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Observation of a broad p-wave resonant state in ^{9}He

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We report on the two-body invariant-mass spectroscopy of ^{9}He, populated via the $1p1n$ knockout reaction from the two-neutron halo nucleus ^{11}Li at $\sim$ 250 MeV/nucleon. A broad p-wave resonant state of ^{9}He was observed at 1.28(1) MeV with a width of 0.82(4) MeV.

The ^{9}He nucleus, consisting of an ^{8}He core and one valence neutron has been extensively studied. The ground state of ^{9}He was first found unbound against single-neutron decay by 1.13(10) MeV [1] and 1.27(10) MeV [2, 3] with a width of about 100 keV, and was first interpreted as a p-wave resonance ($J^{\pi} = 1/2^{-}$) [2, 3]. The study of isobaric analog states of ^{9}He in ^{9}Li suggests a narrow p-wave resonance at 1.1 MeV [4]. Later, the p-wave resonance was identified at 2.0(2) MeV with $\Gamma \sim 2$ MeV and at 1.2(1) MeV with Γ of 130^{+170}_{-130} keV in the $d(^{8}\text{He}, p)^{9}$He transfer reactions with poor statistics [5, 6]. In addition to the p-wave resonance, the ^{9}He spectrum also shows an enhancement close to the ^{8}He-n decay threshold, which is interpreted as an s-wave virtual state ($J^{\pi} = 1/2^{+}$). So far, the experimentally extracted s-wave scattering lengths that quantifies the ^{9}He low-energy virtual state are rather divergent. An upper limit of $a_s \leq -10$ fm was determined using the ^{11}Be(-2p) knockout reaction [7], while a range of -3 fm $< a_s < 0$ fm was suggested using the same reaction [8]. Recently, two possibilities around -2 fm and -7 fm were also obtained [9]. Meanwhile, the ^{11}Li(-1p1n) knockout reaction suggested $a_s = -3.17(66)$ fm [10]. A lower limit of $a_s > -20$ fm [5] and a value of $a_s = -12(3)$ fm [6] were obtained from the ^{8}He induced transfer reactions. Finally, the most recent high resolution ^{8}He + p elastic scattering that populates isobaric analogue ^{9}He ground and excited states showed that ^{9}He does not have narrow resonances between 0 and 2.2 MeV and its lowest state is a broad s-wave resonance around 3 MeV which is most probably a virtual state [11]. A limit of -1.7 fm $< a_s < 0$ fm, *i.e.* close to zero, was suggested from the phase shift analysis [11, 12]. These results suggest that the ^{8}He-n s-wave interaction could be either strong ($a_s \leq -10$ fm) or weak (a_s close to zero), making it difficult to conclude on the ^{9}He structure as well as the influence on the ^{10}He structure [13]. Further experimental and theoretical studies are necessary to understand the structure of ^{9}He and ^{10}He consistently.

Here, we report on the low-lying state of ^{9}He populated from the ^{11}Li(-1p1n) knockout reaction at $\sim$ 250 MeV/nucleon.

The experiment was performed at the Radioactive Isotope Beam Factory operated by the RIKEN Nishina Center and the Center for Nuclear Study of the University of Tokyo. The cocktail secondary beam was produced

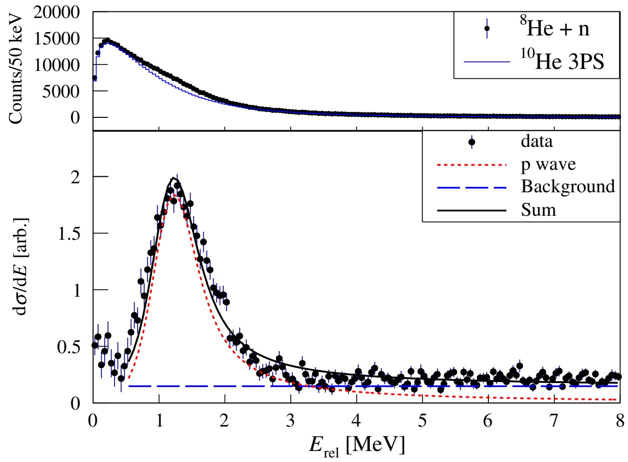

FIG. 1. (Color online) (top panel) Experimental ^{8}He-n relative energy spectrum obtained from the ^{11}Li(-1p1n) reaction. Contaminations from the ^{10}He three-body phasespace decay (3PS) is shown by the blue-solid line. (lower panel) Spectrum after the contaminations subtraction and efficiency correction. The black solid line shows the fit results of a Breit-Wigner shape p-wave resonance folded with the experimental resolution (red short dashed line) on top of a constant background (blue long dashed line).

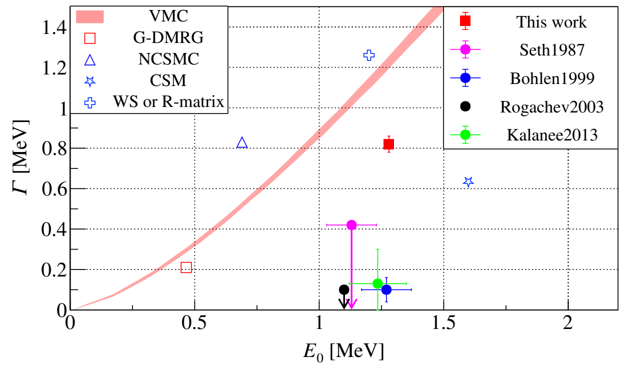

FIG. 2. (Color online) The two-body p-wave resonant energy and decay width of ^{9}He obtained by the present work compared with previous results from Seth *et al.* [1], Bohlen *et al.* [3], Rogachev *et al.* [4] and Kalanee *et al.* [6]. The experimental data are also compared with the different theoretical predictions, including *ab initio* variational Monte Carlo (VMC) [26], Gamow-density-matrix renormalization-group (G-DMRG) [27], no-core shell model with continuum (NCSMC) [28], the shell model in continuum (CSM)[29] as well as the Woods–Saxon (WS) potential and the R-matrix analysis of Ref. [30].

through fragmentation of a 345 MeV/nucleon ^{48}Ca primary beam on a ^{9}Be target. The typical intensity of the primary beam is 400 particle nA. The secondary beam was purified and identified event by event using the BigRIPS two-stage fragment separator [14, 15]. The ^{11}Li beam, with an average energy of 246 MeV/nucleon and a typical intensity of 1×10^5 particles per second, was tracked by two multiwire drift chambers, and bombarded on the 150-mm thick liquid hydrogen target [16] of the MINOS device [17] to induce one-nucleon or two-nucleon knockout reactions. The ^{8}He fragment and decay neutrons were detected by the SAMURAI spectrometer [18] and the neutron detector array NEBULA [19], respectively. The same setup has been used in previous publications [20–24].

The two-body relative energy $E_{\rm rel}$, which is also the energy of ^{9}He above the ^{8}He + n threshold, was reconstructed by the momenta of ^{8}He and the neutron, requiring that only one neutron was detected in the neutron detector array. In the present work, ^{9}He can be populated via ^{11}Li(p,pd) or ^{11}Li(p,2pn) reactions. ^{8}He + n events can also be produced if ^{10}He is populated in the ^{11}Li(p,2p)^{10}He reaction and decays to ^{8}He + 2n, but only one neutron was detected in the neutron detectors [25]. Such contaminations were estimated using Monte Carlo simulations based on the quasi-free one-proton knockout process from ^{11}Li, following by the three-body phasespace decay of ^{10}He to ^{8}He + 2n (3PS). The experimental energy distribution of ^{10}He has been adopted as an input for the phasespace decay. Normalization was performed such that the two-neutron event number in the simulation matches the corresponding experimental data. The simulations reproduce well the experimental relative-energy spectrum of the ^{8}He-n subsystem from the ^{10}He decay.

The obtained ^{9}He $E_{\rm rel}$ spectrum as well as the contaminations from the ^{10}He 3PS are shown in the top panel of Fig. 1. After the contaminations subtraction and efficiency correction, a clear peak was observed in the $E_{\rm rel}$ spectrum, as shown in the lower panel of Fig. 1, which is different with the previous spectrum measured at GSI at similar incident beam energy [10].

The $E_{\rm rel}$ spectrum of ^{9}He was fitted with a Breit-Wigner p-wave resonance on top of a constant background, convoluted with the experimental relative-energy resolution. The energy resolution (FWHM) was obtained from GEANT4 simulations that incorporated the realistic experimental setup and detector response, yielding a value of 0.40 MeV at 1.3 MeV. Both the peak position and decay width of the resonance were taken as free parameters in the fitting. Energy dependence of the decay width has been taken into account [31, 32]. The resulting resonant energy and decay width are $E_0 = 1.28(1)$ MeV and $\Gamma = 0.82(4)$ MeV, respectively. The quoted uncertainties are only statistical. In addition, the channel radius is set as 4.35 fm in the fitting [30]. Increasing the channel radius to 6.0 fm reduces the obtained decay width by about 4%.

The obtained p-wave resonant energy of ^{9}He is ∼0.7 MeV lower than that observed by ^{8}He(d,p) transfer reaction [5], but shows consistency with results from the double-charge exchange reaction [1], other transfer reactions [2, 3, 6] and (p,p) resonance elastic scattering [4]. However, the measured decay width is nearly an order of magnitude larger than the previously reported values

— 0.10(6) MeV [3], < 0.1 MeV [4] and 130^{+170}_{-130} keV [6] — all of which were derived from datasets with limited statistical significance.

On the other hand, the current data can also serve as a benchmark for various *ab initio* and phenomenological nuclear models. The present data, in particularly the much larger decay width around 1 MeV, agrees reasonably well with the shell model in continuum (CSM) calculations [29], the *ab initio* variational Monte Carlo (VMC) calculations [26] and the no-core shell model with continuum (NCSMC) predictions [28], as well as the Woods–Saxon (WS) potential and the R-matrix analysis of Ref. [30]. These theoretical models anticipate a decay width around 1 MeV for the lowest $1/2^-$ state in ^{9}He, that can be attributed to its strong single-particle character. Notably, due to the deuteron spin and parity of 1^+, ^{9}He populated from the ^{11}Li(p,pd) reaction can only exhibit a $1/2^-$ configuration (*i.e.* $^8\text{He} \otimes \nu 0p_{1/2}$). This selection rule likely explains the absence or weak population of the $1/2^+$ state of ^{9}He (Fig. 1 below 0.5 MeV) in the present energy spectrum.

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