# STUDY OF ALPHA-CLUSTER STATES IN $N \neq Z$ NUCLEI USING THE TTIK APPROACH*

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The study resonant scattering, the Thick Target Inverse Kinematics method was developed at the Heavy Ion Accelerator DC-60, Astana, Kazakhstan. In this paper, we report on the results of studies of $^{20,21}$Ne nuclei.

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## 1. Introduction

Interest in clustering phenomena in atomic nuclei, especially in light nuclei, has grown steadily over the last few decades. This can be attributed to the realization of the important role that those cluster degrees of freedom play in nuclear structure. In addition, the dramatic influence of clustering phenomena on the astrophysical important reaction rates adds urgency to the goal of achieving a better understanding of clustering in nuclei. Significant theoretical progress has been achieved in this field. It is no longer necessary to introduce clusters as *a priori*, instead clustering emerges naturally as a result of various microscopic calculations [1–5]. Qualitatively, all theoretical approaches are in agreement that clustering is an important ingredient in understanding of nuclear structure. The challenge is to achieve a quantitative understanding, which is not possible without detailed experimental information on nuclear clusters.

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The alpha clustering is an important concept in nuclear physics, and it has been used over the years to explain certain features in nuclei, especially in light $N = Z$ nuclei. Now, the interest is shifted to $N \neq Z$ nuclei. The properties of many cluster levels in $N = Z$ nuclei do not give us information on nucleon widths due to high nucleon decay thresholds in comparison with the thresholds for the $\alpha$ decay. It is different in $N \neq Z$ nuclei where the nucleon and $\alpha$-particle thresholds are close to each other, like in $^{17}$O, $^{18}$O, $^{21}$Ne, and $^{22}$Ne. In recent years, clustering phenomena in $N \neq Z$ nuclei became much more accessible due to the development of experimental techniques.

Recent developments of rare beams provided novel studies of resonant reactions induced by radioactive nuclei [6]. The Thick Target Inverse Kinematics (TTIK) approach [7] is the perfect tool for rare-beam experiments and searching alpha-cluster states at low energies.

In this paper, we will present details of our application of the TTIK method in a combination with the time-of-flight measurements. We will review the spectroscopic results of the studies of the $^{16}$O and $^{17}$O interactions with helium-4 [8, 9] and the nuclear structure of the populated states, important for astrophysics and for understanding exotic nuclear structure.

## 2. Thick Target Inverse Kinematic approach and Time-of-Flight method

We are studying resonant reactions using the TTIK method at DC-60 cyclotron [10] in Astana, Kazakhstan. Figure 1 presents a scheme of the setup of the TTIK method. The heavy ions enter the scattering chamber through a thin entrance window. We used titanium or havar foils of a 2.0–2.5 $\mu$m thickness as material for the entrance window to isolate a gas-filled scattering chamber and an ion guide. The scattering chamber is filled up

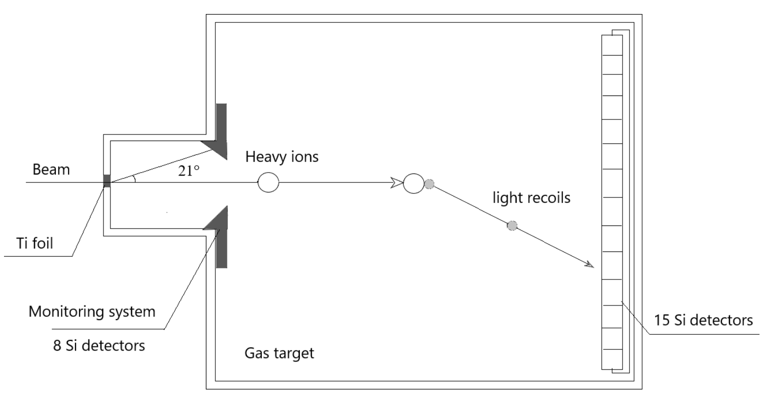


Fig. 1. Scheme of the TTIK approach.

with a high-purity gas of helium-4 or hydrogen. This gas works as a target and as a degrader for a beam. The light recoils emerge from the nuclear interaction of beam ions and nuclei of the gas, and are detected by an array of Si detectors placed in the forward hemisphere of the scattering process. The energy of the beam is slowing down in the gas target due to ionization and, therefore, one can observe continuum excitation functions for resonance reactions from the highest energies of the beam to small energies when the Rutherford scattering dominates.

The TTIK approach excludes usual measurements of a beam intensity using a Faraday cap. To monitor beam intensity, we place eight silicon detectors close to the entrance window. These detectors monitor the elastic scattering of the beam on the window foil. Additionally, the monitor detectors are used to control the time structure of the beam in the process of beam tuning. We implemented the TTIK approach with the Time-of-Flight (TOF) method for particle identification in the gas target. The "common start" regime works in the TOF method: the start signal comes from silicon detectors and the stop-RF signal of the cyclotron. This combination allows us to have the best possible resolution of the TTIK for "naked" Si detectors (without using d$E$–$E$-like telescopes). Figure 2 presents the $E$–$T$ spectrum for integration $^{16}$O with helium-4 at 0° in laboratory frame (180° in c.m.s.). The most intensive line corresponds to alpha particles from the elastic scattering $^{16}$O($\alpha$,$\alpha$)$^{16}$O, and a weaker line below is protons from the $^{16}$O interaction with an admixture of hydrogen in the gas target. The separation of alpha particles from protons is easy.

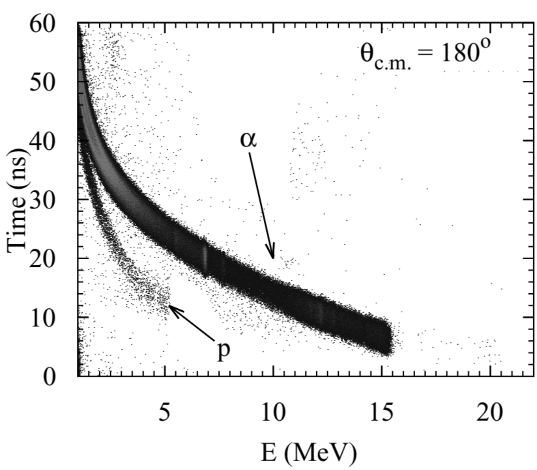


Fig. 2. $E$–TOF spectrum for the products of the interaction of $^{16}$O with helium-4.

## 3. Data analysis

The TTIK approach might bring new results even for well-studied nuclei like in $^{20}$Ne. We used a multilevel multichannel R-matrix code [11] to analysis data of the excitation functions for the $^{16}O(\alpha,\alpha)^{16}O$ elastic scattering. The R-matrix approach was made exclusively for an analysis of the TTIK data to fit the measured excitation functions. The calculated curves were convoluted with the experimental energy resolution. In our analysis [8], we have indicated all strong $\alpha$-cluster states up to 6 MeV; the investigated energy region can influence the R-matrix fit. We found a clear indication for the presence of low-spin states, $0^+$ and $2^+$ at 4 MeV. A single level $2^+$ cannot produce a strong peak at different angles. The present analysis resulted in two practically degenerate states at $\sim$ 8.8 MeV with the same width. Our results for the broad $2^+$ are rather close to the adopted values. However, if this level is moved to 9.0 MeV excitation energy (as in Ref. [12]), then the fit becomes worse, especially in the vicinity of the dip due to the presence of another $2^+$ level at 9.48 MeV. The fit becomes even worse if a very broad $2^+$ level that follows from the parameters of Ref. [13] is considered. Figure 3 shows the best R-matrix fit of the excitation functions of $^{16}O(\alpha,\alpha)^{16}O$ [8] at 180 degrees in the center-of-mass system.

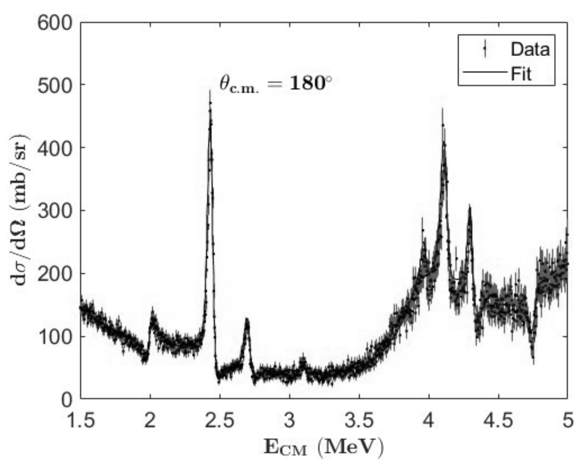


Fig. 3. Excitation function for the $^{16}O(\alpha,\alpha)^{16}O$ elastic scattering. The bold (black) line is the R-matrix fit.

The advantages of TTIK methods [8, 14] enable us to study interactions of rare isotopes with helium-4, which is limited in the classical approach. The first study of resonances in the $^{17}O+\alpha$ elastic scattering was performed in inverse kinematics at the Astana DC-60 cyclotron. The measurements were done at different angles including 180 degrees in the center-of-mass frame.

The same R-matrix approach was used for the data analysis. We found many alpha cluster states in the $^{21}$Ne excitation region of 9–13 MeV [9] including the first observation of a broad $\ell = 0$ state in an odd–even nucleus, which is likely the analog of the broad $0^+$ at 8 MeV in $^{20}$Ne. The observed structure in $^{21}$Ne appeared to be strikingly similar to that populated in the resonant $^{16}$O+$\alpha$ scattering in $^{20}$Ne. We also included the neutron decay to the first excited state, $2^+$, in $^{20}$Ne at 1.63 MeV, because this decay of high-spin states in $^{21}$Ne might proceed with a lower orbital momentum. Figure 4 presents the 180° excitation function for the $^{17}$O($\alpha$,$\alpha$)$^{17}$O elastic scattering.

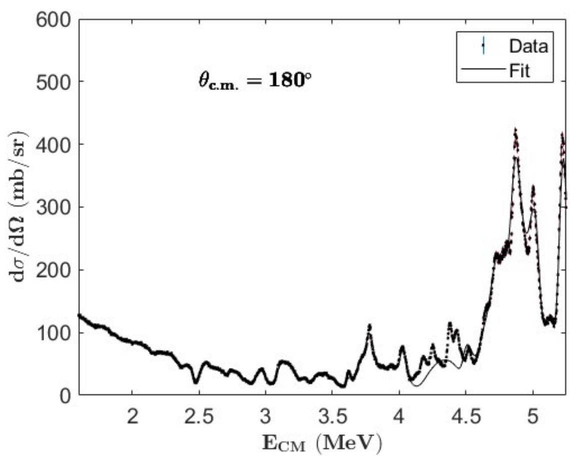


Fig. 4. Excitation function for the $^{17}$O($\alpha$,$\alpha$)$^{17}$O elastic scattering. The thick (black) line is the R-matrix fit.

We have observed the influence of a new and broad $\ell = 0$ level at 3.70 MeV. This resonance manifests itself by a decrease of the cross section in the broad center-of-mass energy region of 2.5–3.5 MeV through the Coulomb nuclear interference. All other resonances, of a different orbital momentum, would not produce the right interference with the Rutherford scattering and would not be broad enough. The broad $\alpha$-cluster states corresponding to a higher nod of the wave function strongly support the $\alpha$-cluster model, which is based on the concept of an $\alpha$-cluster moving in an $\alpha$-core potential. The $\alpha$-core potential generates states corresponding to the same cluster wave function with a higher number of nodes [15]. A classic example is $^{20}$Ne with the ground-state rotational band, a band based on 6.7 MeV, $0^+$ level and a broad $0^+$, 8.7 MeV level [8, 16]. This level is broad because it is 3.97 MeV above the $\alpha$-particle decay threshold in $^{20}$Ne and has a large reduced $\alpha$-particle width. The 3.70 MeV resonance in $^{21}$Ne with the reduced width of 0.24 looks like a twin to the broad level in $^{20}$Ne [9]. A search for such states is difficult because they are weakly excited (the orbital momentum equals zero) and broad [15]. Their presence can easily be attributed to some continuous background. The observation of the 3.70 MeV resonance was possible due to our use of TTIK, which provides measurements of a broad region of the excitation function in a single run. The first observation of this level in odd–even nuclei (together with known states in $^{12}$C, $^{18}$O [15], and $^{20}$Ne [8, 12]) indicates that such states can be found in many light nuclei.

## 4. Conclusion

We performed measurements of the excitation function for the $^{16}$O($\alpha$,$\alpha$)$^{16}$O and $^{17}$O($\alpha$,$\alpha$)$^{17}$O reactions using the TTIK method. The R-matrix analysis of the data established new properties of states in $^{20}$Ne and $^{21}$Ne nucleus. These new data became possible due to the TTIK approach. We believe that the simplicity and high efficiency of the TTIK approach will result in various applications such as neutron and $\gamma$ rays detection in the extended target.

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