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INSTALLATION FOR RESONANCE SPECTROSCOPY OF RADIOACTIVE LIGHT NUCLEI

© 2011 A. G. Artukh[1], A. G. Foshan[2], O. D. Grygorenko[3], S. A. Klygin[1], G. A. Kononenko[1], E. I. Koschy[2], V. E. Kovtun[2], V. V. Ostashko[3], Yu. N. Pavlenko[3], A. N. Ponomarenko[1], Yu. M. Sereda[1,3], A. I. Rundel[3], I. N. Vishnevsky[3], A. N. Vorontsov[1,3], I. I. Zalubovsky[2]

[1] *Joint Institute for Nuclear research, Dubna, Russia*
[2] *V. N. Karazin Kharkiv National University, Kharkiv*
[3] *Institute for Nuclear Research, National Academy of Sciences of Ukraine, Kyiv*

The experimental set-up based on the time-of-flight fragment-separator COMBAS and multi-channel registration system is developed for the studies of exotic light nuclei. Precise correlation method will be used for resonance decay spectroscopy.

Keywords: secondary radioactive beams, exotic light nuclei, fragment-separator, time-of-flight measurements, corellation measurements, resonance spectroscopy.

Introduction

Over the last two decades development in the production of secondary radioactive beams has essentially extended the possibilities of experimental studies of unstable nuclei with proton and neutron excess. Unusual properties of light exotic nuclei off the stability valley have been discovered. In particular, such nuclei as ^{6}He and ^{11}Li demonstrate neutron halo structure and soft modes of collective excitations with different multipolarity.

Systematic study of nuclei with the asymmetrical ratio N/Z allows getting important information about the properties of nuclear matter with a density different from the density of stable nuclei [1, 2]. Understanding of mechanism of cluster formation in nuclei has a fundamental significance in researches of many-body nuclear dynamics. The role of nuclear clustering close to the neutron drip-line is illustrated by Antisymmeterised Molecular Dynamics calculations for the odd B isotopes [3]. According to these calculations an increased clustering into two separated cores (lithium and helium-like components surrounded by valence neutrons) appears with increasing neutron number. The similar clustering effect can be also observed for the Be isotopes. Original molecular-like structure is theoretically predicted for the very neutron-rich carbon isotopes ($^{19-22}$C) [2].

The experimental facility, consisting of the time-of-flight fragment-separator COMBAS (Flerov Laboratory of Nuclear Reactions of Joint Institute for Nuclear Research, Dubna) [4 - 6] and multi-channel registration system, was created with the aim of investigation of cluster structure and other properties of exotic light nuclei. The identification of resonance cluster decay processes will be performed using the correlation method of invariant mass, which will ensure high accuracy of measuring of excitation spectra of nuclei under investigation.

Fragment separator COMBAS and registration system

The separator COMBAS (Figs. 1 and 2) is designed for production and formation of the secondary beams of radioactive nuclei and their transportation to the second target, which is located in the output focal plane F_a. COMBAS consists of cascade of multipole magnets M1 – M8, forming wide aperture separator with the triple (for energies, horizontal lines and vertical lines) focusing of particles in output focus. A separator is arranged from two identical sections (M1 – M4 and M5 – M8) with the plane of symmetry in the middle part (dispersion focus F_d).

The first section of magnets (M1 – M4) executes the functions of momentum filter of high-energy particles with rejection of primary beam. The second section (M5 – M8) compensates dispersion of the first section and minimizes the aberration effects in the output achromatic focus. Foil of degrader, positioned in the plane of maximal dispersion (focus F_d), radically improves the isotopic separation of the second section due to the different ionization losses of energy for separated and background particles. The second section, in which there is no intensive primary beam, can be effectively used for the time–of–flight measurements for additional isotope identification.

The secondary beams of neutron-rich isotopes of light nuclei (He, Li, Be, B, C) will be produced via the reactions of fragmentation of nuclei ^{18}O and ^{22}Ne (Table 1), whose primary beams will be accelerated in the cyclotron U-400M.

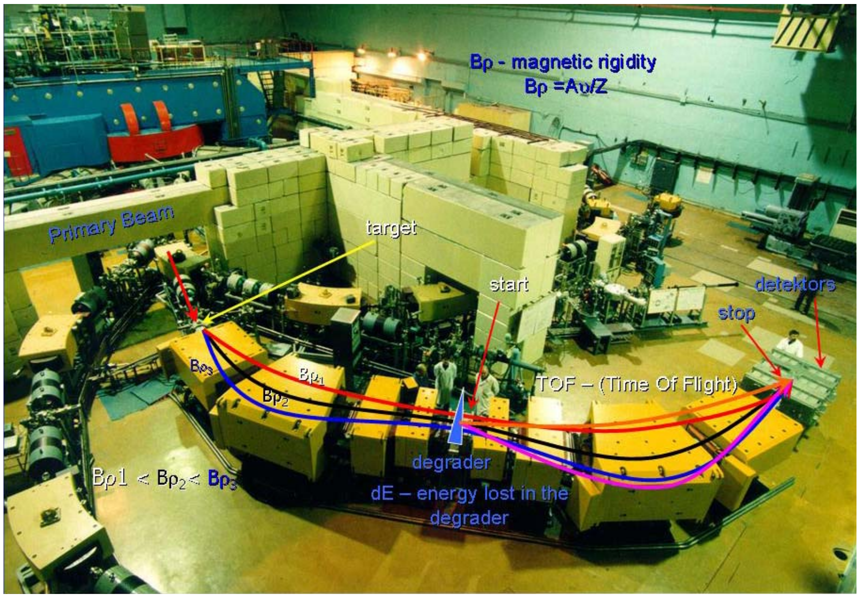


Fig. 1. Fragment-separator COMBAS. The primary beams of the cyclotron U-400M (JINR, Dubna) are used for the production of secondary radioactive beams.

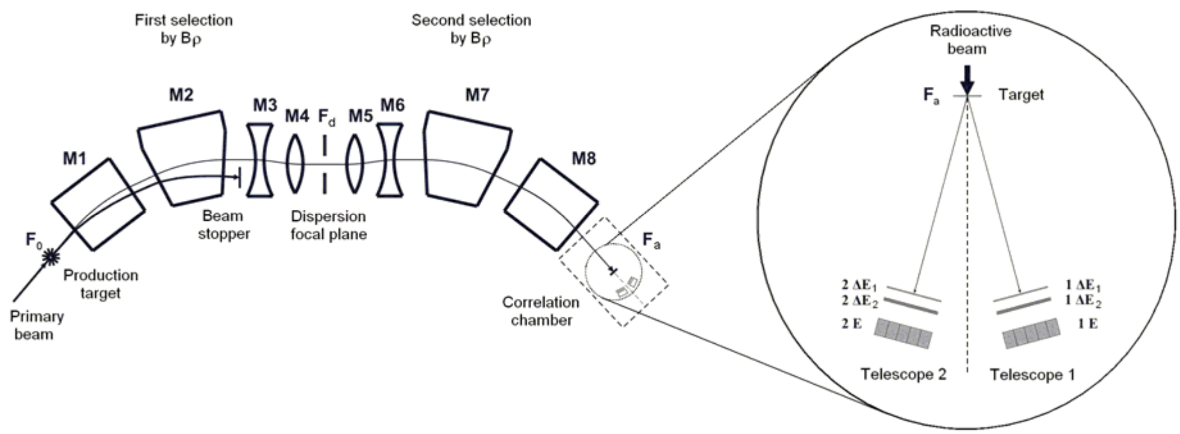


Fig. 2. Experimental set-up for resonance spectroscopy with using of radioactive beams produced by the fragment-separator COMBAS. M1 – M8 – cascade of multipole magnets.

Table 1. **Intensities of secondary beams of radioactive nuclei Be and B obtained in the reactions ^{18}O(35 · A MeB) + ^{9}Be and ^{22}Ne(40 · A MeB) + ^{9}Be**

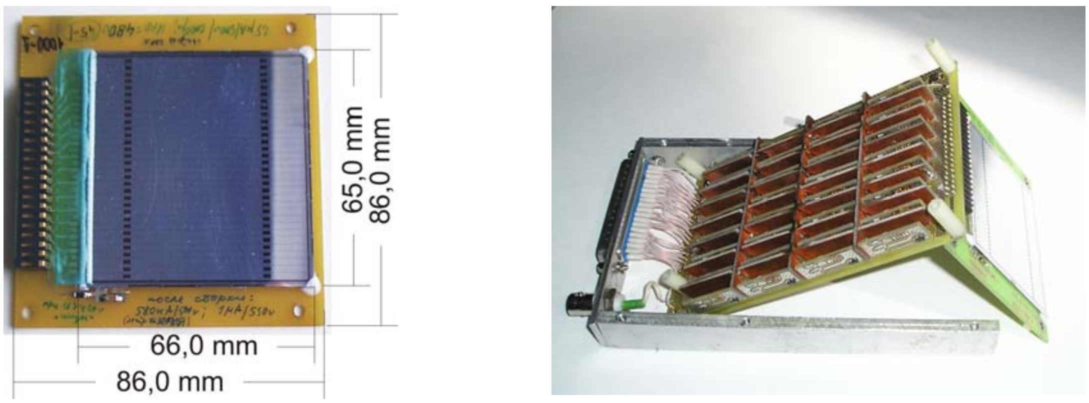
Beam	^{18}O (5 eμA)	^{22}Ne (5 eμA)
Energy, (A MeV)	35.0	40.0
Nucleus ($\tau_{1/2}$, s)	Intensity, s^{-1}	Intensity, s^{-1}
^{12}Be (0,024)	$1{,}5 \cdot 10^5$	
^{14}Be (0,004)	$3 \cdot 10^2$	
^{13}B (0,017)	$1 \cdot 10^6$	$1 \cdot 10^6$
^{14}B (0,014)	$2{,}5 \cdot 10^5$	$5 \cdot 10^5$
^{15}B (0,01)	$1{,}5 \cdot 10^5$	$5 \cdot 10^4$
^{17}B(0,005)		$4 \cdot 10^2$
^{15}C (2,45)	$5 \cdot 10^6$	$2 \cdot 10^6$
^{16}C (0,747)	$1 \cdot 10^7$	$5 \cdot 10^5$

In forward-angle measurements the basic ion-optical parameters of fragment-separator COMBAS and momentum distributions of radioactive ^{6}He, ^{8}He and ^{9}Li nuclei have been studied using the reaction ^{11}B (33 AMeV) + ^{9}Be (332,6 mg/cm^2) [6]. It was found that the image of these beams in the final achromatic focus F_a approximately twice exceeds the size of the beam on a producing target (input focus F_0), on which primary beam had the diameter 6 mm. With intensity of a primary beam ^{11}B in 1 pμA (1 pμA = 5 eμA) the following beam intensities are received: $6.9 \cdot 10^5$ p/s for ^6He, $2 \cdot 10^4$ p/s for ^8He and $4.7 \cdot 10^5$ p/s for ^9Li. Table 2 shows measured COMBAS parameters [6] in comparison with working separator ACCULINA.

Table 2. **Radioactive beam intensities and profile at F_a point**

Beam	COMBAS		ACCULINA	
	Intensity, s^{-1} (per 1 pμA)	FWHM at F_a (X × Y, mm × mm)	Intensity, s^{-1} (per 1 pμA)	FWHM at F_a (X × Y, mm × mm)
^8He	$2 \cdot 10^4$	13 × 10	$5 \cdot 10^3$	18 × 15
^6He	$6.9 \cdot 10^5$	17 × 11	$1 \cdot 10^5$	18 × 15
^9Li	$4.3 \cdot 10^5$	26 × 11	$1 \cdot 10^5$	18 × 15

The registration system consists of two telescopes of Si(ΔE_1)-Si(ΔE_2)-CsI detectors (Fig. 3) and multichannel electronic module, which ensures amplitude analysis and time coincidences of reaction products. Silicon ΔE_1 and ΔE_2 detectors (each containing 32 strips) are designed to determine X, Y-coordinates of registered particles and identify their charge and mass.



a *в*

Fig. 3. ΔE silicon strip-detector (32 strips) (*a*). Strip-detector with preamplifiers (*b*).

Resonance decay spectroscopy

The cluster structure of resonances of exotic light nuclei will be studied in the reactions

$$p + T \rightarrow k + R \rightarrow k + i + j\,, \qquad (1)$$

where the secondary radioactive nuclei produced by fragment-separator COMBAS will be used as a projectile particles.

The resonance cluster decay $R \rightarrow i + j$ (Fig. 4) in reactions (1) will be identified using the following correlation methods:

i) coincidence measurements of angles and energies of accompanying particle *k* and one of decay products (*i* or *j*) ("missing mass spectra");

ii) coincidence measurements of angles and energies of both decay products (*i* or *j*) ("method of invariant mass"). This method, proposed by Robson [7] and named as "resonance decay spectroscopy" [8], has been effectively used for the study of different reactions like (1) (see, for example [8 - 11]).

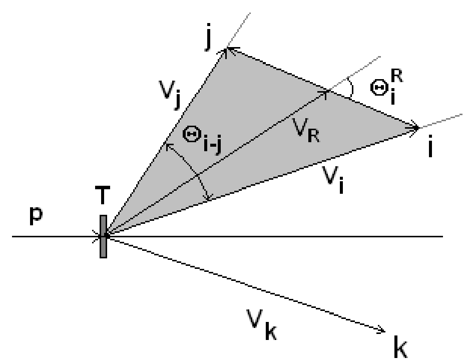


Fig. 4. Velocity diagram for the reaction (1) with three particles in the final state.

The second method provides a simple way to determine the relative energy E_{i-j} of decay products and, consequently, the excitation energy (E_x) of resonance under investigation:

$$E_x = E_{i-j} + E_{thr}\,, \qquad (2)$$

$$E_{i-j} = \frac{m_i E_j + m_j E_i - 2\sqrt{m_i m_j E_i E_j}\cos\Theta_{i-j}}{m_i + m_j}, \qquad (3)$$

where E_{thr} is the threshold of decay into the channel $i + j$ and m_i, m_j, E_i, E_j, Θ_i, Θ_j are the masses, energies and registration angles of particles i and j, $\Theta_{i-j} = \Theta_i - \Theta_j$.

According to Eqs. (2) and (3) the excitation energy resolution is determined only by the accuracy of measurement of the energies E_i, E_j and the relative angle Θ_{i-j}, but not of the absolute values of angles Θ_i and Θ_j. Therefore, precision measurement of excitation energy is possible with poor quality beams, size of which at the target and energy spread is large. This is an important advantage for the experiments with the secondary beams. Moreover, the method of resonance decay spectroscopy can also be used for the reactions with more than three particles in the final states [9, 10].

Conclusions

The use of separator COMBAS, time-of-flight methods, multi-channel system of registration of reaction products and correlation methods of resonance decay identification will allow to get the new precise data on the resonance parameters for exotic light nuclei in the wide energy range (from threshold energies up to excitation energies of dozens MeV). This investigation is planned to begin with boron neutron-rich isotopes, whose cluster structure can be essentially changed with growth of neutron number [2, 3].

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УСТАНОВКА ДЛЯ РЕЗОНАНСНОЇ СПЕКТРОСКОПІЇ РАДІОАКТИВНИХ ЛЕГКИХ ЯДЕР

А. Г. Артюх, А. Г. Фощан, О. Д. Григоренко, С. О. Клигін, Г. О. Кононенко, Є. І. Кощій, В. Є. Ковтун, В. В. Осташко, Ю. М. Павленко, А. М. Пономаренко, Ю. М. Середа, О. І. Рундель, І. М. Вишневський, А. М. Воронцов, І. І. Залюбовський

Для досліджень екзотичних легких ядер розроблено експериментальну установку на основі часопрольотного фрагмент-сепаратора КОМБАС та багатоканальної системи реєстрації. Прецизійний кореляційний метод буде використано для спектроскопії розпаду резонансів.

Ключові слова: вторинні радіоактивні пучки, екзотичні легкі ядра, фрагмент-сепаратор, часопрольотні вимірювання, кореляційні вимірювання, спектроскопія резонансів.

УСТАНОВКА ДЛЯ РЕЗОНАНСНОЙ СПЕКТРОСКОПИИ РАДИОАКТИВНЫХ ЛЕГКИХ ЯДЕР

А. Г. Артюх, А. Г. Фощан, О. Д. Григоренко, С. А. Клыгин, Г. А. Кононенко, Е. И. Кощий, В. Е. Ковтун, В. В. Осташко, Ю. Н. Павленко, А. Н. Пономаренко, Ю. М. Середа, О. И. Рундель, И. Н. Вишневский, А. Н. Воронцов, И. И. Залюбовский

Для исследований экзотических легких ядер разработана экспериментальная установка на основе время-пролетного фрагмент-сепаратора КОМБАС и многоканальной системы регистрации. Прецизионный корреляционный метод будет использован для спектроскопии распада резонансов.

Ключевые слова: вторичные радиоактивные пучки, экзотические легкие ядра, фрагмент-сепаратор, времяпролетные измерения, корреляционные измерения, спектроскопия резонансов.

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