EPJ Web of Conferences **117**, 07013 (2016) DOI: 10.1051/epjconf/201611707013
NN2015

Study of ^{12}C excited states decaying into three α particles using the thick target inverse kinematic technique

M. Barbui[1], K. Hagel[1], J. Gauthier[1], S. Wuenschel[1], R. T. deSouza[2], S. Hudan[2], D. Fang[3], V.Z. Goldberg[1], H. Zheng[1], G. Giuliani[1], G. Rapisarda[1], E-J. Kim[1], X. Liu[1,4] and J.B. Natowitz[1]

[1] Cyclotron Institute, Texas A&M University, College Station, TX, USA
[2] Indiana University, Bloomington, IN, USA
[3] Shanghai Institute of Applied Physics (SINAP), Chinese Academy of Sciences, Shanghai, China
[4] Institute of modern physics, Chinese Academy of Sciences, Lanzhou, China

Abstract

We will show that the Thick Target Inverse Kinematics (TTIK) technique can be used to investigate the breakup of excited self-conjugate nuclei into many alpha particles. Two test runs were performed at Cyclotron Institute of Texas A&M University to study the reaction ^{20}Ne+α at maximum beam energies of 10 and 12 AMeV. Due to the limited statistics, only events with alpha multiplicity up to three were analyzed. The analysis of the three α-particle emission data allowed the identification of the Hoyle state and other ^{12}C excited states decaying into three alpha particles. The results will be shown and compared with other data available in the literature.

Searching for alpha cluster states analogous to the ^{12}C Hoyle state in heavier alpha-conjugate nuclei can provide tests of the existence of alpha condensates in nuclear matter. Such states are predicted for ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si etc. at excitation energies slightly above the multi-α particle

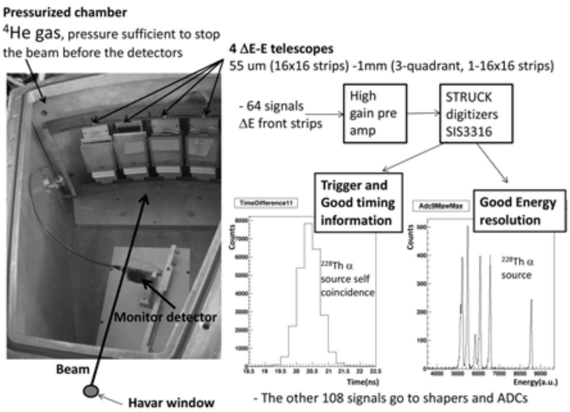

Figure 1: Experimental setup and scheme of the electronics. Good energy and time resolution are obtained by using the STRUCK digitizers SIS3316

decay threshold [1-3]. The Thick Target Inverse Kinematics (TTIK) [4] technique can be successfully used to study the breakup of excited self-conjugate nuclei into many alpha particles. This technique is suited for this purpose because it allows the exploration of a large range of incident energies in the same experiment. In inverse kinematics, the reaction products are focused at forward angles and can be detected with detectors covering a relatively small portion of the solid angle in the forward direction. Since we stop the beam in the gas target volume we can detect the particles emitted at zero degrees. A first test run was performed at Cyclotron Institute at Texas A&M University to study the reaction ^{20}Ne+α. A ^{20}Ne beam at 11 AMeV was provided by the TAMU K150 Cyclotron. After the Havar entrance window the energy of the beam was 10 AMeV. The pressure of the ^{4}He gas was 3800 mbar, sufficient to stop the beam before reaching the detectors. Here the TTIK method was used to study both single α-particle emission and multiple α-particle decays. Due to the limited statistics, only events with alpha multiplicity up to three were analyzed. A description of the experimental setup used in this run and the results regarding the events with α multiplicity 1 and 2 are reported in ref [5]. The analysis of the three α-particle emission data allowed the identification of the Hoyle state and other ^{12}C excited states decaying into three alpha particles. These results will be presented in the following.

We recently improved the experimental setup increasing the solid angle coverage and the detector granularity. Figure 1 shows a picture of the new detector arrangement and some details. Four DeltaE-E telescopes placed at

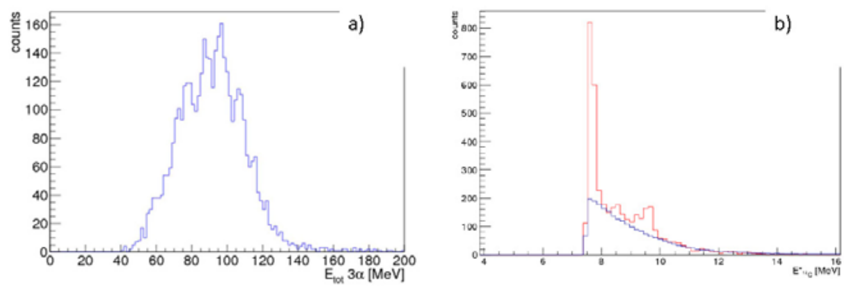

Figure 2: Panel a): Sum of the energy of the 3 alpha particles. Panel b): Excitation energy of ^{12}C. The red line shows the total events the blue line shows the uncorrelated events obtained by mixing α particles from random events

the end of the pressurized chamber are used to detect the reaction products. The signals from the front strips of the DeltaE detectors are processed by high gain pre-amplifiers from Indiana University and digitized using Struck SIS1366 Flash ADCs. Those digitizers provide the energy and time information relative to the cyclotron radio frequency. As before the particle identification is obtained from the two dimensional scatter plots Time-Energy and DeltaE-E. The new setup was tested on December 2014 using a ^{20}Ne beam at 13 AMeV provided by the TAMU K150 Cyclotron on ^{4}He gas at a pressure of 4964 mbar. The overall statistics collected during this test run was 1/3 of that collected in the previous run. However the results are consistent with those obtained in the first test run.
The analysis of the events with α multiplicity three was carried out in two steps. First we analyzed the events where three alpha particles were detected in the central telescope; second we improved the statistics considering the events where two alpha particles were detected in the central telescope and the third could be elsewhere. In both cases we selected the events where the 3 α particles arrived to the detectors within a time window of 15 ns.

Fig. 2-a shows the sum of the energies of the three alpha particles detected in the central telescope. This spectrum is obtained from the measured energies without any assumption or energy loss correction. It is interesting to note that the total energy spectrum shows a series of peaks. Since the detected alpha particles are correlated in time and position we can reasonably assume that they are coming from an excited ^{12}C decaying into three α-particles. If we assume that an excited state in ^{24}Mg decayed into two ^{12}C, one in the ground state, the other with enough excitation energy to split in three α-particles, we can use a recursive procedure to reconstruct

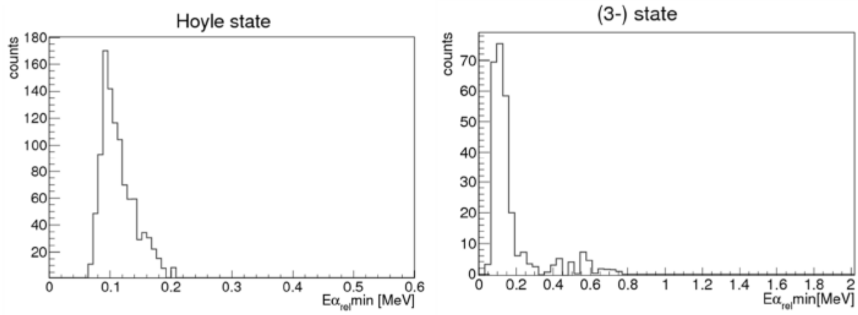

Figure 3: Left panel: minimum relative energy of two alpha particles for the Hoyle state. Right panel: minimum relative energy of two alpha particles for the (3-) state.

the position of the interaction point, based the reaction kinematics and the energy and momentum conservation. The excitation energy of the ^{12}C splitting into three α-particles is obtained from the sum of the kinetic energies of the three α-particles in the center of mass of the ^{12}C and the Q value. It is important to note that the error on the determination of the ^{12}C excitation energy due to an incorrect determination of the interaction point is minimal. In fact, the three detected α-particles have similar and quite large energy in the laboratory system and travel similar flight-paths so that energy loss correction almost cancels out when we calculate ^{12}C excitation energy. The ^{12}C excitation function is shown in Fig. 2-b, together with the spectrum of the uncorrelated events obtained by randomly mixing three alpha particle energies from different events. The spectrum in Fig. 2-b shows two peaks, one at 7.65 MeV, corresponding to the energy of the Hoyle state, and one at 9.64 MeV, corresponding to a (3-) state. In order to determine if the ^{12}C decay is proceeding through the ground state of ^{8}Be we calculated event by event the relative energy of the three possible couples of alpha particles. The minimum of these relative energies is plotted in Fig.3 for the Hoyle state and the (3-) state. In both cases this relative energy peaks around 92 keV, showing that the decay proceeded through the ^{8}Be ground state.

To improve the statistics and allow the detection of higher excitation energy states we extended the event selection to those events with two alpha particles in the central telescope and the third elsewhere. Fig. 4 shows the three alpha particles correlation function obtained in this way.

Compared to Fig.2-b, Fig. 4 shows peaks at larger excitation energies such as 11.8 MeV and 12.7 MeV. Those states correspond to known (2-) and (1+) states in ^{12}C. The small spurious peak at 8.6 MeV can be explained

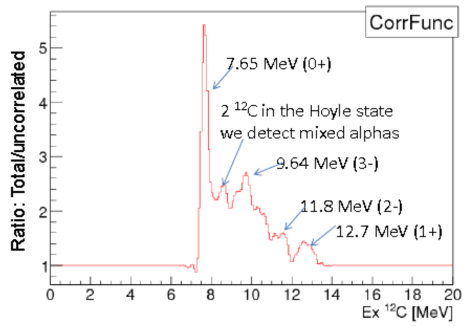

Figure 4: Correlation function obtained form the ratio of the measured spectrum and the uncorrelated events spectrum. The events with two α-particles in the central telescope and the third everywhere are selected

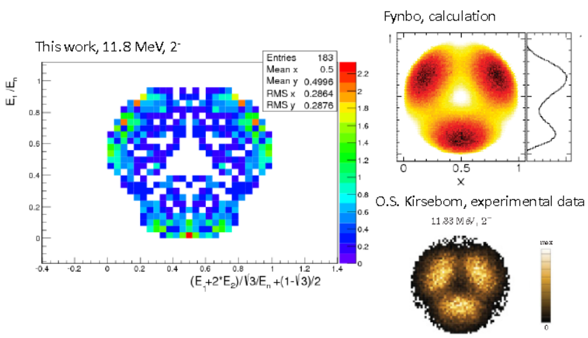

Figure 5: Dalitz plot for the 2^- state at 11.8 MeV compared with other experimental data and calculation

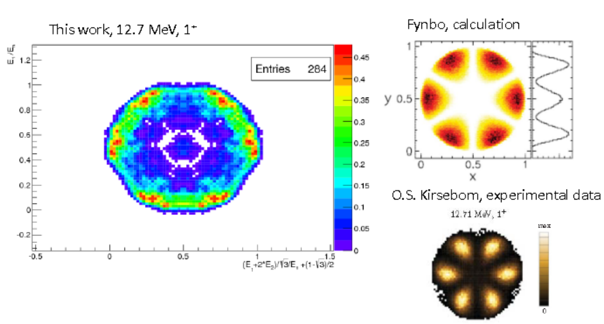

Figure 6: Dalitz plot for the 1^+ state at 12.7 MeV compared with other experimental data and calculation

using a Monte Carlo simulation. It is due to the mixing of alpha particles coming from two ^{12}C nuclei in the Hoyle state. The events corresponding to the Hoyle state, (3-), (2-) and (1+) states were analyzed in more details. The relative energies of the three possible couples of alpha particle energies were calculated event by event, in order to determine if the decay proceeds through the ground state of ^{8}Be or not. The Hoyle state and the (3-) were found to decay through the ground state of ^{8}Be, while the (2-) and (1+) states, were not. Dalitz plots were produced for each state and compared with other available experimental data and calculations [6,7]. Fig.5 and Fig.6 show the results for the (2-) and (1+) states respectively. Even though the statistics is quite low the results are in agreement with other data available in the literature. In conclusion we have shown that it is possible to use the TTIK technique to study excited states of ^{12}C decaying into 3 α-particles, including the Hoyle state. In the future we plan to use the same method and the improved detector system shown in Fig.1 to look for a state analogous to the Hoyle state in ^{16}O. Calculations suggest a candidate 0^+ state at excitation energy of 15.1 MeV.

This work was supported by US DOE and Robert A. Welch Foundation Grant A0330.

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