Search for heavy lithium isotopes $^{10-12}$Li in stopped pion absorption reactions

B.A. Chernyshev, Yu. B. Gurov, L.Yu. Korotkova, S.V. Lapushkin, R.V. Pritula, V.G. Sandukovskiy
korotkovalara@gmail.com
National Research Nuclear University “MEPhI”, 115409 Moscow, Russia

The experimental search for the production of heavy lithium isotopes $^{10-12}$Li was carried out in the stopped $\pi$-mesons absorption reactions on the targets $^{11}$B, $^{12,14}$C. Study of $^{10}$Li was performed in the correlation and inclusive measurements of reactions $^{12}$C($\pi^-$,pp)$X$, $^{14}$C($\pi^-$,pt)$X$, $^{14}$C($\pi^-$,dd)$X$ and $^{11}$B($\pi^-$,p)$X$. Three highly excited states of $^{10}$Li with the resonance energies $E_r = 6.1 \pm 0.1$ MeV, $7.8 \pm 0.1$ MeV and $10.1 \pm 0.1$ MeV were identified together with the well-known levels. The resonance parameters of three low-lying excited states of $^{11}$Li were determined in the $^{14}$C($\pi^-$,pd)$X$ reaction. In the $^{14}$C($\pi^-$,pp)$X$ reaction $^{12}$Li excited state with $E_r = 4.0 \pm 0.2$ MeV and an indication on a level with $E_r \approx 7$ MeV were found.

1. Introduction

Interest in the study of the heavy lithium isotopes is due to extreme properties of these nuclei. Branch of the nuclear physics related to the research of exotic nuclear systems close to the drip line began to develop after the discovery of abnormally large radius of the nucleus $^{11}$Li in the radioactive ion beams experiments [1, 2]. To explain this phenomenon a model based on the hypothesis of a neutron halo of $^{11}$Li was introduced. In this model $^{11}$Li is described as $^6$Li core surrounded by two neutrons. A treatment of $^{11}$Li as a three-body system requires the information on the parameters of the two-body subsystems: n + n and n + $^9$Li. The properties of latter subsystem are directly related to the parameters of $^{10}$Li low-lying states, whose states are nucleon-unstable ones [3]. Besides, the importance of this information for understanding the structure of $^{11}$Li, the interest is due to the fact that $^{10}$Li ground state has an abnormal parity, which is the direct evidence of the appearance of new nucleon magic numbers, instead of traditional [4]. Note that $^{11}$Li is the so-called Borromean nucleus, which means that it is a coupled system, consisting of three items, where each pair is unbound.

$^{11}$Li is the heaviest nucleon-stable isotope with $Z = 3$, but the properties of the heavier isotopes of lithium are also important in terms of studying the drip line boundary area for light nuclei and for the development of theoretical models to describe these systems. $^{12}$Li isotope which is virtual state in the system $^{11}$Li + n was recently discovered [5-7] and the question of its structure is still open.

Experimental studies of the level structure of heavy lithium isotopes $^{10,11}$Li are in progress for a quite long time, but still there are many open questions. The $^{10}$Li ground state is a virtual s-wave state with the scattering length $a \sim -25$ fm [5, 8-9] (refs. to earlier works are presented in [10]). In the effective mass spectrum this state appears as a peak near the $E_r = 0$ MeV ($E_r$ - energy relative to the $^9$Li + n threshold). Information on the first excited state which is p-wave resonance is more uncertain: $E_r$ is in the range $0.3 \leq E_r \leq 0.7$ MeV [5, 8-10]. Data on highly excited states are very limited [10-12].

Experimental studies of the $^{11}$Li excitation spectrum were carried out in a large number of works [6, 9, 14-22]. In all the papers except [16] the $^{11}$Li level was observed at the excited energy $0.6$ MeV $< E_r < 1.3$ MeV with different widths $0.26$ MeV $< \Gamma < 0.75$ MeV [19, 22]. High-energy excited levels...
were observed only in [9, 16, 18], several excited states with the energies 2.5 MeV < \( E_x < 11.3 \) MeV were found. Thus the problem of the precise measurements of \(^{11}\)Li excited levels and their widths remains unsolved.

The first experimental evidence of the possible existence of the resonant state of \(^{12}\)Li was presented in the work [23]. Preliminary data obtained in stopped pion absorption \(^{14}\)C(\(\pi^-\),pp)X indicated on the existence of the level of \(^{12}\)Li with \( E_r = 4.9 \pm 1.5 \) MeV (\( E_r \) – energy relative to the \(^{11}\)Li + n threshold). New evidences on the \(^{12}\)Li production have been appeared recently [5 - 7]. Authors observed the virtual s-wave state with a scattering length \( a \approx -13.7 \pm 1.6 \) fm [5, 7]. Two excited levels with the resonance energies \( E_{r1} = 250 \pm 20 \) keV and \( E_{r2} = 555 \pm 20 \) keV were also found in [7].

Thus, the experimental information on the level structure of heavy lithium isotopes is quite limited and inconsistent especially for \(^{12}\)Li. In this case new data are needed, it is also very important for the development of theoretical models. Our measurements were carried out at low energy pion channel of the Los Alamos Meson Physics Facility (LAMPF) with a two-arm multilayer semiconductor spectrometer [26]. The spectrometer and experimental technique are described more detail in [25, 26].

2. Results
2.1. Spectroscopy of \(^{10}\)Li isotope
2.1.1. Inclusive measurements on \(^{11}\)B target

The missing mass spectra for \(^{11}\)B(\(\pi^-\),p)X and \(^{12}\)C(\(\pi^-\),pp)X reactions are shown on Fig. 1. The sum of neutron and \(^{9}\)Li masses is taken as a reference point.

![Fig. 1. The \( MM \) spectra for \(^{11}\)B(\(\pi^-\),p)X (a) and \(^{12}\)C(\(\pi^-\),pp)X (b) reactions. Dots with error bars are the experimental data. Curves: 1 is the total fit. (a): 2 and 3 are the phase-space distributions for \(^{9}\)Lipn and \(^{7}\)Hept respectively, 4 is the background coincidences. Shaded areas are the Breit–Wigner distributions for the two-particle channels with the formation of the \(^{10}\)Li. (b): 2 is the sum of the phase-space distributions for many-body channels, 3 is the background coincidences.](image-url)

In order to identify the states of \(^{10}\)Li and determine their parameters, we used the least square method in the fitting of the experimental spectrum by the sum of Breit–Wigner shaped resonances, \( n \)-particle phase-space distributions (\( n \geq 3 \)) and the background coincidences. The ground state and the
first excited state were described with the Breit-Wigner threshold functions for s-wave and p-wave states respectively.

The best description of the peak close to zero in the MM spectrum on Fig. 1a can be achieved by introducing the ground state and the first excited state with the resonance energy \( E_r = 0.6 \pm 0.1 \) MeV with \( \Gamma \approx 1 \) MeV. Also in the experimental spectrum we can see the level with \( E_r = 4.8 \pm 0.1 \) MeV and \( \Gamma \approx 2 \) MeV. Highly excited states of the \(^{10}\)Li with \( E_r = 7.7 \pm 0.1 \) MeV with \( \Gamma \approx 2 \) MeV and \( 10.1 \pm 0.1 \) MeV with \( \Gamma \approx 0.5 \) MeV were observed for the first time.

3.1.2. Correlation measurements on \(^{12}\)C target

Three-body reaction channel with the formation of \(^{10}\)Li was also studied in the correlation measurements. The search for the production of the \(^{10}\)Li isotope was performed in the \(^{12}\)C(\(\pi\),pp)X reaction. Measured MM spectrum is shown on Fig. 1b. Here we consider the phase-space distribution with the number of particles in the final state not less than four.

A statistically accurate description of the experimental spectrum can be achieved without taking into account the \(^{10}\)Li ground state. One of the possible explanations of this fact is the mechanism of the \(\pi\)-meson absorption reaction with the formation of two fast protons [11].

The peaks due to the two highly excited states of \(^{10}\)Li are clearly seen. The resonance energy of the first of these states \( E_r = 4.7 \pm 0.1 \) MeV is close to \( E_r = 4.64 \pm 0.10 \) MeV obtained in [7], however, in our measurements the level is more than 3 times wider. The broad state with \( E_r = 7.9 \pm 0.2 \) MeV and \( \Gamma \approx 2 \) MeV was observed for the first time.

3.1.3. Correlation measurements on \(^{14}\)C target

The MM spectra obtained in the correlation measurements of dd- and pt-pairs on the radioactive target \(^{14}\)C are shown on Fig. 2. The contribution of the impurity of \(^{12}\)C is already subtracted. The \(^{12}\)C impurity background was determined using the results from the correlation measurements of dd- and pt-pairs on the \(^{12}\)C target. The MM spectra for the reactions \(^{12}\)C(\(\pi\),dd)X and \(^{12}\)C(\(\pi\),pt)X were normalized to the relative impurity contribution (23%) and was subtracted from the experimental spectra. The small background in the region of negative MM is due to several causes: the statistical errors of the subtraction procedure, background coincidences and the contribution of uncontrolled impurities.

A statistically satisfactory description of the experimental dd-spectrum (Fig. 2a) can be achieved by introducing two excited states of \(^{10}\)Li with the following resonance parameters \( (E_r, \Gamma) \): \( (0.8 \pm 0.1 \) MeV, \( \approx 0.5 \) MeV) and \( (6.1 \pm 0.1 \) MeV, \( \approx 1 \) MeV). It is seen that near \( MM = 0 \) MeV there are some events which may be associated with the formation of a virtual s-wave ground state of \(^{10}\)Li. However the relatively low statistics is not sufficient to allow strict conclusions about its parameters.

The spectrum MM obtained in the correlation measurements pt-pairs on radioactive target \(^{14}\)C was considered in a manner similar to the case of dd-pairs. The spectrum obtained after the subtraction the contribution of the impurity for the reaction \(^{14}\)C(\(\pi\),pt)X is shown on Fig. 2b. A statistically satisfactory description of the experimental spectrum can be achieved by introducing three excited states of \(^{10}\)Li with the following resonance parameters \( (E_r, \Gamma) \): \( (0.7 \pm 0.1 \) MeV, \( \approx 0.2 \) MeV), \( (2.2 \pm 0.1 \) MeV, \( \approx 2 \) MeV). As for \(^{12}\)C(\(\pi\),dd)X reaction, an evidence for the \(^{10}\)Li ground state is absent.

The results for the \(^{10}\)Li level structure obtained in all reaction channels are not in the contradiction. The lack of the level with \( E_r = 2.2 \) MeV in the measurements of \(^{14}\)C(\(\pi\), dd)X is apparently due to the differences in the mechanisms of the (\(\pi\), dd) and (\(\pi\), pt) reactions. Absorption of \(\pi\) on \(^3\)He and \(^4\)He clusters plays an important role in light nuclei [11]. Therefore the (\(\pi\), pt) reaction can occur by the charge exchange (n, p) after the absorption \(\pi^- + \(^4\)He \rightarrow n + t\). In turn the (\(\pi\), dd) reaction can occur by pick-up (n, d) after the absorption \(\pi^- + \(^3\)He \rightarrow n + d\).
Fig. 2. The \( M\bar{M} \) spectra for the \(^{14}\text{C}(\pi^{-}\text{dd})\text{X}\) (a) and \(^{14}\text{C}(\pi^{-}\text{pt})\text{X}\) (b) reactions. Dots with error bars are the experimental data obtained after subtracting \(^{12}\text{C}\) background. Curves: 1 is the total fit, 2 is the sum of the phase-space distributions for many-body channels.

In our measurements the resonance energy of the \(^{10}\text{Li}\) first excited state (average weighted value is \(0.7 \pm 0.1\) MeV) exceeds the value observed in recent studies: \(\approx 0.4\) MeV [6], \(0.510 \pm 0.044\) MeV [4] and \(0.566 \pm 0.014\) MeV [5]. The reason for this discrepancy is unclear. However, the parameters of the first excited state, obtained in inclusive measurements on the target \(^{11}\text{B}\), are in good agreement with [3].

We do not observe a large number of narrow levels with \(E_r > 1\) MeV as in [7]. Also, these states are not observed in [4] and [5], where the energy spectrum of the \(^{10}\text{Li}\) was measured up to 3 MeV and 4 MeV respectively. However, we should like to point out an agreement between the resonance parameters \((E_r = 2.35 \pm 0.10\) MeV, \(\Gamma = 1.2 \pm 0.4\) MeV) obtained in [7] and our results for the second level observed in the \(^{14}\text{C}(\pi^{-}, \text{pt})^{10}\text{Li}\) reaction. So the experimental situation with the level structure of \(^{10}\text{Li}\) is quite ambiguous, which requires new experimental information.

### 3.2. Spectroscopy of \(^{11}\text{Li}\) isotope

The spectrum of the \( M\bar{M} \) obtained in the correlation measurements of pd-pairs on the radioactive target \(^{14}\text{C}\) after impurity subtraction is shown on Fig. 3. The \(^{11}\text{Li}\) mass is taken as reference point. The contribution of the background caused by \(^{12}\text{C}\) impurity was determined using the results from correlation measurements dd-pairs on the \(^{12}\text{C}\) target [6].

A statistically satisfactory description of the experimental spectrum can be achieved by introducing three excited states of \(^{11}\text{Li}\) with the following resonance parameters \((E_r, \Gamma)\): \((0.9 \pm 0.1, \approx 0.3\) MeV), \((2.3 \pm 0.3, \approx 0.7\) MeV) and \((3.9 \pm 0.3, < 0.2\) MeV).

Our results for the energy and width of the first excited level are close to the data obtained for fragmentation reactions in [9, 15, 17-20, 22]. The \(E_r\) variation from 0.6 MeV to 1.3 MeV in these papers was probably caused by data analysis ambiguity. The width observed by us was in agreement with a result \(\Gamma = 0.26 \pm 0.24\) MeV that was recently obtained in [9]. These values are considerably smaller than the results of the microscopic model [28], in which it was predicted that the peak with \(\Gamma = 0.75 \pm 0.60\) MeV observed in [19] is the sum of two \(^{11}\text{Li}\) resonance states.
The energy $E_x = 2.3 \pm 0.3$ MeV of the second excited state coincides within the experimental error with results obtained in heavy ion reactions $E_x = 2.47 \pm 0.07$ MeV [16] and fragmentation reaction $E_x = 2.45 \pm 0.27$ MeV [9], however, the widths observed in these reactions are appreciably larger, i.e. $1.2 \pm 0.2$ MeV and $2.91 \pm 0.72$ MeV respectively. The narrow state with $E_x = 3.9 \pm 0.3$ MeV had not been observed in other works yet.

3.3. Spectroscopy of $^{12}$Li isotope

The spectrum of the $MM$ obtained in the correlation measurements of pp-pairs on the radioactive target $^{14}$C after the impurity subtraction is shown on Fig. 4. The sum of neutron and $^{11}$Li masses is taken as an initial point. The results of measurements for the reaction $^{12}$C($\pi$,pp)X were presented in [26].

The $MM$ spectrum shown on Fig. 4 contains the pronounced peak caused by the $^{12}$Li state with the resonance parameters $E_r = 4.0 \pm 0.2$ MeV and $\Gamma \approx 1$ MeV. Note that the subtraction of the $^{12}$C impurity results in a significant contribution to errors.

In our data near $MM \approx 0$ MeV there is no indication on the existence of the virtual s-wave state observed in [5, 7]. One cause of the suppression of this state might be the appreciable selectivity of the level populations in the A($\pi$,pp)X reaction [29]. Note that certain amplification is observed in the effective mass spectrum of the $^{11}$Li+n system, measured in [5] at $E_r > 3$ MeV. However, the presented data are restricted to the value $E_r = 4$ MeV, which does not allow us to attribute this amplification to the $^{12}$Li state we observed. Even smaller range of the $E_r (< 2$ MeV) was investigated in [7]. The problem of the $^{12}$Li level structure thus remains open.
Fig. 4. The $MM$ spectrum for the reaction $^{14}\text{C}(\pi,\text{pp})X$. Dots with error bars were obtained after subtracting of $^{12}\text{C}$ background. The solid lines are the fit and the sum of phase-space distributions.

4. Conclusion

The production of $^{10-12}\text{Li}$ heavy lithium isotopes was studied in the reactions of stopped pion absorption on $^{11}\text{B}$ and $^{12,14}\text{C}$ nuclei. The results of our measurements are in reasonable agreement with the results of other studies for the reliably defined states of $^{10,11}\text{Li}$. The exception is the $^{10}\text{Li}$ ground state. It is similarly in the missing mass spectrum of the reaction $^{14}\text{C}(\pi,\text{pp})X$: we do not obtained statistically significant indications on $^{12}\text{Li}$ state at $E_r \approx 0$ MeV, which was observed in the fragmentation reactions of radioactive beams in [5, 7]. At the same time in our measurements $^{10}\text{Li}$ states with $E_r = 6.1$ MeV, 7.8 MeV and 10.1 MeV, $^{11}\text{Li}$ state with $E_x = 3.9$ MeV and $^{12}\text{Li}$ state with $E_r = 4.0 \pm 0.2$ MeV were first identified.

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References

1. Tanihata I. et al. 1985 Phys. Rev. Lett. 55 2676.
2. Tanihata I. et al. 1988 Phys. Lett. B 206 592.
3. Audi G. et al. 2003 Nucl. Phys. A 729 3.
4. Jonson B. 2004 Phys. Rep 389 1.
5. Aksyutina Yu. et al. 2008 Phys. Lett. B 666 430.
6. Gurov Yu.B. et al. 2010 Bull. of RAS.: Phys 74 469.
7. Hall C.C. et al. 2010 Phys. Rev. C 81 021302(R).
8. Jeppesen H.B. et al. 2006 Phys. Lett. B. 642 449.
9. Simon H. et al. 2007 Nucl. Phys. A 791 267.
10. Tilley D.R. et al. 2004 Nucl. Phys. A 745 155.
11. Bohlen H.G. al. 1999 Prog. Part. Nucl. Phys 42 17.
12. Kobayashi T. et al. 1997 Nucl. Phys. A 616 223c.
13. Roger T. et al. 2009 Phys. Rev. C 79 031603(R).
14. Kobayashi T. 1992 Nucl. Phys. A 538 343c.
15. Sackett D. et al. 1993 Phys. Rev. C 48 118.
16. Bohlen H.G. et al. 1995 Z. Phys 351 7.
17. Shimoura S. et al. 1995 Phys. Lett. B 348 29.
18. Korsheninnikov A.A. et al. 1996 Phys. Rev. C 53 537(R).
19. Korsheninnikov A.A. et al. 1997 Phys. Rev. Lett. 78 2317.
20. Zinser M. et al. 1997 Nucl. Phys. A 619 151.
21. Gurov Yu.B. et al. 1998 Phys. Rev. Lett. 81 4325.
22. Nakamura T. et al. 2006 Phys. Rev. Lett. 96 252502.
23. Gornov M.G. 1996 PANIC - 1996 Abstracts, Sweden. Uppsala: Un. Press 216.
24. Backenstoss G. 1970 Ann. Rev. Nucl. Sci. 20 467.
25. Gurov Yu.B. et al. 2009 Phys. of Part. and Nucl. 40 1063.
26. Gornov M.G. et al. 2000 NIM in Phys. Res. A 446 461.
27. Gurov Yu.B. et al. 2010 Bull. of RAS.: Phys. 75 491.
28. Ershov S.N. et al. 2004 Phys. Rev. C 70 054608.
29. Gurov Yu.B. et al. 2006 Phys. of Atom. Nucl. 69 1448.