The cluster and single-particle states in ^{13}C $(\alpha,\alpha)^{13}$C reactions

The cluster and single -particle states in ^{13}C (α,α)^{13}C reactions

N A Mynbayev[1], A K Nurmukhanbetova[1], V Z Goldberg[2], G V Rogachev[2], M S Golovkov[3], M Koloberdin[4], I Ivanov[4], D K Nauruzbayev[1], Sh S Berdibek[1], A M Rakhymzhanov[1] and R E Tribble[2]

[1]National laboratory Astana, 53 Kabanbay batyr Ave, 010000, AstanaKazakhstan;
[2] Cyclotron Institute Texas A&M University, 3366 TAMU, College station, TX 77843-3366, USA;
[3] Joint Institute for Nuclear Research, Joliot-Curie 6, 141980 Dubna, Moscow region, Russia
[4] L.N. Gumylov Eurasian National Institute, 2 Satpayev Str, 010000, Astana, Kazakhstan.

E-mail: anurmukhanbetova@nu.edu.kz

Abstract. The excitation functions of elastic scattering of ^{13}C on alpha particle have been measured using the thick-target inverse kinematic method at the heavy ion DC-60 cyclotron. The helium gas was used as a target and also as a degrader to stop the beam. New data (including 180°degree) of the resonances close to the threshold in ^{17}O have been obtained.

1. Introduction

Many α- cluster states in light nuclei are an important issue for nuclear astrophysics and for understanding quasimolecular structure in atomic nuclei. Alpha clustering may generally play a role in helium burning in astrophysical systems. Indeed, even if astrophysical reactions involving helium do not proceed through strong *α*-cluster states (because of high excitation energy), these states can provide an alpha width to the states that are closer to the region of astrophysical interest [1]. *α*-cluster structure in nuclei are usually studied by investigation of self-conjugate *4N* nuclei [2]. Many theoretical calculations [3, 4] have suggested that clustering remains in systems composed of a collection of *α* particles and valence nucleons. There is very little information on *α*-cluster states in neutron rich nuclei [5-9], but it gives indications for the developed cluster structures with very large moments of inertia. The study of non-self-conjugate nuclei has an advantage in that one can investigate isobaric analogue states in mirror systems. Comparison of the results for mirror systems can bring new spectroscopic information and shed light on such properties as the radii of the cluster states.

The non-self-conjugate nucleus ^{17}O produced by $^{13}C(\alpha,n)^{16}O$ is important as the main source of neutrons for the s-process at low energies[10]. Two factors determine the efficiency of this reaction: the abundance of ^{13}C and the rate of the ^{13}C (α,n)^{16}O reaction (see [11], and references therein). Because of the very small reaction cross section below 300 keV, the rate of the $^{13}C(\alpha,n)^{16}O$ reaction at temperatures of ~10^8 K is uncertain [12].

There are several measurements [13] of low energy resonances in the α+^{13}C elastic scattering using a target with ~50% enrichment of ^{13}C. The data were obtained only at four angles, and the analysis was mainly qualitative. The difficulties of the studies of the elastic scattering of α particles on light nuclei at large angles using conventional geometry of the classical experimental approach are understandable. By using this approach, M. Heil with his colleagues obtained more complete experimental data of ^{13}C (α,n) ^{16}O reaction [14].

We measured the elastic scattering of ^{13}C on alpha particle by the thick target inverse kinematics (TTIK) method [15]. The advantage of the TTIK method is that an excitation function can be measured in a large interval using "single" beam energy. It provides also a possibility to make measurements at zero degrees (180º cms) where the resonance cross section is the largest and the potential one is minimal. It is important that the TTIK method provides for an easier access to the low energy of interaction because of the kinematic increase of the energy of light recoils.

2. Experimental procedure and results

The cyclotron DC-60 in Astana was used to study ^{13}C (α, α)^{13}C reaction with ^{13}C beam energy of 1.75MeV/A. The energy of the ^{13}C ions in the scattering chamber is 16 MeV due to the energy loss in entrance window. The setup and procedure for this experiment is described in [16]. The obtained results of excitation function of ^{13}C+ α elastic scattering at 180^0 in center of mass frame is shown in Figure 1.

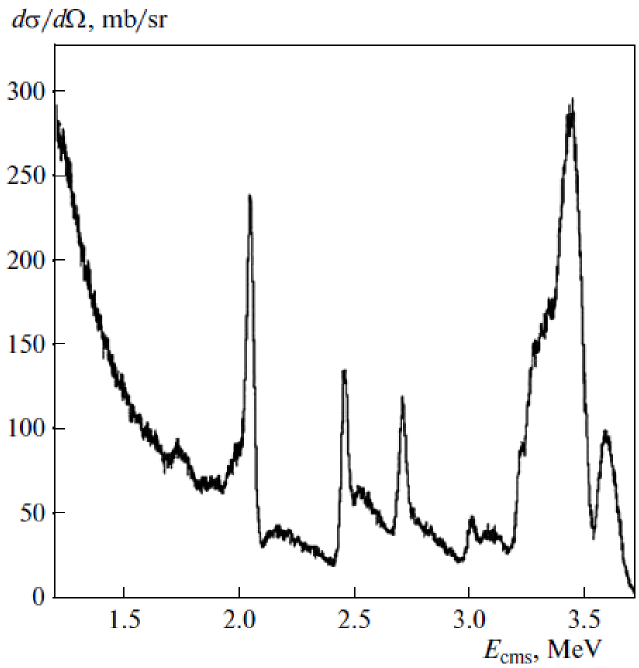

Figure 1. The excitation functions of the elastic scattering of α particles on ^{13}C.

All features of ^{13}C+ α spectrum obtained by M. Heil et. al. [14] can be seen in figure 1. α cluster states with a large spin at 2.05 and 3.47 MeV are clear in Figure 1 because of 180° center of mass system measurement. In addition, a certain new structure can be observed at low energies. The background contribution can be neglected [16].

The complete multilevel *R*-matrix analysis of the data is in progress. We determined the spin-parity, excitation energies and partial widths for 36 excited states in ^{17}O. The complete excitation function for 180^o in center of mass frame for the entire energy range measured in this experiment is shown in Figure 2.

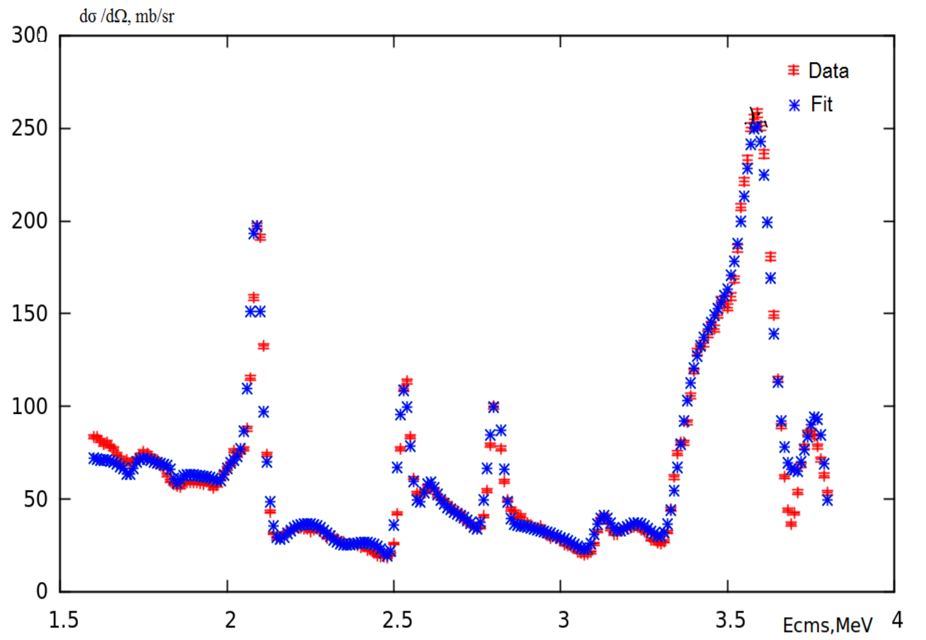

Figure 2. The excitation function for $\alpha+^{13}C$ elastic scattering at 180^0 in center of mass frame.

Figure 2 shows a good agreement between the fitted and experimental data. The parameters of some strong peaks, such as energy in center of mass system, its alpha width, spin, parity and the percentage of the Wigner limit for the alpha particle width of the level, are presented in Table 1. There are levels with the widths as large as 37 % for 9/2 and 47% for 7/2 and these data show that alpha clusterization is important for N not equal Z nuclei. This knowledge could be important to evaluate probabilities of astrophysical reactions induced by alpha particles at low energies. We expect that the complete R-matrix analysis of these data will give information interesting for studies in astrophysics and physics of clusters in atomic nuclei.

Table 1. The parameters of strong peaks in the fits

E_{cms}	Γ_α (keV)	J^π	Percentage of Wigner limit,%
2.081	4	$\frac{7^+}{2}$	37.31
2.532	3.2	$\frac{9^-}{2}$	61.12
2.828	4	$\frac{5^+}{2}$	4.67
3.137	18	$\frac{5^-}{2}$	3.08
3.611	32	$\frac{7^+}{2}$	9.77

3. Conclusion

The use of the TTIK method enabled us to perform an experiment to study of ^{13}C (α, α)^{13}C reaction at 180° in the center of mass system and at low energy. The new structure below 2 MeV was obtained which was not observed before. Some parameters of strong peaks obtained by R-matrix fit are tabulated, but the complete analysis of experimental data will be given in the future.

4. Acknowledgments
The authors are grateful for financial support from 055 budget program of the Ministry of Education grants and from the US Department of Energy (grant no. DOE FG02 93ER40773)

5. References
[1] Tang X D, Rehm K E, Ahmad I, Brune C R, Champagne A, Greene J P, Hecht A A, Henderson D, Janssens R V, Jiang C L, Jisonna L, Kahl D, Moore E F, Notani M, Pardo R C, Patel N, Paul M, Savard G, Schiffer J P, Segel R E, Sinha S, Shumard B and Wuosmaa A H 2007 *Phys. Rev. Lett.* **99** 052502
[2] Freer M 2007 *Rep. Prog. Phys* **70** 2149
[3] Itagaki N and Okabe S. 2001 *Phys. Rev.* C **64** 014301
[4] Von Oertzen W 1997 *Z. Phys* A **357** 355
[5] Freer M, Casarejos E, Achouri L, Angulo C, Ashwood N I, Curtis N, Demaret P, Harlin C, Laurent B, Milin M, Orr N A, Price D, Raabe R, Soić N and Ziman V A 2006 *Phys. Rev. Lett*. **96** 042501
[6] Korsheninnikov A A., Nikolskii E Yu., Kobayashi T, Aleksandrov D V, Fujimaki M, Kumagai H,
[7] Ogloblin A A, Ozawa A, Tanihata I, Watanabe Y, Yoshida K et al 1995 Phys. Lett. B 343 53
Goldberg V. Z., Rogachev G. V., Trzaska W H., Kolata J J., Andreyev A, Angulo C, Borge M J G., Cherubini S, Chubarian G, Crowley G, Van Duppen P, Gorska M, Gulino M, Huyse M, Jesinger P, Källman K M , Lattuada M , Lönnroth T, Mutterer M, Raabe R, Romano S, Rozhkov M V, Skorodumov B B, Spitaleri C, Tengblad O, Tumino A 2004 *Phys. Rev.* C **69** 024602
[8] Buchmann L 2007 *Phys. Rev.* C **75** 012804
[9] Johnson E, Rogachev G V, Goldberg V Z, Brown S, Robson D, Crisp A M, Cottle P D, Fu C, Giles J, Green B W, Kemper K. W, Lee K, Roeder B T, Tribble R E 2009 *Eur.Phys.J.* A **42** 135
[10] Iben I 1975 *Astrophys. J*. **196** 525
[11] Goriely S and Siess L 2001 *Astron. Astrophys*. **378** L25
[12] Angulo C 1999 *Nucl. Phys.* A **656** 3
[13] Kerr G W, Morris J M and Risser J R al 1968 *Nucl. Phys.* A **110** 637
[14] Heil M, Detwiler R, Azuma R E, Couture A, Daly J, Görres J, Käppeler F, Reifarth R, Tischhauser P, Ugalde C, Wiescher 2008 *Nucl.Phys*. A **688** 499
[15] Artemov K P, Beljanin O P, Wetoshkin A L, Wolskj R, Golovkov M S, Goldberg V Z, Madeja M, Pankratov V V,Serikov I N, Timofeev V A, Shadrin VN, Szmider J A 1990 *Yad.Fiz*. **52** 634;1990 *Sov.J.Nucl.Phys*. **52**, 408
[16] Mynbayev N A, Nurmukhanbetova A K., Goldberg V Z, Golovkov M S, Rogachev G V, Dzybin V N, Tribble R E 2014 *JETP* Vol. **119** 4 663–667