STUDY OF ^{8,9,10}He STRUCTURE IN THE EXPERIMENTS WITH A TRITIUM TARGET

S.I. SIDORCHUK[1], A.A. BEZBAKH[1], V. CHUDOBA[1,2], I.A. EGOROVA[3], A.S. FOMICHEV[1], M.S. GOLOVKOV[1], A.V. GORSHKOV[1], V.A. GORSHKOV[1], L.V. GRIGORENKO[1,4,5], G.KAMINSKI[1,6], S.A. KRUPKO[1], YU.L. PARFENOVA[1,8], P.G. SHAROV[1], R.S. SLEPNEV[1], S.V. STEPANTSOV[1], G.M. TER-AKOPIAN[1], R. WOLSKI[1,6]

[1]Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia;
[2]Institute of Physics, Silesian University in Opava, Czech Republic;
[3]Bogolyubov Laboratory of Theoretical Physics, JINR, Dubna, Russia;
[4]GSI Helmholtzzentrum fur Schwerionenforschung, Darmstadt, Germany;
[5]Institute of Nuclear Physics PAN, Krakow, Poland;
[7]Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia

Spectra of unbound states of helium isotopes ^{8,9,10}He were studied in the one- and two-neutron transfer reactions with the use of the ^{6,8}He secondary beams and a cryogenic tritium/deuterium target. Analysis of angular correlations of decay products allowed us to define spin-parities of the states observed in the experiments. In disagreement with shell model expectations the established level ordering in ^{9,10}He testifies the shell breakdown in these nuclei. Angular correlations measured for a decay of the well-known 2^+ state of ^{8}He were applied for the verification of the experimental approach used in this work.

1. Introduction

Bibliography of works dedicated to experimental study of a structure of heavy helium isotopes drastically shortens when increasing the number of valence neutrons in a nucleus studied. While the number of articles linked to ^{8}He exceeds several hundred, only few experiments on ^{10}He are known to date. A structure of expectedly double magic ^{10}He was explored in works [1-3] yielded rather contradictory conclusions about its ground state (g.s.): E_T=1.1÷1.54 MeV, Γ=0.3÷1.9 MeV. More numerous experimental studies of the ^{9}He structure give more consistent results: its g.s. was found to be a low-lying (E_T~1.1 MeV) and very narrow (Γ<0.3 MeV) resonance (see for example

[4-6]). These results were obtained in reactions of rather complicated mechanisms and most likely influenced by an initial state. In this context the neutron transfer reactions are the more reliable tool for studies of a structure of unbound nuclei. The present work is dedicated to the study of low-energy spectra of the helium isotopes ^{8,9,10}He produced in the 1*n*- and 2*n*-transfer reactions with the use of radioactive ^{6,8}He beams and a cryogenic tritium/deuterium target.

2. Experimental approach

Spectra of low-lying states of the ^{8}He, ^{9}He and ^{10}He nuclei were studied at the fragment-separator ACCULINNA (Dubna) [7] in the reactions ^{3}H(^{6}He,*p*)^{8}He, ^{2}H(^{8}He,*p*)^{9}He and ^{3}H(^{8}He,*p*)^{10}He at the energies of bombarding particles 25, 25 and 21.5A MeV, respectively. A target cell cooled down to 26 K was filled in with tritium/deuterium at the pressure ~1 atm. A charged particle emitted from a nuclear system of interest (^{6}He from ^{8}He^{2+} or ^{8}He from ^{9,10}He) was detected in coincidence with a recoil proton. A kinematical range corresponding to small center-of-mass (CM) angles where the proton is emitted backward with respect to the beam direction was chosen for the measurements. The experimental layout and the kinematical scheme for ^{10}He as an example are shown in Fig. 1.

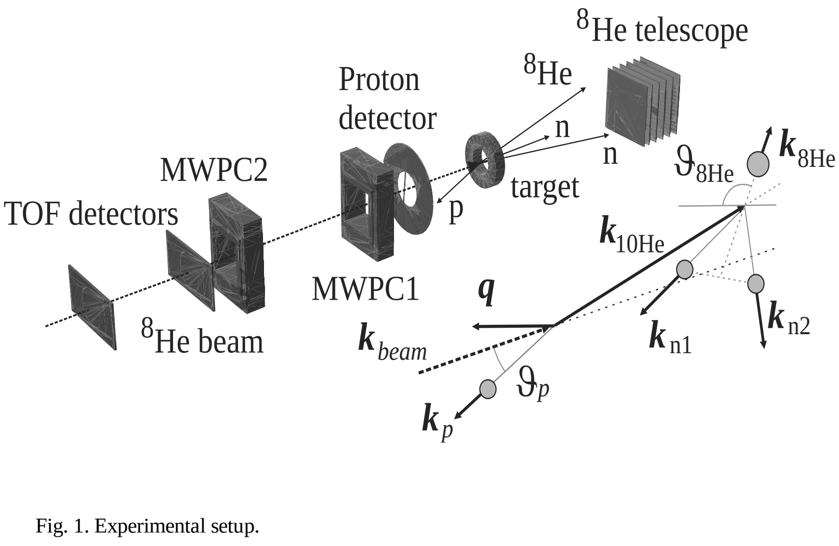

Fig. 1. Experimental setup.

The recoil proton was detected by the annular Si detector installed upstream the target while high energy charged particle emitted from $^{8}He/^{9}He/^{10}He$ hit a telescope placed as shown in Fig. 1. Two plastic scintillators and two multiwire proportional chambers (MWPC) provided a TOF measurement and a tracking of incoming beam particles. Detection of two coincident particles in the reaction output channel gave us a missing mass of the nucleus of interest and angular distribution of a charged decay product in the CM of produced $^{8,9,10}He$ with respect to the transferred momentum vector $\boldsymbol{q}$ (Fig. 1). This approach developed for the study of the structure of nuclei beyond the drip-line [8-10] implies a direct experimental identification of states populated in a reaction using the analysis of interference patterns in angular distributions of the decay products.

3. Results

Helium-10. The ^{10}He missing mass spectrum obtained in the experiment is shown in Fig. 2(a) by the grey histogram.

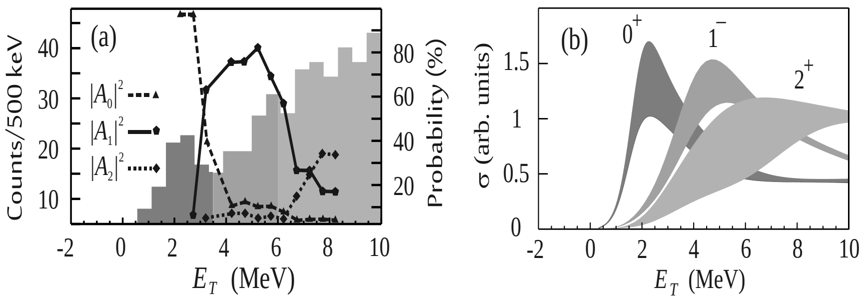

Fig. 2. (a) ^{10}He missing mass spectrum. Three parts of the spectrum marked by different colors correspond to events with different angular distributions shown in Fig. 3. Spectrum decomposition in components with different spin-parities J^{π} is shown by points. (b) Theoretically predicted ^{10}He spectra for different J^{π}.

For the analysis we selected the events satisfying the condition A broad peak with the maximum at the energy ~2 MeV we interpret as the ^{10}He g.s. but at higher energies the spectrum shape is smooth and featureless.

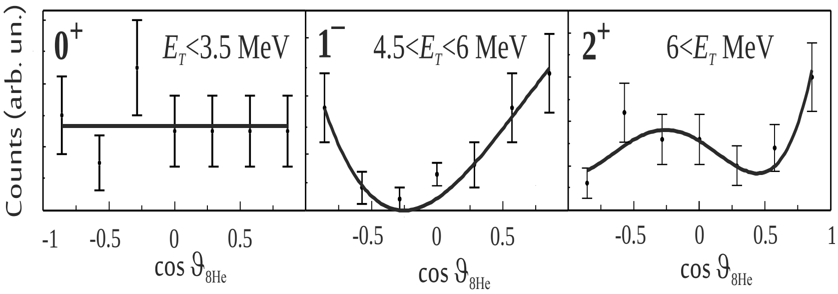

Fig. 3. Angular distributions of ^{8}He measured in different energy ranges of ^{10}He excitation and satisfying condition $E_{nn}/E_T < 0.5$. Curves show fits made by using Eq. (1).

However, the angular correlations of the ^{10}He decay products show prominent peculiarities allowing us to select in this spectrum three energy ranges corresponding to different quantum states. $E_{nn}/E_T < 0.5$, where E_{nn} is the *n*-*n* relative energy. Three energy regions with qualitatively different angular behavior marked in Fig 2(a) by different colors were found in the spectrum: (i) E_T<3.5 MeV; (ii) 3.5<E_T<6 MeV; and (iii) E_T>6 MeV. Angular distributions for these ranges were fitted with the expression

$$w = \left|A_0 P_0(x) + A_1\sqrt{3}P_1(x) + A_2\sqrt{5}P_2(x)\right|^2 + |D|^2 \qquad (1)$$

where P_l are Legendre polynomials with $x = \cos\vartheta_{8He}$ (see Fig. 1), A_l are the amplitudes of *s*-, *p*- and *d*-wave contributions, while the *D* takes into account a decoherent "background" linked to ^{10}He states not included in the analysis explicitly.

The more detailed energy behavior of the amplitudes made for 1.5 MeV energy bins with a 0.5 MeV step is shown in Fig. 2 (a) by points of different types. According to the results of the fit an asymmetry of the ^{8}He emission noticeable in the energy range E_T>4.5 MeV is a consequence of the *s*-*p* (4.5<E_T<6 MeV) and *s*-*p*-*d* interference (E_T >6 MeV).

Theoretical consideration provides for the ^{10}He g.s the dominant $[p^2_{1/2}]$ structure at about 2 MeV in a good agreement with the present experimental data [11]. Calculations of Ref. [11] extended to the 1^- and 2^+ excitations of ^{10}He are also well consistent with the experimental results (see Fig 2(b)].

Helium-9. The spectrum of ^{9}He was studied in the ^{2}H(^{8}He,*p*)^{9}He reaction [9]. The lowest resonant state of ^{9}He was found at 2.0±0.2 MeV with a width of ~2 MeV and identified as $1/2^-$.

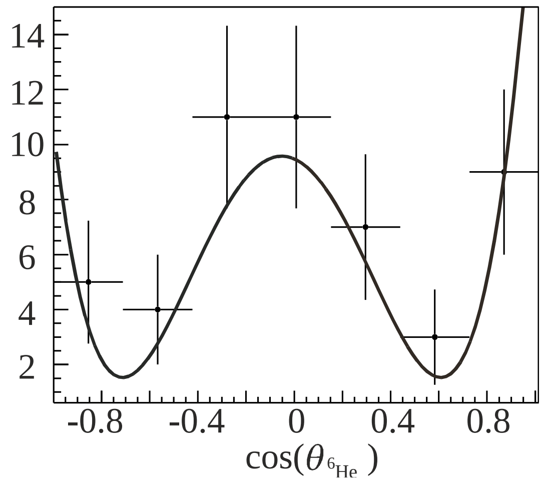

Fig. 4. Angular distribution of ^{6}He emitted from $^{8}He^{2+}$ for the ^{8}He excitation energy range E_x<3.8 MeV.

The observed angular correlation pattern was uniquely explained by the interference of the $1/2^-$ resonance with a virtual $1/2^+$ state and with a $5/2^+$ resonance at energy >4.2 MeV. Three-body calculations for the ^{10}He low-energy spectrum using experimental results obtained for ^{9}He show good qualitative agreement with the experimental data obtained in the reaction ^{3}H(^{8}He,*p*)^{10}He [see Fig 2(b)].

Helium-8. The reaction ^{3}H(^{6}He,*p*)$^{8}He^{*}$ leading to the population of low-lying excited states of ^{8}He was studied at the energy of ^{6}He of about 25A MeV. Being completely analogous to the reaction ^{3}H(^{8}He,*p*)^{10}He discussed above, this reaction, in particular, can be considered as a benchmark for the verification of the approach and the results obtained for ^{10}He. Angular distribution of ^{6}He emitted from $^{8}He^{*}$ for events from the excitation energy range corresponding to the well-known first excited state 2^+ (E_x~ 3.7 MeV) is shown in Fig. 4. The curve is a result of the fit done with the use of the formula (1) and shows a clear evidence of a d-wave dominating in this energy range.

4. Conclusions

The angular correlations measured for ^{10}He decay products show prominent interference patterns interpreted as a coherent superposition of a 0^+ g.s. (E_T=2.1 MeV, Γ~2 MeV) with a broad 1^- state located in the energy range 4.5 - 6 MeV and a 2^+ state above 6 MeV. The level ordering established in the experiment confirms the shell breakdown phenomenon, earlier observed for another member of the N = 8 isotone chain – ^{12}Be [12]. The energy positions and the widths of the ^{10}He low-lying states are in agreement with theory predictions based on the resonance parameters of the ^{9}He subsystem obtained in the 1n-neutron transfer reaction ^{2}H(^{8}He,p)^{9}He

References

1. A.A. Korsheninnikov, K. Yoshida, D.V. Aleksandrov et al., *Phys. Lett.* **B326** 31 (1994).
2. A.N. Ostrowski, H.G. Bohlen, B. Gebauer et al., *Phys. Lett* **B338** 13 (1994).
3. H.T. Johansson, Yu. Aksyutina, T. Aumann et al., Nucl. Phys. A 847 (2010) 66.
4. K.K. Seth, M. Artuso, D. Barlow et al., *Phys. Rev. Lett*. **58** 1930 (1987).
5. W. von Oertzen, H.G. Bohlen, B. Gebauer et al., Nucl. Phys. **A588** 129 (1995).
6. H.T. Johansson, Yu. Aksyutina, T. Aumann et al., *Nucl. Phys.* **A842** 15 (2010).
7. A.M. Rodin, S.I. Sidorchuk, S.V. Stepantsov et al., *Nucl. Instr. Methods* **B126** 236 (1997).
8. M.S. Golovkov, L.V. Grigorenko, A.S. Fomichev et al., *Phys. Rev.* **C72** 064612 (2005).
9. M.S. Golovkov, L.V. Grigorenko, A.S. Fomichev et al., *Phys. Rev.* **C76** 021605 (2007).
10. S.I. Sidorchuk, A.A. Bezbakh, V. Chudoba et al., *Phys.Rev. Lett.* **108** 202502 (2012).
11. L.V. Grigorenko and M.V. Zhukov, *Phys. Rev.* **C77** 034611 (2008).
12. H. Iwasaki, T. Motobayashi, H. Akiyoshi et al., *Phys. Lett.* **B491** 8 (2000).