. [14]. The calculations have shown that the ground state \((J^\pi = 0^-)\) is at the threshold \(E_r = 0.05 \text{ MeV} \) and \(\Gamma = 0.21 \text{ MeV}\), and the first excited state has spin-value \(0^+\) and has resonant parameters \(E_r = 1.68 \text{ MeV} \) and \(\Gamma = 1.12 \text{ MeV}\). The following values parameters of the \(^{10}\text{He}\) ground state were obtained within the continuum shell model: \(E_r = 1.649 \text{ MeV}\) and \(\Gamma \leq 0.746 \text{ MeV}\) [15]. The Faddeev-type calculation which includes \(^{8}\text{He}\) core excitations [16] provides an agreement with experimental data for \(^{10}\text{He}\) ground state \((J^\pi = 0^-)\): \(E_r = 0.803 \text{ MeV}\), \(\Gamma = 0.665 \text{ MeV}\) and excited state \((J^\pi = 2^-)\): \(E_r = 3.97 \text{ MeV}\), \(\Gamma = 4.71 \text{ MeV}\). These calculations also predict the existence of a state \((J^\pi = 1^-)\) between these two levels with \(E_r = 1.25 \text{ MeV}\), \(\Gamma = 0.21 \text{ MeV}\).
By this means that there are still noticeable differences in the position of the ground and excited levels determined in various experiments and theoretical calculations. In such a situation it is important to use a new reaction for the formation of $^{10}$He. Reaction of stopped pion absorption by light nuclei was successful in the study of the level structures of heavy helium isotopes $^{6,7,8}$He [17-20]. In present work this method has been used for $^{10}$He in the measurement of the reaction $^{14}$C($\pi^-$, $p^{10}$He)X.

2. Experiment

Measurements were carried out in the low energy pion channel of LANL using the two-arm multilayer semiconductor spectrometer [21]. A beam of 30 MeV negatively charged pions was slowed down by the beryllium moderator and was then stopped in a thin target ($\approx 24$ mg-cm$^{-2}$). The pion stop rate in the target was about 6·10$^4$ s$^{-1}$. In one experimental run the measurements were carried out on the isotope-pure $^{12}$C target and $^{14}$C “radioactive” target (76% is $^{14}$C, 23% is $^{12}$C). The contribution of uncontrollable impurities in both targets was $\leq 1\%$. Measurements on $^{12}$C target make it possible to accurately estimate the background from $^{12}$C in measurements on the “radioactive” target.

Charged particles, including the hydrogen isotopes $p$, $d$, and $t$ and the helium isotopes $^{3-4}$He, emitted after pion absorption in the targets were detected by two semiconductor telescopes arranged at an angle of 180° with respect to each other. The total sensitive thickness of each telescope was $\sim 43$ mm.

The energy resolution (FWHM) was better than 0.5 MeV for single charged particles ($p$, $d$, $t$) and 2 MeV for double charged particles ($^{3-4}$He) [22]. A search for the $^{10}$He excited states was carried out on the peaks in the missing mass spectrum (MM) measured in the $^{14}$C($\pi^-$, $p^{10}$He)X reaction. In these measurements the MM resolution was $\approx 3$ MeV. The error of the MM absolute calibration ($\delta$MM) did not exceed 100 keV [22].

The spectrometer and experimental techniques are described more detail in [21, 22].

3. Results and discussion

The MM spectrum obtained in the correlation measurements of $p^{10}$He pairs on the “radioactive” target $^{14}$C is shown in figure 1. The mass of $^{10}$He ground state [23] is taken as a reference point. Note that the MM value and the resonance energy $E_r$ are related by the ratio $E_r = E_r - E_{rh}$ where $E_{rh} = 1.07$ MeV – resonant energy of ground state [23]. The contribution of the $^{12}$C impurity is clearly seen from events in the non-physical region of $MM < 0$ MeV. In order to subtract this background, the MM spectrum measured $^9$He in the $^{12}$C($\pi^-$, $p^{10}$He)X reaction was used. This spectrum is shown in figure 2. The mass of the ground state is taken as the reference point. To subtract the contribution of these events from the spectrum in figure 1, the events measured on the $^{12}$C target were calculated based on the kinematics of absorption on the $^{14}$C isotope and were normalized by the percentage contribution of the $^{12}$C impurity (23%) to the "radioactive" target. The subtracted contribution is shown by shaded histogram.

The spectrum after impurity subtraction is shown in figure 3. Unfortunately, the statistics of events is poor and is comparable in size to the data of other authors.

In the spectrum in figure 3, a peak is observed in the region $MM \sim 6$ MeV ($E_r \sim 7$ MeV). In order to highlight this structure we have included the phase-space distributions in the description of the spectrum. Only one the final many-particle state ($p^2$He$^2$He3n) contributes to the spectrum. An important result of the description is the absence of final states with the formation of ground states of $^8$He and $^9$He ($p^2$He$^8$Hen, $p^2$He$^9$He$^8$n and $p^2$He$^9$He$^2$2n).

The MM spectrum after subtraction the contribution from the phase-space distribution is shown in figure 4. In the region $MM \sim 6$ MeV ($E_r \sim 7$ MeV) a peak is clear seen. This value of the resonant energy is close to the results obtained in [3, 7, 9] (see table 1). In the measured spectrum the contribution of the final states with the formation of $^8$He and $^9$He is absent suggesting that the observed state has the structure $^8$He +4n or $^8$He +3n.

Our data do not point to the formation of low-lying $^8$He states, which is probably related to the structure of the $^{14}$C nucleus. In stopped pion absorption, the main contribution to the formation of
weakly bound states is made by quasi-free processes in which the nucleons of the residual nucleus do not directly participate [22].

**Figure 1.** The MM spectrum obtained in the correlation measurements of $p^3$He pairs on the "radioactive" target $^{14}$C. Points with error bars denote the experimental data. The shaded histogram – contribution from $^{12}$C impurity.

**Figure 2.** MM spectrum for the reaction $^{12}$C($\pi^-$, $p^3$He)X. Points with error bars denote the experimental data. Curve 1 – summary phase-space distribution; peaks are the Breit-Wigner distributions for the ground and excited states.

**Figure 3.** MM spectrum for the reaction $^{12}$C($\pi^-$, $p^3$He)X. Points with error bars denote the experimental data. Solid line – distributions over phase volumes $\pi^-$ + $^{14}$C $\rightarrow$ $p$ + $^{3}$He + $^{7}$He + 3n.

**Figure 4.** MM spectrum after subtraction the contribution from the phase-space distribution. Points with error bars denote the experimental data.

The Feynman diagram describing such a process for the $^{14}$C($\pi^-$, $p^3$He)$^{10}$He reaction is shown in figure 5. Thus, we can conclude that the $^4p + ^{10}$He configuration in $^{14}$C is unlikely. It is interesting to note that as follows from figure 2 configuration $^4p + ^{8}$He can exist, which leads to the population of low-lying states in the $^{12}$C($\pi^-$, $p^3$He)$^{8}$He reaction.
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