STRUCTURE AND LOW-LYING STATES OF THE ^{8}HE EXOTIC NUCLEUS VIA DIRECT REACTIONS ON PROTON

V. LAPOUX*, N. KEELEY, F. SKAZA, N. ALAMANOS, F. AUGER, A. DROUART, A.GILLIBERT, L. NALPAS, E. C. POLLACCO and J-L. SIDA

DSM/DAPNIA/SPhN, CEA-Saclay,
Gif-sur-Yvette, F-91191, France
**E-mail: vlapoux@cea.fr*

D. BEAUMEL, E. BECHEVA, Y. BLUMENFELD, F. DELAUNAY and J-A. SCARPACI

IPN-Orsay, CNRS-IN$_2$P$_3$, Orsay, F-91406 France

L. GIOT and P. ROUSSEL-CHOMAZ

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

K. W. KEMPER

Department of Physics, Florida State University,
Tallahassee, Florida 32306-4350, USA

R.S. MACKINTOSH

Department of Physics and Astronomy, The Open University,
Milton Keynes, MK7 6AA, UK

A. PAKOU

Dpt of Physics, The University of Ioannina, Ioannina, 45110, Greece

R. RAABE

IKS, University of Leuven, Leuven, B-3001, Belgium

K. RUSEK

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

S. STEPANTSOV and R. WOLSKI

Flerov Laboratory of Nuclear Reactions, JINR,
Dubna, RU-141980, Moscow region, Russia

The structure of the ^{8}He exotic nucleus 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 excitation spectrum of ^{8}He was extracted. Above the known 2_1^+ excited state at 3.6 MeV, a second resonance was found around 5.4 MeV. Within the coupled-reaction channels framework, the cross sections were analyzed and the spectroscopic factors for the (p,d)^{7}He$_{gs}$, the (p,t)^{6}He(0^+), and the (p,t)^{6}He(2^+) were deduced. It is inferred that the ^{8}He ground state has a different neutron-skin structure from the one suggested by previous $\alpha + 4n$ models assuming a pure $(1p_{3/2})^4$ configuration.

Keywords: (p,p') scattering; weakly-bound nuclei; resonances; coupled-reaction channel analysis.

1. Goals

In order to test the validity of the nuclear models and to improve their predictive power, the properties of the exotic nuclei such as very diffuse nuclear surfaces, low-lying resonances or new magic shells are experimentally investigated using radioactive ion beams. With the facilities developed worldwide, we can begin the exploration of the effect of large variation of isospin along isotopic chains. Using the particle spectroscopy technique, direct reactions such as (p,p') scattering and one-nucleon transfer reactions are measured to obtain the signatures for the new properties.

In this scope we have studied the wave function of the ^{8}He exotic nucleus. This nucleus has the largest N/Z ratio amongst the known nuclei and the nuclear correlations producing this weakly-bound structure at the drip line have to be clarified. Our experimental goals were to explore the structure and to obtain the low-lying resonant states using (p,p') scattering.

In the Helium chain, large spatial extensions of the neutron distributions have been found for ^{6}He and ^{8}He, producing a halo in the case of ^{6}He[1] and a possible neutron skin for ^{8}He.[2] From reaction cross sections[3] and high energy proton elastic scattering,[4] it is shown that ^{8}He has a matter rms radius of 2.5±0.1 fm. It means that it has almost the same size as ^{6}He, although having two neutrons more. The 4-neutron skin structure expected in the ^{8}He nucleus is generally described as the 5-body COSMA model[2] does, with parameters adjusted to reproduce the 4-neutron separation energy: an inert Alpha core surrounded by four valence neutrons. In this model, the neutron $1p_{3/2}$ subshell is fully occupied, which results in the neutron-skin structure and in a rather compact nucleus compared to ^{6}He.

During our complete experiment, all the reaction channels (elastic, inelastic and transfer) were simultaneously measured in the same conditions. From the analysis of the (p,p') angular distributions, it is possible to test the validity of the various microscopic calculations proposed for this nucleus. All previous data were not conclusive about the resonant states above the first excited 2^+ state measured at RIKEN.[5] This state was obtained from the inelastic ^{8}He(p,p') scattering measured at 73 A.MeV,[5] but there was not enough statistics to provide information on the ^{8}He structure and on other resonant states. We carried out the measurement in inverse kinematics using the ^{8}He beam delivered by the SPIRAL facility at GANIL and an optimized particle detection set-up.

2. Experimental set-up

The direct reactions of ^{8}He on a proton-rich target of polypropylene foil were measured at the incident energy of 15.7 A.MeV. We used the dedicated tools to study direct reactions induced by radioactive beams: the beam tracking detectors CATS,[6] to define the impact of the beam on the target, and the particle detector array MUST.[7] The MUST array was a wall of 8 modules located at 15 cm from the target. Each MUST module was a telescope (active area of 6x6 cm^2), with a 300 μm thick position-sensitive Si-strip followed by a 3 mm-thick Si(Li) stage. The emitted light charged particles [proton from (p,p') reaction, deuteron from (p,d) or triton from (p,t)] were detected and identified by the MUST telescopes. The heavy ejectiles were measured in coincidence in a wall of plastic scintillator located at forward angles. Mean intensity during the experiment was 5000/s (maximum value was 10^4/s). With the CATS and MUST devices, the scattering angle in the laboratory (lab) frame and the energy of the recoiling nuclei were reconstructed event by event; the angular resolution was of 0.4° (lab). In the excitation spectrum obtained from proton scattering, using the thin (1.48 mg/cm^2) to measure the angles below $40^\circ_{c.m}$, and the thick one (8.25 mg/cm^2), the energy resolution was ranging from 600 keV to 1.2 MeV.

3. Results

Elastic, inelastic and transfer reaction cross-sections were extracted from the ^{8}He+p data and compared to theoretical calculations yielding accurate results on the structure of the ^{8}He.[8–10] We summarize here the main findings. The angular distribution for elastic scattering is shown in Fig. 1 (top). The entrance channel potential was calculated with the microscopic complex JLM nucleon-nucleus potential,[11] using the no-core shell model (NCSM) ^{8}He ground state densities.[12] The usual parameter set, for the normalization of the real and imaginary parts of the potential for the light nuclei, is taken as : $\lambda_V = 1.0$ and $\lambda_W = 0.8$. In this case, data were found to be poorly reproduced. A better agreement was obtained with λ_V and λ_W left as free parameters (dashed line). However, even with these uncommon values, the elastic scattering at forward angles was still not well reproduced. The reaction framework was reconsidered. Since the ^{8}He(p,d) cross sections were found as large as the elastic ones in the angular range from 30 to $60^\circ_{c.m}$, it was a clear indication of strong coupled-channel (CC) effects[8] from the pick-up reaction (p,d) to the elastic scattering. Therefore, the data were analyzed using the coupled-reaction-channel (CRC) method and microscopic potentials, following the procedure detailed in Ref. 13.

From the coupled-channels Born approximation (CCBA) analysis,[9] the spectroscopic factor (S.F.) for neutron pick-up to the ^{7}He$_{gs}$ was $C^2S = 4.4 \pm 1.3$; through the improved continuum discretized CC analysis- using microscopic potentials and explicit coupling to the (p,d) channel- the best fit gave $C^2S = 3.3$[8] and both elastic and (p,d) data were reproduced.[8]

Within a CC analysis using microscopic potentials and explicit coupling to the (p,d)

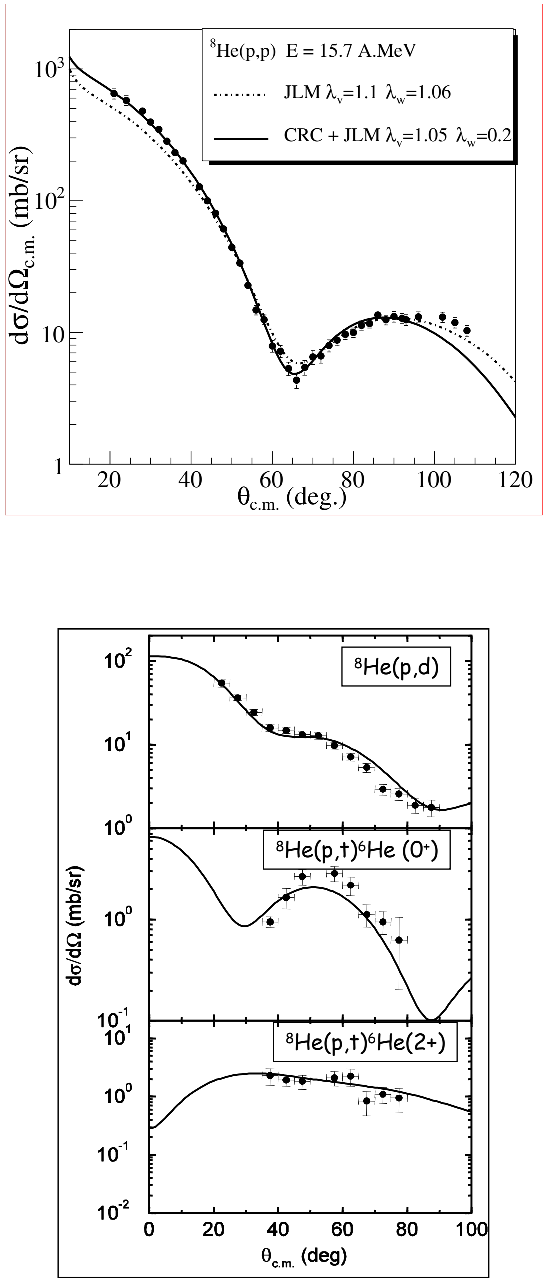

Fig. 1. Experimental and calculated cross sections for ^{8}He(p,p) and ^{8}He(p,d), (p,t) at 15.7 A.MeV.[8,10] In the coupled reaction scheme, including the (p,d) and (p,t) transfer channels with the S.F. described in the text, the whole set of reactions are reproduced.[10]

and also to (p,t) channels it was possible to reproduce both elastic and (p,d), (p,t) data, as shown by the full curve in Fig. 1.

The S.F. of the $^{8}He_{g.s.}$ respected to $^{7}He_{3/2^-}$ g.s.[8] and $^{6}He(0^+)$ and $^{6}He(2^+)$ were deduced[10] : the C^2S values are 2.9, 1.0 and 0.014, respectively. These factors are in agreement with the results obtained from the analysis of the quasi-free scattering of ^{8}He measured at GSI:[14] they found the $^{8}He/^{6}He_{0+}$ overlap of 1.3±0.1; and the S.F. for $^{8}He/^{7}He_{3/2^-}$ was of 3.3±0.3. The S.F. correspond to a structure for the ^{8}He ground state mainly built on the $^{6}He_{0+} + 2n$ configuration. This is in contrast with the previously admitted structure for ^{8}He, described by the COSMA model and considered as a mixing between $^{6}He_{0+} + 2n$ and $^{6}He_{2+} + 2n$ configurations.
In our analysis, we found that it was needed to describe the ^{8}He ground state as built on a mixing between the $(1p_{3/2})^4_\nu$ and the $(1p_{3/2})^2_\nu$ $(1p_{1/2})^2_\nu$ configurations[10] to interpret our complete data set. This gave also a consistent analysis of the previous measurements, using the same S.F. inputs as for the SPIRAL data:
– through the CCBA the previous ^{8}He(p,d) data measured at 50 A.MeV[15] was reproduced;[9]
– the $^{8}He(p,t)^{6}He(0^+)$ and $^{8}He(p,t)^{6}He(2^+)$ reactions at 61.3 A.MeV[16] were reproduced by the CRC calculations.[10]
This analysis demonstrates how important the reaction framework is to draw correct conclusions on the S.F. and to deduce the microscopic structure. Moreover, from the analysis within the CRC framework, we have extracted the features of the density distributions of the ^{8}He ground state.[18] The calculations were done with the ^{8}He+p JLM potential including the ground state densities given either by the ab-initio NCSM[17] or by the COSMA model. The elastic data are better reproduced using the NCSM. 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. In summary, the ground state is found to be a neutron-skin structure close to the one given by the NCSM,[17] but different from the COSMA model[2] which assumes an $\alpha + 4n$ configuration corresponding to a pure $(1p_{3/2})^4_\nu$ sub-shell closure.
Preliminary CRC calculations of the (p,p') scattering were done, including only the (p,d) coupling. The microscopic potential was obtained from the JLM calculations using the NCSM ground state and transition densities.[17] It is found that the CRC calculations of the angular distributions overestimate the data with this set of densities. To test various profiles of the transition densities, and to deduce the quantitative characteristics of the transition densities, it is now required to take into account in the CRC calculations not only the (p,d) but also the (p,t) coupling effect on the (p,p') reaction. This work is in progress.

The ^{7}He and ^{8}He excitation energy spectra were extracted by missing mass method respectively from the ^{8}He(p,d) and (p,p') reactions.

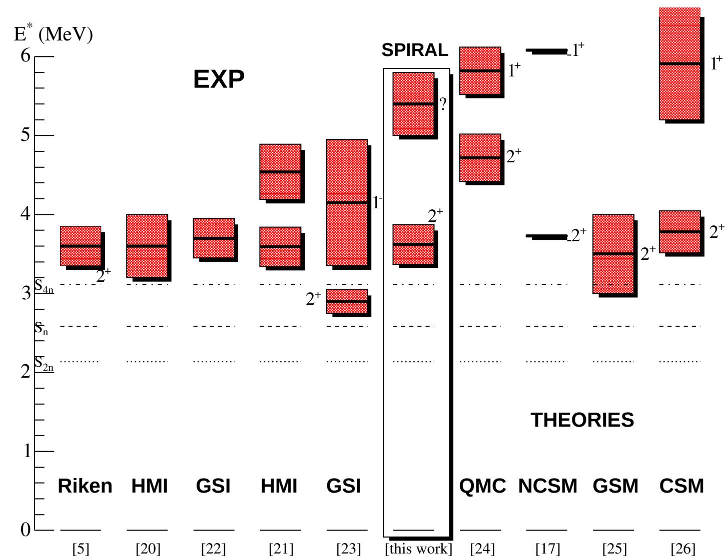

Fig. 2. Experimental and theoretical spectra of ^{8}He. The areas drawn for each resonance correspond to the FWHM widths.

The analysis of the ^{7}He spectrum is detailed in Ref. 9. From the ^{8}He excitation energy spectrum, the characteristics of the first two resonant excited states were obtained: the first 2^{+} is obtained at 3.62 $\pm$0.14 MeV (width 0.3 $\pm$0.2 MeV), and a second state was found at 5.4 $\pm$0.5 MeV (width 0.5 $\pm$0.3 MeV).[18] The analysis will be detailed in a forthcoming article.[19] As shown in Fig. 2, the values for the first 2^{+} state are consistent with the previous data obtained by (p,p'),[5] by multi-nucleon transfer[20,21] or break-up[22] reactions, and in contrast with the data in.[23] The resonances predicted by various theories, like the ab-initio calculations[24] or the ab-initio NCSM[17] overestimate our results. In the Gamow Shell Model (GSM),[25] through the consistent description of the bound states and the particle continuum, the ground state of the weakly-bound ^{6,8}He is found bound by the continuum-coupling correlations, and the position of the first excited state 2^{+} is well predicted. In the Continuum Shell Model (CSM),[26] which includes also the particle continuum effects, the predictions for the first two resonant states are consistent with our data.

4. Conclusions and prospective

The reaction framework is crucial to obtain a consistent analysis of the reaction channels and to deduce the spectroscopic factors and the ground state structure. It is shown that the (p,d) coupling changes deeply the features of the entrance potential and strongly affects the extraction of the structure information. The spectroscopic factors of the ^{8}He$_{gs}$ respected to ^{7}He$_{gs}$, ^{6}He(0^{+}) and ^{6}He(2^{+}) were deduced.[10] The ^{8}He ground state is mainly built on the ^{6}He$_{0^+}$ + $2n$ configuration and there is a significant probability of finding the valence neutrons in other configuration than the full sub-shell $(1p_{3/2})^4$, such as $(1p_{3/2})^2(1p_{1/2})^2$. The ^{8}He$_{gs}$ structure is found well described by a neutron-skin density, similar to the one obtained by the NCSM.[17] The results obtained in the case of ^{8}He also demonstrate the need for a complete data set of direct reactions in order to understand the coupled-channel effects between elastic, inelastic and transfer reactions. This is a necessary step to be able to investigate the structure of weakly-bound nuclei. The same features can be expected throughout the nuclear chart, and particularly for neutron-rich nuclei with low particle threshold and continuum states close to the ground state.

To study the evolution of the neutron excitations in the neutron-rich isotopes, systematical studies of low-lying unbound excited states will be pursued through direct reactions on proton target. Dedicated tools have been developed to improve the efficiency, angular coverage and resolution of our present devices. Recently, the new Si-strip telescope array MUST2 has been built in a DAPNIA-IN$_2$P$_3$-GANIL collaboration.[27] As for ^{8}He, the low-lying spectroscopy of nuclei close or at the drip-line will be used as benchmarks for the most recent microscopic structure models developed to take into account explicitly the continuum-coupling effects. Through the confrontation between predictions and experimental results along the extended isotopic chains, the ingredients of the structure models will be checked. It is expected that the parameters of the nuclear interaction, isospin-dependent, spin-isospin dependent terms, and also the modelling of the spin-orbit coupling, pairing terms and continuum coupling effects could be extensively investigated and reevaluated.

In the following years, using beams of other drip-line nuclei like ^{24}O, it should be possible to carry out a complete (p,p') analysis. The present RIBF facility at RIKEN, in the mid-term future accelerators like SPIRAL2 at GANIL or FAIR at GSI, and in the long-term future the European facility EURISOL, will offer new exotic beams and the opportunity to extend the systematics of the low-lying resonances in the neutron-rich nuclei.

References

1. A. Lagoyannis et al., *Phys. Lett. B* **518**, 27 (2001).
2. M.V. Zhukov, A.A. Korsheninnikov and M.H. Smelberg, *Phys. Rev. C* **50**, 1 (1994).
3. J. A. Tostevin and J. S. Al-Khalili, *Nucl. Phys A* **616**, 418c (1997).
4. J. S. Al-Khalili and J. A. Tostevin, *Phys. Rev. C* **57**, 1846 (1998).
5. A.A. Korsheninnikov *et al.*, *Phys. Lett. B* **316**, 38 (1993).
6. S. Ottini *et al.*, *Nucl. Inst. Meth. A* **431**, 476 (1999).
7. Y. Blumenfeld *et al.*, the MUST collaboration, *Nucl. Inst. Meth. A* **421**, 471 (1999).
8. F. Skaza *et al.*, *Phys. Lett B* **619**, 82 (2005).
9. F. Skaza *et al.*, *Phys. Rev. C* **73**, 044301 (2006).
10. N. Keeley *et al.*, *Phys. Lett. B* **646**, 222 (2007).

11. J. P. Jeukenne, A. Lejeune and C. Mahaux, *Phys. Rev. C* **16**, 80 (1977).
12. P. Navrátil and W. E. Ormand, *Phys. Rev. C* **57**, 3119 (1998).
13. N. Keeley, N. Alamanos, and V. Lapoux, *Phys. Rev. C* **69**, 064604 (2004).
14. L.V. Chulkov *et al.*, *Nucl. Phys. A* **759**, 43 (2005).
15. A.A. Korsheninnikov *et al.*, *Phys. Rev. Lett.* **82**, 3581 (1999)
16. A.A. Korsheninnikov *et al.*, *Phys. Rev. Lett.* **90**, 082501 (2003).
17. P. Navrátil and W.E. Ormand, *Phys. Rev. Lett.* **88**, 152502 (2002); P.Navrátil, priv.co.
18. F. Skaza *et al.*, *Nucl. Phys. A* **788**, 260c (2007).
19. V. Lapoux *et al.*, in preparation.
20. W. von Oertzen, *Nucl.Phys. A* **588**, 129c (1995).
21. H.G. Bohlen *et al.*, *Prog. Part. Nucl. Phys.* **42**, 17 (1999).
22. T. Nilsson *et al.*, *Nucl. Phys. A* **583**, 795 (1995).
23. K. Markenroth *et al.*, *Nucl. Phys. A* **679**, 462 (2001).
24. S. C. Pieper, R. B. Wiringa, and J. Carlson, *Phys. Rev. C* **70**, 054325 (2004).
25. N. Michel, W. Nazarewicz, M. Ploszajczak, J. Okolowicz, *Phys. Rev. C* **67**, 054311 (2003).
26. A. Volya and V. Zelevinsky, *Phys. Rev. Lett.* **94**, 052501 (2005).
27. E.C. Pollacco *et al*, the MUST2 collaboration, *Eur. Phys. J. A* **25**, 287 (2005).