Evidence for a New Low-Lying Resonance State in ${}^7\text{He}$

M. Meister,^{1,2} K. Markenroth,¹ D. Aleksandrov,³ T. Aumann,⁴ L. Axelsson,¹ T. Baumann,^{4,*} M. J. G. Borge,⁵ L. V. Chulkov,³ W. Dostal,⁶ B. Eberlein,⁶ Th. W. Elze,⁷ H. Emling,⁴ C. Forssén,¹ H. Geissel,⁴ M. Hellström,⁴ R. Holzmann,⁴ B. Jonson,¹ J. V. Kratz,⁶ R. Kulesa,⁸ Y. Leifels,⁴ A. Leistenschneider,⁷ I. Mukha,^{2,3} G. Münzenberg,⁴ F. Nickel,⁴ T. Nilsson,¹ G. Nyman,¹ A. Richter,² K. Riisager,⁹ C. Scheidenberger,⁴ G. Schrieder,² H. Simon,² O. Tengblad,⁵ and M. V. Zhukov

¹Experimentell Fysik, Chalmers Tekniska Högskola och Göteborgs Universitet, S-412 96 Göteborg, Sweden

²Institut für Kernphysik, Technische Universität, D-64289 Darmstadt, Germany

³Kurchatov Institute, R-123182 Moscow, Russia

⁴Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany

⁵Instituto Estructura de la Materia, CSIC, E-28006 Madrid, Spain

⁶Institut für Kernchemie, Johannes Gutenberg-Universität, D-55099 Mainz, Germany

⁷Institut für Kernphysik, Johann-Wolfgang-Goethe-Universität, D-60486 Frankfurt, Germany

⁸Instytut Fizyki, Uniwersytet Jagelloński, PL-30-059 Kraków, Poland

⁹Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C, Denmark

(Received 26 February 2001; revised manuscript received 26 December 2001; published 26 February 2002)

Low-lying resonance states in ${}^7\text{He}({}^6\text{He} + n)$, formed after fragmentation reactions of a 227 MeV/nucleon ${}^8\text{He}$ beam on a carbon target, have been studied. Coincidences between ${}^6\text{He}$ nuclei and neutrons, corresponding to the one-neutron knockout channel in ${}^8\text{He}$, were selected. The relative energy spectrum in the ${}^6\text{He} + n$ system shows a structure, which is interpreted as the ${}^7\text{He}$ ($I^\pi = 3/2^-$) ground state, unbound with 0.43(2) MeV relative to the ${}^6\text{He} + n$ system and a width of $\Gamma = 0.15(8)$ MeV overlapping with an excited ($I^\pi = 1/2^-$) state observed at 1.0(1) MeV with a width of $\Gamma = 0.75(8)$ MeV.

DOI: 10.1103/PhysRevLett.88.102501

PACS numbers: 24.30.Gd, 25.60.-t, 27.20.+n

The chain of neutron-rich He isotopes presently attracts much interest. This is mainly due to the fact that their structure may be described as a tightly bound α core surrounded by a number of neutrons. This “core + valence neutrons” structure is the basis of a model [1] introduced to explain the halo structure of ${}^6\text{He}$ [2,3] and the five-body cluster structure of ${}^8\text{He}$ [4–6]. Their subsystems ${}^5\text{He}$ and ${}^7\text{He}$ are unbound and have ground states of $I^\pi = 3/2^-$, corresponding to a neutron in a $p_{3/2}$ orbital according to the standard shell model [7].

Even if ${}^5\text{He}(\alpha + n)$ is assumed to be well understood, some ambiguities remain. The position of the excited $1/2^-$ state has generally been considered to lie approximately 4 MeV above the ground state [7], but several experiments rather indicate an excitation energy of 2.0 to 2.6 MeV [8,9]. Recent calculations [10,11] predict an energy difference of 1.2 to 1.4 MeV between the $p_{3/2}$ and $p_{1/2}$ states.

The ${}^7\text{He}$ ground state was observed for the first time by Stokes and Young [12] and found to be situated 440 keV above the ${}^6\text{He} + n$ threshold. In different experiments [13–15] an excited state at 3.3 MeV has been observed, which have been found to possess the exotic ${}^6\text{He}^* + n$ configuration and decays mainly to $\alpha + 3n$. In this Letter we present new data for ${}^7\text{He}$, which shows a state not observed before (the preliminary results have previously been published in [16]).

The experiment was performed at Gesellschaft für Schwerionenforschung Darmstadt mbH, Germany, where a 227 MeV/nucleon ${}^8\text{He}$ secondary beam was produced in a 8 g/cm² beryllium production target by a 340 MeV/

nucleon primary ${}^{18}\text{O}$ beam. The produced nuclei were subsequently separated using the fragment separator (FRS) before interacting with a 1.3 g/cm² carbon target. The charged fragments produced in the interaction of ${}^8\text{He}$ with the ${}^{12}\text{C}$ nuclei were then transmitted through the large-gap dipole magnetic spectrometer, ALADIN, and the neutrons were detected with the large area neutron detector, LAND. The experimental setup has been described in detail in Refs. [16–20].

Events with one neutron in coincidence with a ${}^6\text{He}$ fragment after ${}^8\text{He}$ breakup were selected in the present analysis. Detection of only one neutron means that the second one either has been absorbed or deflected strongly by the target after a large momentum transfer. Such a reaction corresponds to a one-neutron knockout channel. It has previously been shown [17,18,21] that the sudden approximation, i.e., a sudden neutron removal where the rest of the system remains almost unperturbed, describes the reaction mechanism well.

The cross section as a function of relative energy E_r between the ${}^6\text{He}$ fragment and the neutron, reconstructed from the measured momenta of neutron, $\mathbf{p}_n$ and ${}^6\text{He}$, $\mathbf{p}_{{}^6\text{He}}$ [22] is shown in Fig. 1. The experimental data are compared with an expected resonance energy distribution for the population of the ${}^7\text{He}$ ground state with the resonance parameters adopted from Ref. [7]. The calculation was performed using the Monte Carlo method with a Breit-Wigner shaped resonance and takes into account effects of the experimental resolution and acceptance, following the procedure outlined in Ref. [18].

FIG. 1. Coincidence cross section of the ${}^6\text{He}$ - n system after breakup of 227 MeV/nucleon ${}^8\text{He}$ as a function of the relative energy E_r . Experimental data are shown as open circles with error bars. The inset shows the efficiency curve for the setup. The solid line is the result of a Monte Carlo calculation with a Breit-Wigner expression for the p -wave ground state of ${}^7\text{He}$ with $I^\pi = 3/2^-$, $E_r = 0.44$ MeV, and $\Gamma = 0.16$ MeV [7]. The simulation includes corrections for experimental acceptance and resolution.

The resolution function of the setup was extracted using a Monte Carlo method and hereafter folded with an R -matrix expression [18] in order to describe the data points. For that, the resolution in neutron momenta was derived from a simulation of neutron tracks in the LAND detector using real one-neutron data obtained in an experiment on proton-neutron coincidences after deuteron breakup, at an energy close to the energy of the present experiment [23]. The momentum resolution for charged fragments was determined with direct beams of the corresponding nuclei. The energy and angular straggling in the target and detectors were taken into account. The resulting overall resolution of the setup was checked by reproducing the experimental spectra for excitation of the well known narrow 2^+ state in ${}^6\text{He}$ [19]. The efficiency of the setup is almost constant over the full energy range studied in this experiment and gives only a minor correction to the data points (see the inset in Fig. 1).

As can be seen in Fig. 1, the experimental data (symbols) cannot be described assuming a population of the ${}^7\text{He}$ ground state alone (solid curve, calculated as described above with parameters for the ${}^7\text{He}$ ground state from literature). The calculated curve describes the maximum of the cross section well but decreases too fast towards higher energies compared to the experimental data. Note that this tail towards higher excitation energies can be seen in the experimental data obtained by Stokes and Young [12], but not in the recent paper by Bohlen *et al.* [14].

A possible reason for the observed discrepancy seen in Fig. 1 could be the appearance of correlations in the relative energy distributions of the breakup fragments as a remnant of the correlations in the ground-state wave function of the projectile. Such correlations, even though not reflecting a resonance structure, may form a peaklike back-

ground in the spectra [24,25]. In order to get a feeling for these background correlations an estimate was made using the three-body model from Ref. [25]. It was found that this contribution would be very small. The calculated background increases slowly with a maximum at about 6 MeV and, if present, would have no influence on the energy region under consideration here.

In the preliminary analysis the discrepancy between the experimental data and the single resonance description was accepted as a first evidence for the presence of an unknown excited state in ${}^7\text{He}$ at low energy [16]. The results of a detailed analysis are presented in this Letter.

An attempt to describe the experimental spectrum in a free parameter fit with a single resonance resulted in the minimal reduced χ^2_{red} equal to about 2.8. However, the best fit using two resonances shown as the full drawn line in Fig. 2 was achieved with $\chi^2_{\text{red}} = 1.5$, with the position of the ground state at $E_r = 0.43(2)$ MeV [$\Gamma = 0.15(8)$ MeV] and the second state at $E_r = 1.0(1)$ MeV [$\Gamma = 0.75(8)$ MeV]. Note that the derived position and width of the ${}^7\text{He}$ ground state are in good agreement with the data obtained by Stokes and Young [12]. We interpret the second resonance, with a fraction of 35(10)% of the total cross section for the one-neutron knockout channel, as the $I^\pi = 1/2^-$ state of ${}^7\text{He}$. Figure 3 shows the parameter dependence of the fit, where a clear minimum in χ^2 can be distinguished for the parameters given above. The projection of the grey area in the figures to the respective axis reflects 1 standard deviation of each individual parameter.

In this context it is also important to note that the same experimental setup and data analysis procedure were used for the ${}^5\text{He}$ data, where the α - n cross section is dominated by the $p_{3/2}$ ground state [18,21].

FIG. 2. Same data as in Fig. 1 with the assumption of contributions from two p -wave resonances. The solid line shows a fit to the experimental data using two Breit-Wigner shaped resonances keeping all six parameters free. The dashed line represents the contribution from the ${}^7\text{He}$ ground state with $E_r = 0.43(2)$ MeV and $\Gamma = 0.15(8)$ MeV. The dotted line corresponds to an excited state positioned at $E_r = 1.0(1)$ and $\Gamma = 0.75(8)$ MeV. The inset shows the separate resonances excluding any experimental effects in comparison with the data.

FIG. 3. Contour plot showing the dependence of χ^2 for the $N = 31$ degrees of freedom on the resonance parameters E_r and Γ if two resonances are assumed. For each point on the contour lines all remaining parameters were varied in order to minimize χ^2 again. The projection of the grey area in the figures to the respective axis reflects 1 standard deviation of each individual parameter [26].

Table I summarizes the present data on excited states in ${}^7\text{He}$. In three earlier experiments an excited state has been found at an energy of about 3.3 MeV above the ${}^6\text{He} + n$ threshold [13–15].

This state was first interpreted as corresponding to a neutron in the $p_{1/2}$ orbital and ${}^6\text{He}$ in the ground state. However, the data presented in Ref. [13] showed that this resonance mainly decays into the $\alpha + 3n$ channel, which

TABLE I. Experimentally determined positions of resonances above the ground state in the ${}^7\text{He}$ system. Excitation energies E^* and resonance widths Γ are given in MeV.

Reaction	E^*	Γ	Method	Ref.
${}^{12}\text{C}({}^8\text{He}, n){}^7\text{He}$	0.6(1)	0.75(8)	Invariant mass	Present
${}^1\text{H}({}^8\text{He}, d){}^7\text{He}$	2.9(3)	2.2(3)	Missing mass	[13]
${}^9\text{Be}({}^{15}\text{N}, {}^{17}\text{F}){}^7\text{He}$	2.95(10)	1.9(3)	Missing mass	[14]
${}^{10}\text{B}(\pi^-, pd){}^7\text{He}$	2.8(2)	2.0	Missing mass	[15]

implies that the most probable configuration is of the form $[{}^6\text{He}^*(2^+) \otimes 0p_{1/2}]_{5/2^-}$.

With this interpretation one would expect the position of the ${}^7\text{He}(1/2^-)$ resonance, with a neutron in a $p_{1/2}$ state coupled to the ${}^6\text{He}(\text{g.s.})$, to be about 2 MeV lower in energy. With the selection of the ${}^6\text{He} + n$ channel, made in the present experiment, where the $5/2^-$ state is excluded from the data set, we thus find the most reasonable I^π assignment of the state observed at 1.0 MeV to be $1/2^-$.

We note that the ratio between the contribution from the excited state and the ground state is 0.54(10), which is close to the ratio of the statistical factors of the states $(2I_{\text{exc}} + 1)/(2I_{\text{g.s.}} + 1) = 0.5$. We also note that the measured width of this resonance is close to the single particle limit for a neutron in an $\ell = 1$ orbital [27].

Further support for the spin-parity assignment $I^\pi = 1/2^-$ comes from recent calculations of the ${}^7\text{He}$ system where the sequence of negative-parity states $3/2^-(\text{g.s.})$, $1/2^-$, $5/2^-$ has been obtained [28–31]. The position of the $1/2^-$ state relative to the ground state was obtained at about 3 MeV in shell-model [31] and in refined resonating group model calculations [6], at 2.2 MeV in large-base shell-model calculations [28], and around 0.9 MeV in quantum Monte Carlo calculations [29,30,32]. The experimentally estimated position of the $1/2^-$ resonance is thus in reasonable agreement with the last result.

The proposed level scheme of ${}^7\text{He}$ is shown in Fig. 4. The position of the $1/2^-$ resonance is in the vicinity of the $\alpha + 3n$ threshold and below that of ${}^6\text{He}^*(2^+) + n$.

The energy difference between the ground state and the excited state in ${}^7\text{He}$ obtained here is about 0.6 MeV, which should be compared to the lowest estimate of this energy difference in ${}^5\text{He}$ which is 1.2 MeV [10,11]. We

FIG. 4. Proposed level scheme of ${}^7\text{He}$, where the parameters of the ground state and the first excited state are taken from this Letter (energies in MeV).

thus find a considerable decrease of the splitting of the two lowest states when adding two more neutrons to ^5He [33]. We note that the spin-orbit force is proportional to $-(1/r)dV/dr$ so that systems with large spatial extension tend to show a smaller splitting. The difference in size and diffuseness between ^4He and ^6He should therefore be reflected in the current observation.

The recent many-body quantum Monte Carlo calculations reproduce fairly well the energy splittings between $3/2^-$ and $1/2^-$ states for ^5He and ^7He [29,30,32]. Thus the few-body configuration $\alpha + 3n$ can contribute to the structure of the low-lying $1/2^-$ state in ^7He .

The proximity of the two states in ^7He gives an important clue for the understanding of the ground-state structure in ^8He . The relative contribution from the $1/2^-$ state indicates a strong admixture of a $(0p_{1/2})^2$ component in the ^8He ground-state wave function. The angular distribution of decay neutrons from ^7He was found [16] to have a correlation function

$$W(\theta) \sim 1 + 0.7(1)\cos^2(\theta), \quad (1)$$

where θ is the angle between the ^7He momentum vector and the decay neutron. The decrease of the anisotropy term as compared to ^5He [21] may again be attributed to the more complicated structure of ^8He [16], which most likely has a component of an excited ^6He in its ground-state configuration.

In summary, the one-neutron knockout reaction observed in the fragmentation of 227 MeV/nucleon ^8He in a carbon target has been used to study resonances in the ^7He system. The cross section for the $^6\text{He} + n$ channel as a function of the relative energy shows a structure near the threshold, which can be interpreted in a consistent way to reflect the known ^7He $I^\pi = 3/2^-$ ground-state resonance overlapping with the $I^\pi = 1/2^-$ excited state at 1.0(1) MeV with a width $\Gamma = 0.75(8)$ MeV. The relative weight of the two components is 65:35 (with an uncertainty of 10 for either value) and thus close to the ratio of the spin weight factors.

This work was supported by the BMBF under Contracts No. 06 DA 915I, No. 06 OF 838, and No. 06 MZ 864 and by GSI under Contracts No. DA RICK, No. OF ELZK, and No. MZ KRAK and partly supported by the Polish Committee of Scientific Research under Contract No. KBN/2P03B/144/10, by the EC under Contract No. ERBCHGE-CT92-0003, by CICYT under Contract No. AEN92-0788-C02-02 (M.J.G.B.), by RFBR under Contract No. 01-02-16685, and by WTZ under Contract No. RUS 674-98. One of us (B.J.) acknowledges support by Alexander von Humboldt Research.

*Present address: NSCL, Michigan State University, East Lansing, MI 48824-1321.

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