“Development and application of new experimental techniques at complex ACCULINNA-2@U-400M”

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The cycle of papers consist of 5 papers.

The new facility fragment-separator ACCULINNA-2 was built at heavy ions accelerator U- 400M in 2017. In 2018 experimental program with high quality radioactive ion beams ^{6}He, ^{8}He, ^{9}Li, ^{10}Be (E ~ 26-44 MeV/nucleon) and cryogenic deuterium target was started at new complex. The new information about spectra of neutron-rich nuclei ^{6,7}H, ^{7}He, ^{8,9,10}Li and its rare decay channels was obtained. The results about hydrogen isotopes were published in 2020-2022: (A.A. Bezbakh, et al., “Evidence for the first excited state of ^{7}H”, Physical Review Letters 124 (2020) 022502, I.A. Muzalevskii et al., “Resonant states in ^{7}H: Experimental studies of the ^{2}H(^{8}He,^{3}He) reaction”, Physical Review C 103 (2021) 044313, E.Yu. Nikolskii et al., “^{6}H states studied in the ^{2}H(^{8}He,^{4}He) reaction and evidence of an extremely correlated character of the ^{5}H ground state”, Physical Review C 105 (2022) 064605), observation data of ^{7}He submitted to IJMPE (A.A. Bezbakh et al., “Properties of the ^{7}He ground state studied by the ^{6}He(d, p)^{7}He reaction”), result about ^{8,9}Li was recently published [1,2], data analysis of ^{9}Li(d,p)^{10}Li $\rightarrow$ n+^{9}Li experiment is going on.

For a detailed study of the structure of these and many other exotic nuclei, research was carried out at the ACCULINNA-2@U-400M complex aimed at further development of experimental methods and techniques of physical experiment [3-5].

Experimental technique for the study of ^{6,7}H in ^{2}H(^{8}He,^{4}He)^{6}H and ^{2}H(^{8}He,^{3}He)^{7}H reactions was further developed using reference reactions ^{2}H(^{10}Be,^{4}He)^{8}Li and ^{2}H(^{10}Be,^{3}He)^{9}Li, respectively [1, 2]. In these experiments with a ^{10}Be beam (44 MeV/nucleon), several methodological problems were solved:

1) According to the known ^{9}Li level spectrum, an absolute calibration of the measurement data of the spectrum of states of exotic nuclei with the missing mass method was obtained. This calibration was of fundamental importance for the ^{6,7}H spectra;

2) The dependence of the excitation energy resolution on the thickness of the deuterium target is obtained, and the measured values are compared with the results of Monte Carlo simulations;

3) from the data of the differential cross section $d\sigma/d\Omega$ for the reaction ^{2}H(^{10}Be,^{3}He)^{9}Li$_{g.s}$ information on the efficiency (luminosity) of the detecting equipment was obtained.

From the analysis of the obtained angular distributions of the reaction ^{2}H(^{10}He,^{3}He)^{9}Li$_{g.s.}$, important physical results were obtained using the FRESCO code: 1) for the clustering channel ^{10}Be = p + ^{9}Li$_{g.s.}$, the spectroscopic factor SF 1.7 was determined, which coincided with the theoretical calculation; 2) for the reaction ^{2}H(^{10}Be,^{4}He)^{8}Li population of the second excited level of ^{8}Li (2.255 MeV, 3^{+}) was observed, while in the measured spectrum of levels population of the main and first excited states of ^{8}Li was not detected. This experimental result agrees well with the description of the ^{8}Li spectrum from this reaction, taking into account the structure of the ^{10}Be and ^{8}Li nuclei using a shell model.

Paper [3] is devoted to modeling an experiment for a further study of the structure of ^{7}H and its decay channels using an array of 100 neutron detectors based on hexagonal BC-404 plastics assembled into a compact wall. In addition to the existing array of 48 stilbens [A.A. Bezbakh et al., 61:631-638 (2018)], this neutron wall will significantly increase the luminosity of experiments with the registration of two, three and even four neutrons from the decay of ^{7}H. It will allow one to obtain information about the spectra and decay trajectories of all particles emitted during the multi-neutron decay of ^{7}H nuclei obtained in the ^{2}H(^{8}He,^{3}He)^{7}H reaction, as well as when studying the decay spectra of a number of nuclei: ^{6}H, ^{10}He, ^{13}Li, etc.

In order to improve the quality of experiments with secondary beams at the ACCULINNA-2 facility, further development of techniques continues [4]. Among them, are the following: 1) time-of- flight detectors for event-by-event measurement of particle energies with a high accuracy of ~ 70 ps, i.e. 0.2% in energy, for example, for ^{9}Li with a total energy of 266 MeV, the accuracy is E ~ 0.5 MeV (FWHM); 2) system of beam tracking on the target providing coordinate resolution at the interaction point ~ 1.2 mm. The paper presents a detailed technique for setting, calibrating and processing the measurements. It shows the possibilities of work with exotic beams and comparison with modeling the operation of detectors.

In [5], the characteristics and operation features of the system of cryogenic physical targets at the ACCULINNA-2 facility are described. A new technique for producing thin hydrogen targets in solid phase at reduced pressure is presented, which is important for improving the resolution of experiments with exotic beams. The complex is unique as it provides safe operation with all isotopes of hydrogen, including tritium, and helium - ^{3}He, ^{4}He. The thickness of the target can vary depending on the physical task in a wide range, namely, $10^{19} – 7*10^{21}$ atom/cm^{2} with the thickness of the input/output stainless steel windows at the level of 6-10 mkm.

Thus, in this series of works, almost the entire range of methodological works is presented, from the conceptual elaboration of new methods for detection of reaction products to a detailed analysis of the operation of systems, as well as the application of test reactions (experiments) for the calibration and testing of the entire detecting system and data processing techniques in real conditions. It is expected that the U-400M heavy ion accelerator, after modernization, will resume its work in early 2024 and, taking into account the developed methods, experiments with radioactive beams will begin at a qualitatively new level.

List of papers:

1. E.Yu. Nikolskii, I.A. Muzalevskii, S.A. Krupko, A.A. Bezbakh, V. Chudoba, S.G. Belogurov, D. Biare, A.S. Fomichev, E.M. Gazeeva, A.V. Gorshkov, L.V. Grigorenko, G. Kaminski, M. Khirk, O. Kiselev, D.A. Kostyleva, M.Yu. Kozlov, B. Mauyey, I. Mukha, Yu.L. Parfenova, A.M. Quynh, V.N. Schetinin, A. Serikov, S.I. Sidorchuk, P.G. Sharov, R.S. Slepnev, S.V. Stepantsov, A. Swiercz, G.M. Ter-Akopian, R. Wolski, M.V. Zhukov.“Study of proton and deuteron pickup reactions (d,^{3}He), (d,^{4}He) with ^{8}He and ^{10}Be radioactive beams at ACCULINNA-2 fragment separator”, Nuclear Instruments and Methods in Physics Research B 541 (2023) 121–125.
2. E.Yu. Nikolskii, S.A. Krupko, I.A. Muzalevskii, A.A. Bezbakh, R. Wolski, C. Yuan, S.G. Belogurov, D. Biare, V. Chudoba, A.S. Fomichev, E.M. Gazeeva, M.S. Golovkov, A.V. Gorshkov, L.V. Grigorenko, G. Kaminski, M. Khirk, O. Kiselev, D.A. Kostyleva, B. Mauyey, I. Mukha, Yu.L. Parfenova, A.M. Quynh, S.I. Sidorchuk, P.G. Sharov, N.B. Shulgina, R.S. Slepnev, S.V. Stepantsov, A. Swiercz, G.M. Ter-Akopian, “Study of proton and deuteron pickup reactions ^{2}H(d,^{3}He)^{9}Li and ^{2}H(d,^{4}He)^{8}Li with 44 AMeV ^{10}Be radioactive beam at

ACCULINNA-2 fragment separator”, Physics of Atomic Nuclei, Vol. 86 № 6 (декабрь 2023).

3. A.A. Bezbakh, S.G. Belogurov, V. Chudoba, A.S. Fomichev, A.V. Gorshkov, L.V. Grigorenko,
4. G. Kaminski, M.S. Khirk, A.G. Knyazev, S.A. Krupko, B. Mauyey, I.A. Muzalevskii, E.Yu. Nikolskii, A.M. Quynh, P.G. Sharov, R.S. Slepnev, S.V. Stepantsov, G.M. Ter-Akopian, R. Wolski, “Detector array for the ^{7}H nucleus multi-neutron decay study”, JINR Preprint E13-2022-56; Particles and Nuclei Letters Vol. 20, No.4 (2023) 629-636.
5. Krupko S.A., Abakumov A.M., Belogurov S.G., Bezbakh A.A., Golovkov M.S., Gorshkov A.V., Gorshkov V.A., Rymzhanova S.A., Slepnev R.S., Fomichev A.S. “Diagnostics of the secondary beam at the ACCULINNA-2 fragment separator”, Physics of Particles and Nuclei Letters. - V. 20, № 5 (2023) P.1035–1045.
6. С.А. Крупко, А.В. Горшков, А.А. Безбах, А.С. Фомичев, Г.М. Тер-Акопьян, “Система криогенных физических мишеней установки ACCULINNA-2”, Препринт ОИЯИ Р13-2022-48, «Письма в ЭЧАЯ» № 1 (2024).