FIELDS, PARTICLES, AND NUCLEI

Formation of ^8He in the $^9\text{Be}(\pi^-, p)X$ and $^{10}\text{B}(\pi^-, pp)X$ Stopped Pion Absorption Reactions

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The structure of levels of the ^8He heavy helium isotope has been studied in the $^9\text{Be}(\pi^-, p)X$ and $^{10}\text{B}(\pi^-, pp)X$ stopped pion absorption reactions. Measurements have been performed with a two-arm multilayer semiconductor spectrometer at the LANL. Indications to the existence of a soft dipole mode at the excitation energy $E_x \approx 3$ MeV have been obtained. A state with a high excitation energy of 12.2(5) MeV has been observed for the first time.

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1. INTRODUCTION

Among nucleon-stable nuclei, the ^8He heavy helium isotope has the record neutron-to-proton number ratio $N/Z = 3$. The separation energy of two neutrons is $S_{2n}(^8\text{He}) = 2.14$ MeV, which exceeds a corresponding value of 0.973 MeV for ^6He [1]. Consequently, it can be assumed that the ground state of ^8He is an α particle core surrounded by four valence neutrons rather than the three-particle system $^6\text{He} + n + n$. As shown experimentally [2, 3] and theoretically [4, 5], the wavefunction includes not only the $(p_{3/2})^4$ component but also a noticeable impurity of the $(p_{3/2})^2(s_{1/2})^2$, $(p_{3/2})^2(d_{5/2})^2$, and $(p_{3/2})^2(p_{1/2})^2$ components.

Excited levels of ^8He were observed in a limited number of experimental works (see the compilation of worldwide data [1] and reviews [6–8]), where the statistical significance of the results is low. This is apparently one of the reasons for the uncertainty of the energy of the first excited state, which lies in the interval $E_{x1} = 2.7\text{--}3.6$ MeV [1]. Another explanation of such a spread can be based on the observation of the superposition of two states— 2^+ resonance and the soft dipole mode with $J^P = 1^-$ —in the experiments reported in [9]. Consequently, differences in results can be due to different populations of these states. The authors of [9] attributed the first excited state to the soft dipole mode at $E_x \approx 3$ MeV, and the second excited state $J^P = 2^+$ is in the excitation energy range

of 3.6–3.9 MeV. However, the authors of [1, 3, 10, 11] stated that the first excited state has the quantum numbers $J^P = 2^+$, whereas the spin and parity of the second excited state are unknown [11].

Higher excited states of ^8He were observed in [1, 5, 10, 11]. The parameters of these states are summarized in Table 1. We note that the observed excitation spectrum in reactions on ion beams is limited by the energy $E_x = 7.5$ MeV [9].

We previously studied the structure of the levels of ^8He in the $^{11}\text{B}(\pi^-, pd)X$ [12], $^{12}\text{C}(\pi^-, p^3\text{He})X$, $^{14}\text{C}(\pi^-, t^3\text{He})X$, and $^{14}\text{C}(\pi^-, d^4\text{He})X$ [13] stopped pion absorption reactions.

The results are summarized in Table 1. We note that highly excited states with $E_x = 9.3(4)$ and 12.2(3) MeV were observed for the first time in [12]. The state with $E_x \approx 6.4$ MeV and $\Gamma \sim 0.6$ MeV was also observed for the first time in three reactions [12, 13]. It is noteworthy that the level with the close energy $E_x \approx 6.03(10)$ MeV but with the noticeably smaller width $\Gamma = 0.15(15)$ MeV was observed in the $^{10}\text{Be}(^{12}\text{C}, ^{14}\text{O})^8\text{He}$ reaction of capture of two protons [14].

In this work, in order to obtain new information and to confirm the previously obtained results on the spectroscopy of ^8He , we study the $^9\text{Be}(\pi^-, p)X$ and $^{10}\text{B}(\pi^-, pp)X$ reactions. We reported preliminary

Table 1. Experimental results on excited levels of ^8He

E_x , MeV	Γ , MeV	J^P	Reaction, reference
2.6–3.6	~ 0.6	2^+	[1]
≈ 3		(1^-)	[9] $^{10}\text{B}(\pi^-, pp)^8\text{He}$
≈ 3	~ 0.6	$(1^-), 2^+$	[11]
3.6–3.9	≈ 0.5	2^+	[9, 27]
3.9 ± 0.2	≈ 0.5		$^9\text{Be}(\pi^-, p)^8\text{He}$, $^{11}\text{B}(\pi^-, pd)^8\text{He}$ [12], $^{12}\text{C}(\pi^-, p^3\text{He})^8\text{He}$, $^{14}\text{C}(\pi^-, t^3\text{He})^8\text{He}$, $^{14}\text{C}(\pi^-, d^4\text{He})^8\text{He}$ [13]
≈ 4.2	1.2	(1^-)	[1, 11]
4.6 ± 0.3	≈ 0.5		$^9\text{Be}(\pi^-, p)^8\text{He}$, $^{10}\text{B}(\pi^-, pp)^8\text{He}$, $^{11}\text{B}(\pi^-, pd)^8\text{He}$ [12]
5.4(5)	0.5(3)	1^+	[3, 9]
(6.03(10))	0.15(15)		[14]
≈ 6.4	~ 0.6		$^{10}\text{B}(\pi^-, pp)^8\text{He}$, $^{11}\text{B}(\pi^-, pd)^8\text{He}$ [12], $^{14}\text{C}(\pi^-, t^3\text{He})^8\text{He}$, $^{14}\text{C}(\pi^-, d^4\text{He})^8\text{He}$ [13]
7.16(4)	0.1(1)	(1^-)	[14]
9.3(4)	1.7(3)		$^{11}\text{B}(\pi^-, pd)^8\text{He}$ [12]
12.2(3)	0.8(3)		$^{10}\text{B}(\pi^-, pp)^8\text{He}$

information on the $^9\text{Be}(\pi^-, p)X$ reaction obtained on a limited statistical sample in [15].

It is noteworthy that we successfully used the stopped pion absorption reaction to study the structure of levels of other heavy helium isotopes ^6He [16, 17] and ^7He [18–20].

2. EXPERIMENT

The experiment was performed at the low-energy pion channel of the LANL using a two-arm multilayer semiconductor spectrometer [21, 22]. A 30-MeV negative pion beam passed through a beryllium moderator and was stopped in a thin target ($\sim 24 \text{ mg cm}^{-2}$). The pion stop rate in targets was about $6 \times 10^4 \text{ s}^{-1}$. The ^9Be target was isotopically pure, the ^{10}B target contained 15% ^{11}B impurity, and the contribution of uncontrolled impurities in both targets was $\leq 1\%$. The measurements on the ^9Be , ^{10}B , and ^{11}B targets were performed within a single experimental run, which allowed minimizing errors of subtraction of the contribution of the ^{11}B impurity from the measurements on the ^{10}B target.

Charged particles produced at the absorption of pions by nuclei of the target were detected by two multilayer semiconductor telescopes located at an angle of 180° with respect to each other. The energy resolution in the detection of protons was ΔE (FWHM) $\approx 0.45 \text{ MeV}$ [21]. The missing mass (MM) resolution at the detection of pp pairs was ΔMM (FWHM) $\approx 1 \text{ MeV}$

[22]. The accuracy of the absolute matching of the scale in inclusive and correlation measurements was better than 200 keV [22]. The spectrometer and experimental method were described in detail in [21, 22].

3. RESULTS AND DISCUSSION

States of ^8He were sought in peaks of the missing mass spectra measured in the $^9\text{Be}(\pi^-, p)X$ and $^{10}\text{B}(\pi^-, pp)X$ reactions.

The missing mass spectrum obtained in inclusive measurements of the $^9\text{Be}(\pi^-, p)X$ reaction is shown in Fig. 1. Masses were measured from the mass of the ground state of ^8He . The experimental spectrum was described by the sum of Breit–Wigner distributions and n -particle phase volume distributions ($n > 2$) taking into account the energy resolution of the setup. The description of the ground state is the instrumental line of the setup. The ground and two excited states of ^8He with the parameters (E_x, Γ) of (3.9(2) MeV, $\approx 0.5 \text{ MeV}$) and (4.6(3) MeV, $\approx 0.5 \text{ MeV}$) were reliably identified in the description of the spectrum. Comparison with our preliminary results ($E_x = 4.4(2) \text{ MeV}$) shows that peak observed in [15] is a superposition of two states, which could not be separated in view of a limited statistical significance.

The experimental spectrum also exceeds the description in three regions near the energies $E_x \approx 3$, 6.5, and 12 MeV, which indicates a possible existence

Fig. 1. (Color online) Missing mass (MM) spectrum for the ${}^9\text{Be}(\pi^-, p)X$ reaction. Points with error bars are experimental data. The solid lines are the descriptions of the ground and excited states: (1) complete description and phase volume distributions for the (2) $\pi^- + {}^9\text{Be} \rightarrow p + {}^6\text{He} + 2n$, (3) $\pi^- + {}^9\text{Be} \rightarrow p + {}^7\text{He} + n$, and (4) $\pi^- + {}^9\text{Be} \rightarrow p + {}^6\text{He}^*(1.797) + 2n$ reactions. Arrows mark the spectral regions where experimental data exceed the description.

of excited states in these regions. The separation energy of two neutrons is $S_{2n}({}^8\text{He}) = 2.14$ MeV; therefore, the excess of events near the threshold of the reaction can hardly be explained without the hypothesis of the existence of a low-lying state.

The missing mass spectrum obtained in correlation measurements of the ${}^{10}\text{B}(\pi^-, pp)X$ reaction after the subtraction of the contribution of the ${}^{11}\text{B}$ impurity is shown in Fig. 2. The mass is measured from the mass of the ground state of ${}^8\text{He}$. The experimental spectrum is described by the sum of Breit–Wigner distributions and n -particle phase volume distributions ($n > 3$) taking into account the energy resolution of the setup.

As seen in Fig. 2, the reaction of stopped pion absorption by light nuclei with the production of two fast protons ${}^{10}\text{B}(\pi^-, pp)X$ has a pronounced selectivity: the ground state of the residual nucleus is not observed in the final state. Similarly, the formation of the ground state of neutron-rich nuclei is suppressed in the ${}^9\text{Be}(\pi^-, pp){}^7\text{H}$ [23], ${}^{11}\text{B}(\pi^-, pp){}^9\text{He}$, ${}^{12}\text{C}(\pi^-, pp){}^{10}\text{Li}$ [24], and ${}^{14}\text{C}(\pi^-, pp){}^{12}\text{Li}$ [25] reactions.

The main mechanism of production of two protons is apparently the absorption of a pion on a pp pair with

Fig. 2. (Color online) Missing mass (MM) spectrum for the ${}^{10}\text{B}(\pi^-, pp)X$ reaction. Points with error bars are experimental data. The solid lines are the descriptions of the excited states: (1) complete description and (2) phase volume distributions for the $\pi^- + {}^{10}\text{B} \rightarrow p + p + {}^6\text{He}^*(1.8) + 2n$ reaction. The inset shows the difference between the experimental spectrum and its description in the range $0 < MM < 16$ MeV. Arrows mark the average values of the difference.

the subsequent charge exchange reaction of a neutron on the residual nucleus ${}^8\text{Li}(n, p){}^8\text{He}$. Unfortunately, we did not find experimental information on this reaction. The ${}^8\text{He}(p, n){}^8\text{Li}$ reaction was measured at the RIKEN with a 190-MeV ${}^8\text{He}$ beam in the inverse kinematics [26]. Although a sufficiently large number of events were collected, the authors identified transitions only to two excited states of ${}^8\text{Li}$ with $E_x = 0.98$ and ≈ 8 MeV; the latter state was observed for the first time. As in our measurements, the ${}^8\text{Li}_{\text{g.s.}} \leftrightarrow {}^8\text{He}_{\text{g.s.}}$ transition is absent. This absence is possibly due to the exclusion of the Gamow–Teller transition between these states having the spins and parities of $2^+({}^8\text{Li}_{\text{g.s.}})$ and $0^+({}^8\text{He}_{\text{g.s.}})$. We also do not know the calculation of spectroscopic factor for the separation of two protons in ${}^8\text{Li}$. For this reason, exact calculations describing this mechanism are hardly possible. We note that the corresponding spins in all other (π^-, pp) reactions differ by unity and have opposite parities: $(1/2^+)$ (${}^7\text{H}_{\text{g.s.}}$) and $3/2^-$ (${}^7\text{He}_{\text{g.s.}}$), $1/2^+$ (${}^9\text{He}_{\text{g.s.}}$) and $3/2^-$ (${}^9\text{Li}_{\text{g.s.}}$), 1^- (${}^{10}\text{Li}_{\text{g.s.}}$) and 0^+ (${}^{10}\text{Be}_{\text{g.s.}}$), and $(1^-, 2^-)$ (${}^{12}\text{Li}_{\text{g.s.}}$) and 0^+ (${}^{12}\text{Be}_{\text{g.s.}}$).

Thus, events observed near the threshold in Fig. 2 are apparently due to the first excited state of ^8He . This assumption is confirmed by some excess of the experimental spectra of the $^9\text{Be}(\pi^-, p)X$ (Fig. 1) and $^{11}\text{B}(\pi^-, pd)X$ [12] reactions over the description in this energy range. This excess cannot be described by the threshold Breit–Wigner distribution. This is in agreement with the assumption that the soft dipole mode whose shape is not described by the Breit–Wigner distribution is observed in this reaction [9]. We also note that the continuous spectrum is described by a single phase volume distribution involving the $^6\text{He}^*(1.8)$ excited state without channels with the ground state of ^6He .

Three excited states of ^8He with the parameters (E_x, Γ) of (4.6(3) MeV, ≈ 0.5 MeV), (≈ 6.4 MeV, ≈ 0.5 MeV), and (12.2(5) MeV, 0.8(3) MeV) are separated in the missing mass spectrum of the $^{10}\text{B}(\pi^-, pp)X$ reaction. We also observe the excess of the experimental data over the description in the region near 9.5 MeV.

The level with $E_x \approx 4.6$ MeV detected in the $^{10}\text{B}(\pi^-, pp)X$ reaction was also observed in the $^9\text{Be}(\pi^-, p)X$ and $^{11}\text{B}(\pi^-, pd)X$ reactions at low excitation energies. At the same time, we did not obtain indications of the level with $E_x \approx 3.6$ MeV, which was observed in numerous experiments, in particular, in reactions with stopped pions (see Table 1); this additionally shows the selectivity of the reaction. The observation of these two states in the $^9\text{Be}(\pi^-, p)X$ and $^{11}\text{B}(\pi^-, pd)X$ reactions simultaneously implies the existence of excitation of three low-energy levels: the soft dipole mode at the excitation energy $E_x \approx 3$ MeV and two resonance states. We note that the resonance states are located near the thresholds of the decay of ^8He into $^4\text{He} + 4n$ (3.11 MeV) and $^5\text{He} + 3n$ (4.0 MeV). The number of levels observed in this region in ion experiments is smaller apparently because the number of collected events is insufficient.

The observation of the state with $E_x \approx 6.4$ MeV in the $^{10}\text{B}(\pi^-, pp)X$ reaction confirms the results obtained in the $^{11}\text{B}(\pi^-, pd)X$ [12], $^{14}\text{C}(\pi^-, t^3\text{He})X$, and $^{14}\text{C}(\pi^-, d^4\text{He})X$ [13] reactions. In all these cases, the width of the level (~ 0.6 MeV) is significantly larger than the width $\Gamma = 0.15(15)$ MeV of the level with $E_x \approx 6.03(10)$ MeV [14], which indicates that these states have different natures. The analysis carried out in [13] justified the assumption that the structure of the valence shell of the state (6.4 MeV) has the form $(p_{3/2})^2(p_{1/2})^2$. The comparison of the widths indicates that the spin of the state with $E_x \approx 6.4$ MeV is smaller

than the spin of the state with $E_x \approx 6.03$ MeV, which is assigned the spin and parity $J^P = 2^-$ [14].

The existence of a level near 9.5 MeV is confirmed by the observation of the state with $E_x = 9.3(4)$ MeV and $\Gamma = 1.7(3)$ MeV detected in the $^{11}\text{B}(\pi^-, pd)X$ reaction [12].

The state with a high excitation energy of 12.2(5) MeV was observed for the first time. This state lies below the threshold 14.445 MeV of the $^8\text{He} \rightarrow ^3\text{H} + ^3\text{H} + 2n$ decay; consequently, this state cannot be due to the excitation of the α -particle core. A state with a close excitation energy $E_x = 11.5(3)$ MeV, but with a noticeably lower statistical significance, was observed in the $^{11}\text{B}(\pi^-, pd)X$ reaction [24]. Since the measurement errors overlap, the same state is possibly observed in these reactions. Some excess of the experimental data for the $^9\text{Be}(\pi^-, p)X$ reaction over the description is observed in this region (Fig. 1), but this excess is statistically insignificant because of a rapid increase in the continuous spectrum in inclusive measurements.

We note that the existence of two highly excited states above 9 MeV was predicted in a number of theoretical work (see review [7]).

4. CONCLUSIONS

Excited states of the ^8He heavy helium isotope have been sought in the missing mass spectra obtained in the measurements of the $^9\text{Be}(\pi^-, p)X$ and $^{10}\text{B}(\pi^-, pp)X$ reactions. Three states have been detected in the low excitation energy range. The first excited state is likely a soft dipole mode at $E_x \approx 3$ MeV. The existence of the levels at $E_x \approx 6.4$ and 9.3 MeV, which we previously observed in other stopped pion absorption reactions on light nuclei, has been confirmed. A state with a high excitation energy of 12.2(5) MeV has been detected for the first time.

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