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α-cluster resonances in light nuclei

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Abstract. Thick target inverse kinematics technique was combined with Time of Flight method to study resonance reactions induced by heavy ions at low energy, to minimize background and to identify various possible nuclear processes in extended target. The ^{17}O, ^{20}Ne spectrum, the cluster and nucleon spectroscopic factors were calculated using cluster-nucleon configuration interaction model.

1 Introduction

The phenomenon of alpha clusterization is well known in light 4N nuclei (^{8}Be, ^{12}C, ^{16}O...). In particular, it remarkably manifests itself as twin bands of an alternate parity with large reduced α particle widths. Because of the importance of this phenomenon in nuclear structure and due to large abundance of helium in the Universe, the properties of α-cluster states are also an important factor for the understanding of nuclear processes in stars. The astrophysical important reactions proceed often trough the states which are very close to the α particle decay threshold or even through subthreshold states. The small cross sections for corresponding energies well below the Coulomb barrier cannot be measured in laboratories. To calculate these cross sections one needs to know the "interaction" of the cluster states with the states around because strong α-cluster states can provide α width to the states that are closer to the region of astrophysical interest through configuration mixing [1]. The problems of a description of α-cluster states using models based on the shell model conception are well discussed (see [2] and references there). Twenty years ago C. Spitalery just began to develop the ideas of the Trojan Horse Method (THM). He also actively investigated new experimental approaches to study nuclear structure; these appeared as a result of the technological developments in the acceleration of rare beams.

New insight in the problem of the relationship between the single particle and cluster degrees of freedom can be obtained through the experimental studies of the α-cluster states in N≠Z nuclei. In N≠Z nuclei, the nucleon decay threshold is usually below that for α particle (opposite to the 4N nuclei case), and the penetrability factors do not inhibit the nucleon decay from the states in question. Therefore, data on the decay properties of the α-cluster states in N≠Z nuclei might give insight in the relation between the single particle and cluster degrees of freedom. Moreover, the properties of the

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alpha cluster states in proton and neutron-rich nuclei can be compared using the isospin conservation in the reaction with mirror nuclei. However, any investigation of resonance interaction of a radioactive nucleus with helium seemed very difficult. Indeed, radioactive nuclei cannot be used as a target, and rare beams cannot be used to study a broad energy region with good energy resolution using small controlled changes of the energy as it was in conventional measurements. The first work to study alpha cluster states in N≠Z nuclei using ^{18}Ne rare beam (and a comparison with the ^{18}O data) was made using a novel Thick Target Inverse Kinematics (TTIK) method [3] in collaboration with Prof. Spitaleri's group [4]. It showed exciting and unexpected differences in the excitation functions of mirror reactions ^{18}O(α,α) and ^{18}Ne(α,α). This work is considered as a breakthrough in the new field.

In this report we discuss some details of the experimental work on resonance scattering at DC-60 cyclotron in Astana, Kazakhstan and the results of a comparison of the prediction cluster-nucleon configuration interaction model (CNCIM) [5] with the experimental data.

2 Experimental method and results

The DC-60 cyclotron [6] accelerates heavy ions up to the 1.9 MeV/A energy. The TTIK technique [3] is used in the measurements. The incoming ions are slowed down and stopped in a helium (or hydrogen) gas of the extended target. The light recoils, α particles and protons produced in a scattering event are detected. They hit a Si detector array located in forward hemisphere. Together with the amplitude signal, the Si detectors provided for a fast signal. This signal together with a "start" signal from RF of the cyclotron was used for the Time-of-Flight measurements. The combined E-TF

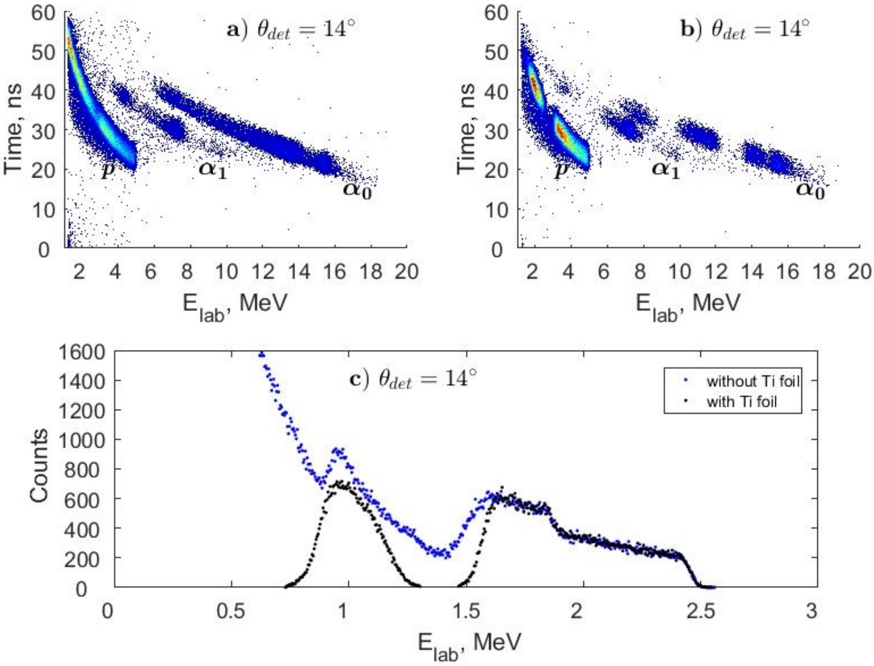

Figure 1. E-TF spectra of protons and α particles from the interaction of ^{15}N with hydrogen (a) without and (b) with the foil in the gas, and (c) energy spectra of protons from the ^{15}N(p,p) reaction.

measurements enable us to minimize the background and to separate elastic and inelastic scattering [7]. The TTIK approach provides for a continuous excitation function as a result of the slowing down of the beam. The best energy resolution of the method is reached at zero degrees (180° c.m.), and it is typically 25 keV c.m.

More details of the experimental technique are given in Ref.[7]. There is still a source of an uncertainty in TTIK measurements especially when resonance data are practically absent (the α+^{17}O case); it is beam energy loss in the gas at low energy [8]. To address this issue we developed a simple device to place a thin (2 um) Ti foil at different distances from the entrance window. The foil can be placed along the beam path or taken away during the experiment without cycling vacuum.

Fig.1.a,b demonstrates Energy vs Time (E-T) spectra for p, α_0 and α_1 events corresponding to ^{15}N(p,p), ^{15}N(p,α)^{12}C$_{g.s.}$ and ^{15}N(p,α)^{12}C* reactions without and with the foil on the path of the ^{15}N beam in hydrogen gas target. Fig.1.c represents a projection of the p, events on to E axis. A rapid change of the yield when the beam crosses the foil (Fig.1.b) enables us to check the energy loss of heavy ions in the gas. As a result, the 5.81 MeV energy loss of ^{15}N in hydrogen can be obtained with a precision of 120 keV, and the time when the beam reaches the foil can be obtained with precision of 0.45 ns. An analysis of the obtained results showed that the calculations [9] satisfactory fit the observations (see more details elsewhere).

Fig.2. shows a comparison of our data with the ^{17}O(p,p) results of Ref.[10]. As seen in Fig.2, our approach to the evaluation of the energy loss of heavy ions in the hydrogen gas results is in good agreement with the energy calibration obtained in the classical measurements. The cross section differences are probably related to the angular dependence of the cross sections.

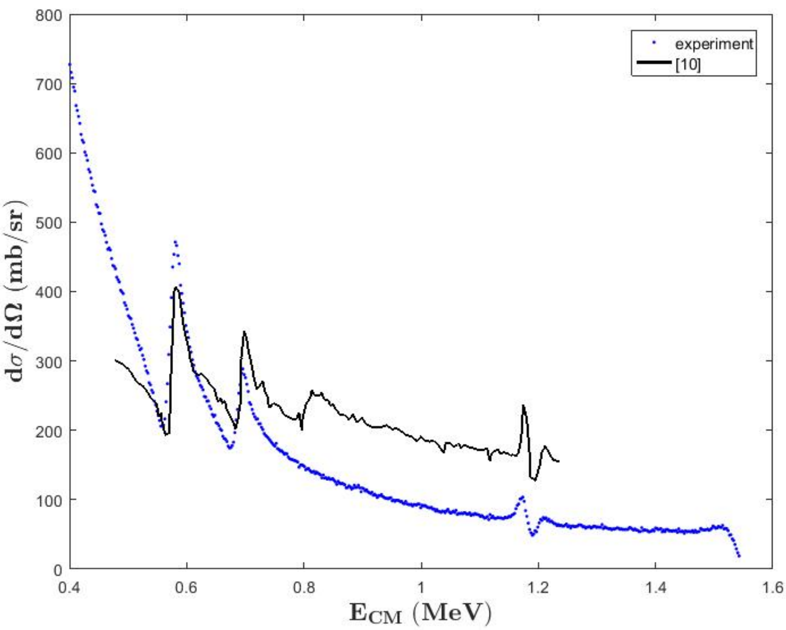

Figure 2. The ^{17}O(p,p) elastic scattering excitation function: the blue line is our experimental data at 180° c.m. and black line is data of Ref. [10] at 161° c.m.

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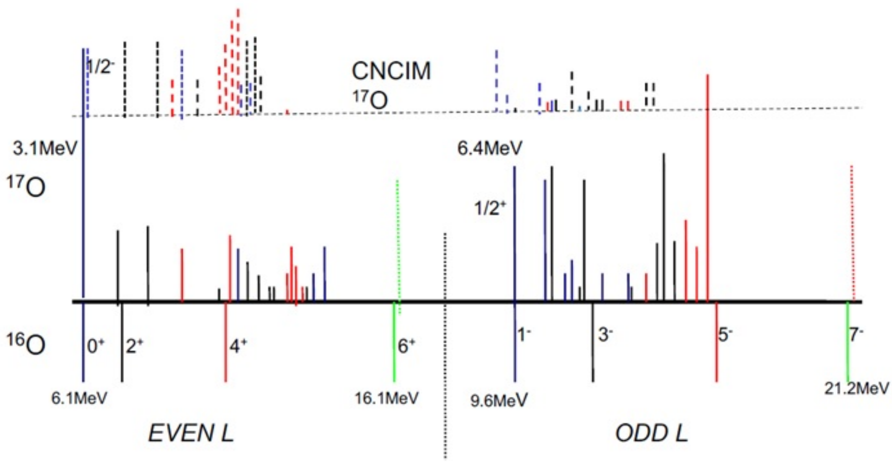

Figure 3. α-cluster structure in ^{17}O, comparison with predictions of CNCIM model.

The experimental elastic scattering excitation functions were analyzed using multilevel multichannel R matrix code [11]. We have obtained data on alpha and nucleon widths of the resonances. Below we report results on the alpha particle decay properties of the nuclear states. While it was found that all strong α-cluster states have nucleon widths, these will be analyzed elsewhere. Fig.3 shows the α-cluster Spectroscopic Factors (SF) for the ^{17}O states obtained as a result of the excitation functions analysis [12] in comparison with the predictions CNCIM model. The length of the sticks is proportional to the value of SF.

We characterize the α-cluster properties of the states above the α-particle decay threshold by SF $= \gamma_\alpha = \Gamma_{\alpha\,\mathrm{exp}}/\Gamma_{\alpha\,\mathrm{cal}}$, where $\Gamma_{\alpha\,\mathrm{cal}}$ is the α-particle width calculated in the α-core potential. To calibrate the potential, the SFs were first calculated for the well-known α-cluster states in ^{16}O. The Woods-Saxon potential was used to calculate the limit ($\Gamma_{\alpha\,\mathrm{cal}}$) for the width of the single-particle states. First we fit the widths of known α-cluster states, 1^- and 4^+, in ^{16}O so that $\gamma_\alpha = \Gamma_{\alpha\,\mathrm{exp}}/\Gamma_{\alpha\,\mathrm{cal}} \sim 1.0$. The real part of the potential was changed to fit the binding energy of the states. The radius of the potential was chosen to be $R = r_0 \times 12^{1/3}$; the Coulomb potential was taken into account as a charge sphere potential with $R_{Coul} = R$. We made our first calculations (1) with $r_0 = 1.31$ fm and the diffuseness $a = 0.65$ fm, then we set $r_0 = 1.23$ fm (2), and we finally performed a third set of calculations (3) with $r_0 = 1.23$ fm and $a = 0.6$ fm. The results are summarized in Table I. The γ_α calculations for the states in investigated nuclei (^{17}O and ^{20}Ne) are made with the final (third) set of parameters, because these parameters provide for a better description of the widths of the known ^{16}O α-cluster states.

As it seen in Fig.3, the α-cluster strength is distributed over many states in ^{17}O, quite different from the ^{16}O case (one could expect that the number of states in ^{17}O would be just two times higher

Table 1. α + ^{12}C levels in ^{16}O

^{16}O level	$\Gamma_{\alpha\,\mathrm{exp}}$ keV [13]	$\gamma_\alpha(1)$; -V_0 MeV	$\gamma_\alpha(2)$; -V_0 MeV	$\gamma_\alpha(3)$; -V_0 MeV
1^-, 9.58 MeV	420 ± 20	0.70; 138.2	0.72; 150.0	0.84; 158.5
4^+, 10.36 MeV	26 ± 3	0.68; 125.3	0.88; 139,6	1.21; 143.2

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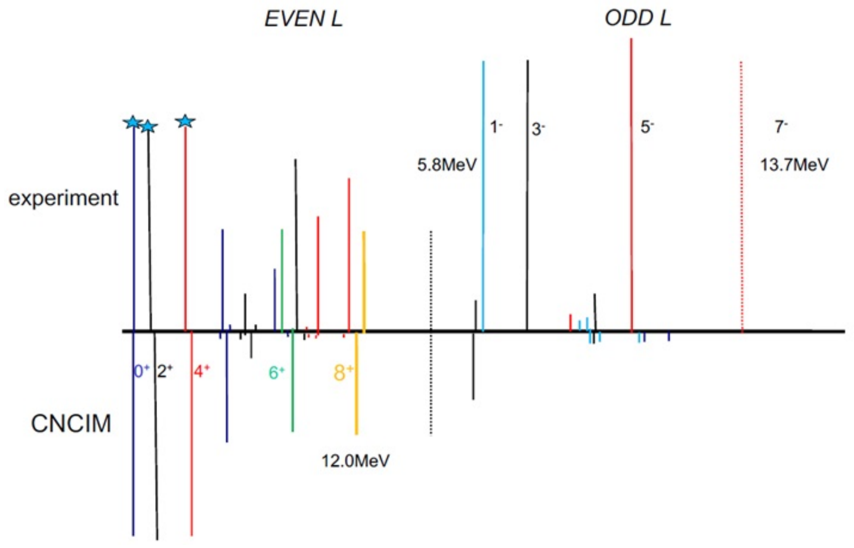

Figure 4. α-cluster structure in ^{20}Ne, comparison with predictions of CNCIM model.

than in ^{16}O). The comparison with CNCIM calculations shows that the theoretical model is able to generate strong α-cluster SF which are close to the known values for the strong states. It is true at relatively small excitation energy. At higher excitation energy, there is evident disagreement which cannot be corrected by inclusion of *f2p* shells.

Fig.4 shows a spectrum of the α-cluster states in ^{20}Ne in comparison with the prediction of the CNCIM model. The model describes well the properties of the famous α-cluster ground state band up to 8^+ level (experimental SFs for the states below the α particle decay threshold in ^{20}Ne obtained from the α-cluster transfer reactions). However, the model generates SF which are too small for the positive parity states with a larger number of nods of the cluster wave functions [14]. Similar drastic disagreement is evident for the levels belonging to the cluster band of negative parity.

3 Summary

1. TTIK approach greatly improves the possibilities to study resonance interaction of rare isotopes with helium and hydrogen at low energies.

2. A new development of shell model, CNCIM model, succeeded in the prediction of large SF observed experimentally for strong α-cluster states in light nuclei. An evident achievement of the model is a detailed description of the ground state band in ^{20}Ne. However, the model predictions for the states at higher excitation energy are in evident disagreement with the experimental data. The reasons of this disagreement are not evident.

3. We hope that the analysis of these widths will help to understand relationship between two degrees of freedom. There is a CNCIM characterization of ^{20}Ne at low energies by 7 MeV excitation energy allowing to predict reasonably well the excitation energy of the states and their cluster and single-particle properties. The disagreement between theoretically predicted and experimentally spectra is observed at broad resonances of high energies.

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References

[1] M.L.Avila, G.V.Rogachev, V.Z.Goldberg, E.D.Johnson, K.W.Kemper, Yu.M.Tchuvil'sky, A.S.Volya Phys.Rev. C **90**, 024327 (2014)

[2] B. A. Brown and W. A. Richter, Physical Review C **74**,34315 (2006).

[3] K. Artemov, O.P. Belyanin, A.L. Vetoshkin, R. Wolski, M.S. Golovkov, V.Z. Goldberg, M. Madeja, V.V. Pankratov, I.N. Serikov, V.A. Timofeev, Sov. J. Nucl. Phys. **52**, 408 (1990)

[4] V.Z.Goldberg, G.V.Rogachev, W.H.Trzaska, J.J.Kolata, A.Andreyev, C.Angulo, M.J.G.Borge, S.Cherubini, G.Chubarian, G.Crowley, P.Van Duppen, M.Gorska, M.Gulino, M.Huyse, P.Jesinger, K.-M.Kallman, M.Lattuada, T.Lonnroth, M.Mutterer, R.Raabe, S.Romano, M.V.Rozhkov, B.B.Skorodumov, C.Spitaleri, O.Tengblad, A.TuminoPhys.Rev. C **69**, 024602 (2004)

[5] A. Volya and Y. M. Tchuvil'sky, Physical Review C **91**, 44319 (2015)

[6] B. Gikal, S. Dmitriev, P. Apel et al., Physics of Particles and Nuclei Letters 5(7) (2008) **642**

[7] A. K. Nurmukhanbetova, V. Z. Goldberg, D. K. Nauruzbayev, G. V. Rogachev, M. S. Golovkov, N. A. Mynbayev, S. Artemov, A. Karakhodjaev, K. Kuterbekov, A. Rakhymzhanov, Z. Berdibek, I. Ivanov, A. Tikhonov, V. I. Zherebchevsky, S. Y. Torilov, and R. E. Tribble, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **847**, 125 (2017).

[8] Helmut Paul. Nuclear Stopping Power and It's on the determination of electronic stopping Power. AIP Conf. Proc. **1525**, 309 (2013);

[9] J. F. Ziegler and J. P. Biersack, in Treatise on Heavy-Ion Science: Volume 6: Astrophysics, Chemistry, and Condensed Matter, edited by D. A. Bromley (Springer US, Boston, MA, 1985), pp. 93–129.

[10] J. C. Sens, F. Rietsch, A. Pape, and R. Armbruster, Nuclear Physics A **199**, 232 (1973).

[11] E. D. Johnson. The Cluster Structure of Oxygen Isotopes. The Florida State University, 2008.

[12] N.A.Mynbayev, A.K.Nurmukhanbetova, V.Z.Goldberg, M.S.Golovkov, G.V.Rogachev, V.N.Dzyubin, M.V.Koloberdin, I.A.Ivanov, R.E.Tribble J.Exper.Theo.Phys. **119**, 663 (2014); Zh.Eksp.Teor.Fiz. **146**, 754 (2014)

[13] D. R. Tilley, C. M. Cheves, J. H. Kelley, S. Raman, and H. R. Weller, Nuclear Physics A **636**, 249 (1998).

[14] D. K. Nauruzbayev, V. Z. Goldberg, A. K. Nurmukhanbetova, M. S. Golovkov, A. Volya, G. V. Rogachev, and R. E. Tribble, Physical Review C **96**, 14322 (2017).