Low-lying states and structure of the exotic ^{8}He via direct reactions on proton

F. Skaza[a], V. Lapoux[a*], N. Keeley[a], N. Alamanos[a], F. Auger[a], D. Beaumel[b], E. Becheva[b], Y. Blumenfeld[b], F. Delaunay[b], A. Drouart[a], A. Gillibert[a], L. Giot[c], E. Khan[b], L. Nalpas[a], A. Pakou[d], E. Pollacco[a], R. Raabe[a], P. Roussel-Chomaz[c], K. Rusek[e], J-A. Scarpaci[b], J-L. Sida[a], S. Stepantsov[f] and R. Wolski[f].

[a]CEA-Saclay, DSM/DAPNIA/SPhN F-91191, Gif-sur-Yvette, France

[b]IPN-Orsay, IN2P3-CNRS, 91406 Orsay Cedex, France

[c]GANIL, Bld Henri Becquerel, BP 5027, F-14021, Caen, France

[d]Dpt of Physics, Univ. of Ioannina, 45110 Ioannina, Greece

[e]DNR, The Andrzej Soltan Institute for Nuclear Studies, PL-00681 Warsaw, Poland

[f]JINR, FLNR Dubna 141980 Dubna, Moscow region, Russia.

The structure of the light exotic nucleus ^{8}He was investigated using direct reactions of the ^{8}He SPIRAL beam on a proton-rich target. The (p,p') scattering to the 2_1^+ state, the (p,d)^{7}He and (p,t)^{6}He transfer reactions, were measured at the energy $E_{lab} = 15.7$ A.MeV. The light charged particles (p,d,t) were detected in the MUST Si-strip telescope array. The excitation spectrum of ^{8}He was extracted from the (p,p') reaction. Above the known 2_1^+ excited state at 3.6 MeV, a second resonance was found around 5.4 MeV. The cross sections were analyzed within the coupled-reaction channels framework, using microscopic potentials. It is inferred that the ^{8}He ground state has a more complex neutron-skin structure than suggested by previous $\alpha + 4n$ models assuming a pure $(1p_{3/2})^4$ configuration.

1. Introduction

The structure and the spectroscopy of the radioactive nuclei are explored to find new phenomena and properties of the nuclear matter. The goal is also to determine the evolution of the nuclear structure and of the excitations along the isotopic chains, towards the drip-lines. By studying more and more neutron-deficient or neutron-rich systems, we can check the validity of the nuclear interactions in extreme cases of the nuclear matter, at large isospin, and we also test our modeling of the exotic weakly-bound nuclei. Neutron-halo or neutron-skin nuclei are examples of the new phenomena encountered close to the drip-line. For instance, ^{6,8}He are found to develop large spatial extensions of their neutron distributions with 2 and 4 neutrons respectively, surrounding a core formed by 2 protons

*E-mail: vlapoux@cea.fr

and 2 neutrons, producing a halo in the case of ^{6}He [1] and a possible neutron-skin for ^{8}He [2]. Within the ab-initio Quantum Monte-Carlo (QMC) calculations [3] the binding energies of the light nuclei ($A < 10$) are well reproduced including 2-body and 3-body nuclear forces. No core shell model (NCSM) calculations were also developed in the last few years and applied to light p-shell nuclei. They give relatively good results for the spectroscopy of the neutron-rich nuclei [4]. But the predictive power and the validity of the models have to be checked, especially for the low-lying spectroscopy of the nuclei at large isospin. A good test case is the drip-line ^{8}He nucleus which has the largest ratio $N/Z = 3$ amongst the known nuclei. Its 4-neutron separation energy S_{4n} is of 3.1 MeV only. From reaction cross sections [5] and reanalysis of the high-energy proton elastic scattering of ^{8}He [6], it is shown that ^{8}He has a matter root mean square (rms) of 2.5 ± 0.1 fm. It means that, although having 2 more neutrons than ^{6}He, it has almost the same size. The weak S_{4n} and the rms radius are consistent with the neutron-skin structure assumed for this nucleus. Generally ^{8}He is described according to the structure proposed by the 5-body COSMA model [2]: an inert α core with 4 valence neutrons occupying a full $1p_{3/2}$ subshell and forming the neutron-skin.
^{8}He, like ^{6}He, has no bound excited state. In order to explore its structure and spectroscopy we measured (p,p') reaction. It is a powerful probe to investigate the ground state (gs) and transition densities to excited states of the light exotic nuclei, as shown by the recent results obtained on the halo of ^{6}He [1]. Previous ^{8}He(p,p') data exist; the (p,p') was measured at RIKEN [7] and a 2^+ resonance was observed at 3.57 ± 0.12 MeV (width $\Gamma = 0.5 \pm 0.35$ MeV). But the low statistics and reduced angular range for the (p,p') distributions did not allow to perform a detailed microscopic analysis of the density profiles, as done for ^{6}He in [1].

2. Experimental set-up

The ^{8}He(p,p') experiment was carried out at GANIL using the ^{8}He beam produced by the SPIRAL facility at $E_{lab} = 15.7$ A.MeV. The proton-rich target was a polypropylene foil of $(CH_2)_n$. Data were taken with a 8.25 mg/cm^2-thick target (and a thin 1.48 mg/cm^2-one to measure the angles below $40^\circ_{c.m.}$ for the elastic scattering). The light charged particles (p,d,t) produced in the (p,p'), (p,d) and (p,t) reactions induced by ^{8}He on proton were detected in the MUST device [8], an array of 8 Si-strip and Si(Li) telescopes (each with an active area of 6×6 cm^2) devoted to the detection off the light recoiling charged particle. The MUST array was settled at 15 cm from the target. The light particles were identified and their position and energies were measured in MUST in coincidence with the heavy ejectiles, He isotopes, detected in a wall of plastic scintillators. The incident beam profile on the target was reconstructed using two MWPC beam detectors, the CATS [9]. Event by event, the scattering angle in the laboratory frame θ_{lab} and the energy E of the light charged particle detected in MUST are reconstructed. The yields of the detected particles are plotted in the correlation spectrum between E and θ_{lab}, presented in Fig. 1. The particles were identified in MUST and the events associated to the various reactions (elastic, inelastic scattering to the 2^+_1 state, 1 and 2-neutron transfer) can be seen along the kinematical lines drawn to guide the eye and superimposed to the experimental spectrum. We discuss the excitation spectrum of ^{8}He extracted from the (p,p') reaction

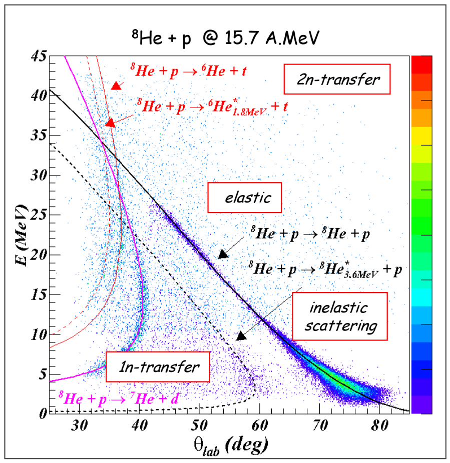

Figure 1. *Kinematical plots of events for the direct reactions discussed in the text.*

in Sec. 3. The elastic, inelastic (p,p') and transfer reactions ^{8}He(p,d)^{7}He [10,11] and (p,t) [12] were measured simultaneously, the angular distributions were deduced. The analysis is summarized in Sec. 4.

3. Discussion of the ^{8}He excitation spectrum

The full analysis of the excitation spectrum for the ^{8}He will be explained in [13]. The excitation spectra for ^{8}He were analyzed for different angular slices in the c.m. frame to check the consistency of the extracted parameters of the possible resonances. The continuum background contribution was determined by a Monte-Carlo simulation of the physical background produced by few-body kinematics with several decay channels, and filtered by the experimental response. The ingredients of the simulation were the phase space calculations, the detection efficiency and the experimental angular and energy resolutions. A new resonance, at 5.4$\pm$0.5 MeV with an intrinsic width $\Gamma = 0.5 \pm 0.3$ MeV was found [13], in addition to the known resonance 2^+_1 that we observed at 3.62 ± 0.14 MeV ($\Gamma = 0.3 \pm 0.2$ MeV). The 2^+_1 state is consistent with the previous data obtained by (p,p') [7], multi-nucleon transfer [14,15] or break-up [16] reactions, and in constrast with the data in [17]. The resonances predicted by the ab-initio QMC calculations [3] or the ab-initio NCSM [18] are not in agreement with our results, as shown in Fig. 2. Moreover, the binding energy of ^{8}He obtained in NCSM is of -22.9 MeV, to be compared to the experimental one : -31.4 MeV. The crucial role of the continuum correlations and of the coupling to the scattering states, missing in such approaches, might explain why these theories fail in reproducing the unbound states. Recently, the models treating explicitly the continuum couplings of bound and scattering states, like the Gamow Shell Model [19] showed that the weakly-bound nuclei ^{6,8}He, are bound by the continuum coupling correlations, and that the low-lying spectroscopy of these nuclei is modified by these couplings. In the continuum shell model [20], the predicted resonant states of ^{8}He are in agreement with the resonances obtained from our (p,p') data. The excitation spectrum for the unbound

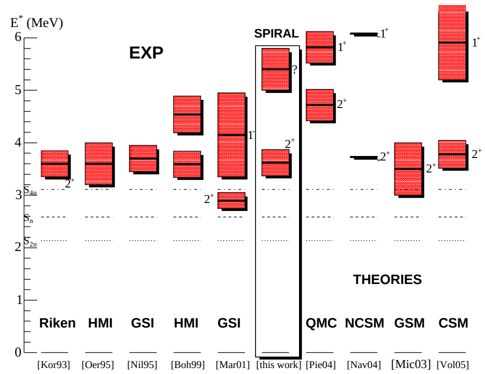

Figure 2. *Experimental and theoretical spectra of ^{8}He. The areas drawn for each resonance correspond to the FWHM widths.*

^{7}He was also extracted from the ^{8}He(p,d) reaction. The analysis is discussed in [11]. In particular, a resonance is indicated at low energy at 0.9±0.5 MeV (1.3 MeV above ^{6}He+n threshold), with width $\Gamma = 1.0 \pm 0.9$ MeV. Within the recoil corrected continuum SM calculations, the possibility of this $1/2^-$ low-lying state of ^{7}He is not excluded [21].

4. Analysis of the reactions in the Coupled-reaction

For the first time, we have a data set of direct reactions induced by ^{8}He on proton at the same incident energy. In Fig.3, the experimental ^{8}He(p,d)^{7}He$_{gs}$ cross sections are large ($>$ 10 mb/sr for the forward angles) compared to the elastic ones [10]. These orders of magnitude show that the coupling effect between the (p,p) and the (p,d)^{7}He$_{gs}$ are important. The appropriate analysis of these direct reactions should not use the framework the Distorted Wave Born Approximation (DWBA). To take into account the strong coupling effect of the (p,d) on the (p,p), the cross sections were analyzed within the framework of the coupled-reaction-channel (CRC) method [22] using the continuum discretized coupled channel (CDCC) calculations. The entrance potential was calculated with the microscopic complex JLM [23] nucleon-nucleus potential, using the ^{8}He gs densities generated by the NCSM [18]. Both the elastic ^{8}He(p,p) and the ^{8}He(p,d)^{7}He$_{gs}$ reactions are reproduced in the CRC framework [10]. This coupling strongly affects the extraction of the structure information. The first analysis of the ^{8}He(p,p) elastic and (p,d) transfer reactions within the CCBA calculations gave a spectroscopic factor (SF) for the neutron pick-up from ^{8}He to the ^{7}He gs of 4.4±1.3 [11]. With the CDCC analysis, we have obtained the best fit with a SF of 3.3 [10]. In a further step, including also explicitly the (p,t) reaction with (p,p) and (p,d) in the coupled reaction scheme, all the data are well reproduced [12], as shown in Fig. 3. Previously, various data sets were available for (p,d) [24] and (p,t) [25] transfer reactions of ^{8}He, but at different incident energies and for a single reaction channel, mea-

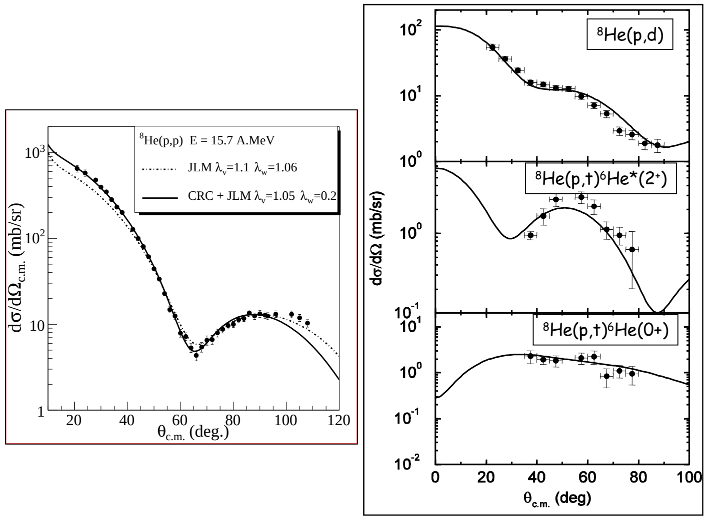

Figure 3. *Experimental and calculated cross sections for* ^{8}*He(p,p) and* ^{8}*He(p,d) at 15.7 A.MeV [10,12]. See details in the text.*

sured without the elastic data. These data were found consistent with the COSMA model, but they were not complete in terms of angular range and reaction channels, moreover the analysis in [24,25] was carried out using the limited DWBA framework. To interpret not only our complete data set but also to analyze consistently the previous measurements, we found that we needed to use an ^{8}He ground state built on a mixing between the $(1p_{3/2})^4_\nu$ and the $(1p_{3/2})^2_\nu$ $(1p_{1/2})^2_\nu$ configurations [12]. Moreover, the elastic data are reproduced by the calculations performed with the ^{8}He+p JLM potential including the gs densities given by the NCSM model. It is not the case with the COSMA densities. The rms radii for the proton, neutron and matter distributions are respectively 2.00, 2.59 and 2.46 fm to be compared to the corresponding rms radii given by the COSMA model: 1.69, 2.74 and 2.52 fm. This comparison shows that the ^{8}He is better modeled with a neutron-skin thickness of $\langle r^2\rangle_{\rm n}^{1/2} - \langle r^2\rangle_{\rm p}^{1/2} \simeq 0.6$ fm, rather than equal to 1 fm. It means that the proton-neutron correlations needed to describe the ^{8}He structure are different from the ones assumed in the COSMA model. The NCSM 0^+ to 2^+ transition densities [18] were also used to calculate the cross sections for the (p,p') scattering to the 2^+ state in the CRC framework. We found that the calculations overestimated the (p,p') data; analysis is in progress [13].

5. Conclusions

The results on the spectroscopy of the ^{8}He drip-line nucleus were obtained by (p,p') and transfer reactions on proton. They were discussed and compared to previous separate measurements. They were found consistent with the predictions made by the recent nuclear models including the continuum-coupling effect to the resonant and scattering states. From the analysis within the CRC framework, we obtained that the reactions could be described using the ^{8}He gs densities predicted by the NCSM model, with neutron-skin features different from those proposed by the COSMA model. It means that ^{8}He has a larger proton rms radius and a smaller neutron-skin thickness than assumed in the $\alpha+4n$ model. These findings are also consistent with our analysis of the (p,t) reaction, which showed that the gs includes not only the $(1p_{3/2})^4$ but also the $(1p_{3/2})^2(1p_{1/2})^2$ configuration. We also found that the 2^+ state was weakly excited by the (p,p') probe, and that the present NCSM calculations are overestimating the proton and neutron excitations. The strong coupling effects of the (p,d) pickup on the (p,p') reactions, observed here for ^{8}He, are expected *a priori* to play an important role for all the reactions involving weakly-bound nuclei. The various reaction channels allow to determine the coupling factors to be used in the analysis. In general, we can have insight on these effects by measuring a complete set of direct reactions. This is an essential aspect of our future experimental program with exotic beams at energies from 10 to 50 MeV/n.

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