Studying the Hoyle state with β-delayed particle-decays using TexAT

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Following the commissioning run for TexAT (a general purpose active-target time projection chamber (TPC)) [1] the possibility to investigate nuclear structure using new techniques became possible. Of particular interest in the overlapping areas of nuclear structure (in terms of α-clustering phenomena) and nuclear astrophysics (via the triple-α process) is the Hoyle state, a 0^+ state in ^{12}C situated above the 3α threshold with an excitation energy of 7.654 MeV. This state has a structure widely understood to correspond to 3 α-particles but the geometrical and physical interpretation of such a conclusion is still yet to be fully understood [2]. The Hoyle state is placed at a sufficient energy in ^{12}C such that it enhances the triple-α reaction rate by 7 orders of magnitude, allowing for the synthesis of ^{12}C and heavier elements, bypassing the A=5, 8 bottleneck in nucleosynthesis [3]. An experiment was performed using TexAT which had two objectives. Firstly, demonstrating the possibility of reconstructing the Hoyle state as it decays in 3 α-particles in TexAT at low pressures. Secondly, perform the most sensitive measurement of the direct 3α breakup branching ratio.

The first of these objectives is important for a subsequent experiment to be performed at Ohio State in 2019 where the $^{12}C(n,n_2)$ reaction rate is to be measured. In certain stellar environments, the inverse of this reaction (de-excitation of the Hoyle state via neutron scattering), can also enhance the triple-α reaction rate by an additional factor of up to 200. By measuring this inverse reaction, models of high density, high temperature stars can accurately reflect this important reaction which can have a dramatic effect on further nucleosynthesis processes.

The second experimental objective is rooted in nuclear structure physics. The 3α structure of the Hoyle state has been suggested as a condensate of α-particles in relative s-orbitals [4]. By virtue of the (pseudo)-bosonic nature of the α-particle, this idea therefore suggests a state of nuclear matter whereby the system transitions from a fermionic to a bosonic system presenting a fantastic chance to probe the properties of the nuclear force by observing this phase transition. Experimental efforts to determine whether such a hypothesis is true have focused on measuring the branching ratio of the Hoyle state whereby, rather than decaying sequentially to the ^{8}Be(g.s) then into a final state of α-particles, the decay occurs directly without any intermediate steps yielding a final state of 3 α-particles. The energy sharing of the α-particles are different with the direct decay corresponding to a more equal sharing of energy whereas with the sequential decay, one of the α-particles always carries roughly half of the decay energy and the other particles share the remainder with a known distribution. Measuring the decay of the Hoyle state and studying this energy partition can therefore provide a sensitive probe of the direct decay and therefore elucidate on whether this α-condensate picture of the Hoyle state is correct. Recent experimental efforts have so far deduced an upper limit of 0.03% (95% C.L.) [5,6].

States in ^{12}C above the 3α-decay threshold (7.27 MeV) were therefore studied via the decay of ^{12}N. This β^+ decay has a half-life of 11.0 ms therefore must be investigated using the implantation technique rather than 'in-flight'. For this experiment, the Hoyle state is populated by ~1% of ^{12}N decays. The Hoyle state then decays itself (while at rest inside the TPC gas) into 3 α-particles which share 390 keV. This low energy therefore requires experimental care which is facilitated in this experiment by using a low pressure (20 Torr CO_2) fill gas in TexAT which gave the α-particles a long enough range that tracks can be measured. A decay-by-decay measurement can be achieved using the experimental setup shown in Fig. 1. This experiment was performed using the K500 cyclotron in September 2018 where experimental difficulties with TexAT meant only a limited amount of statistics were obtained. The

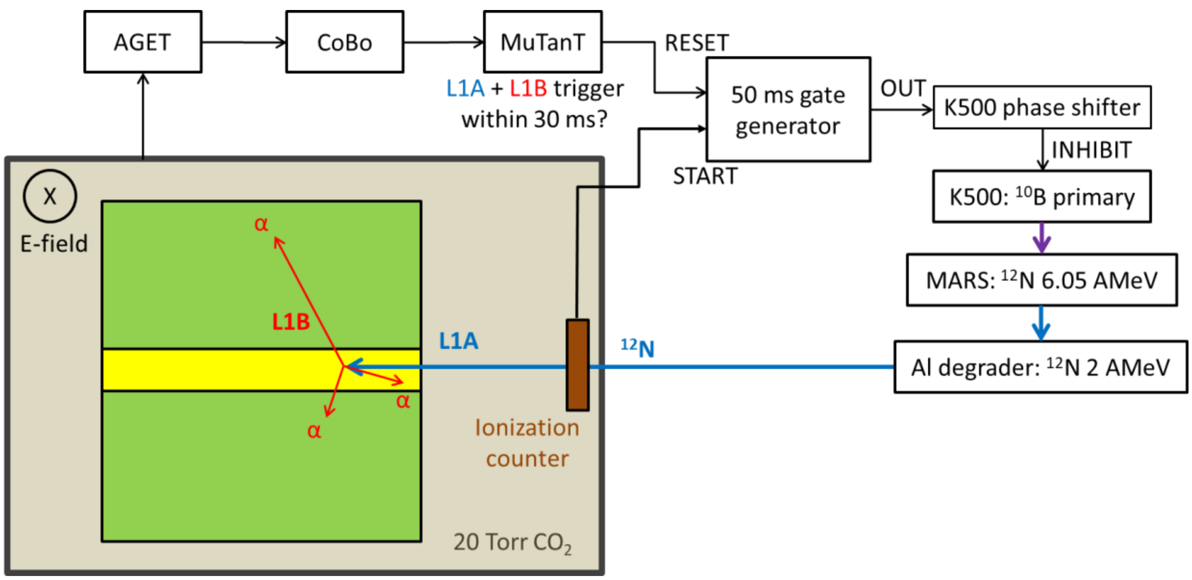

FIG. 1. TexAT layout for the ^{12}N → 3α experiment in September 2018. The gate generator, triggered by the ion counter and reset by the successful measurement of a 3 α-particle decay, feeds into the K500 cyclotron phase shifter. This allows for the beam to be stopped after an implantation has taken place. In the March 2019 experiment the gate generator was replaced by using the CoBo busy signal and half-events were read out (corresponding to L1A trigger but no L1B trigger within 30 ms).

experiment was repeated in March 2019 with 10 days of beam time. The primary beam of ^{10}B then provided a ^{12}N secondary beam via the (^{3}He,n) reaction in the gas-cell on the MARS line. The secondary beam entered the detector at around 2 AMeV with a typical production intensity of 30 pps.

The measured data were split into two different frames using the 2p-mode in the GET electronics system [7,8] with two separate triggers. The first, the L1A trigger, corresponds to the track of the ^{12}N being implanted in the TPC and stopping. From this information, the decay position of the ^{12}N can be determined as well as verification via the energy deposited along its path that the track is a ^{12}N implant rather than a beam contaminant. The second trigger, the L1B, corresponds to the 3 α-particle decay of states in ^{12}C following the β^+ decay of ^{12}N. The TPC allows for 3D tracks of the three α-particles to be reconstructed. By measuring the total energy deposited, the excitation energy can be calculated by E_x =

$E_{measured}$ + Q. Additionally, selecting tracks where the range of the α-particles correspond to that expected from the decay of the Hoyle state (with the maximum α-particle energy being 190 keV), a clean selection on Hoyle decays can be achieved, as seen in Fig. 2 for a subset of the data obtained in September 2018.

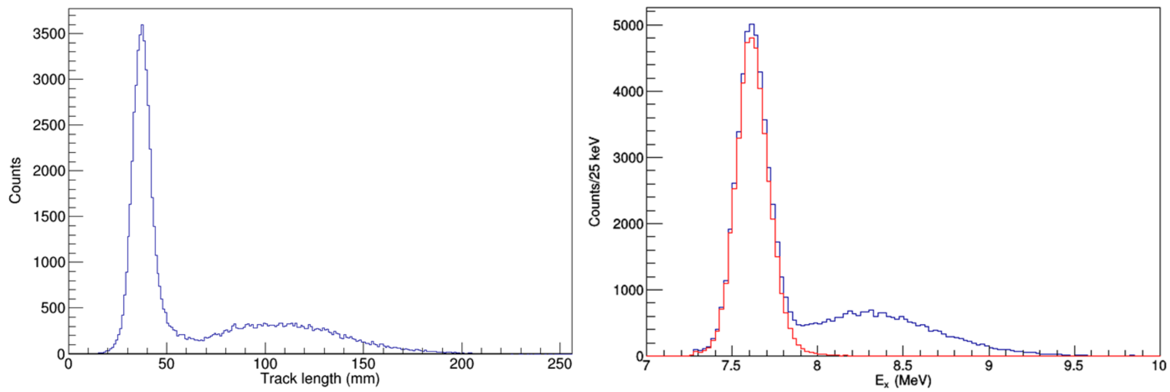

FIG. 2. Left: Length of the longest track from the measured 3 α-decay. The peak around 38 mm corresponds to the expected decay length from the Hoyle state. Right: Excitation function for 3 α-particle events following the decay of ^{12}N. The value is calculated from the total energy deposited in the TPC plus the Q-value of the decay (7.27 MeV). The red line corresponds to selecting events where the longest α-particle track is commensurate with a 190 keV energy corresponding to the decay of the Hoyle state into ^{8}Be(g.s) + α.

The first experimental objective, to demonstrate the ability to reconstruct 3 α-particles in TexAT has been completed and this experiment has allowed the analysis code to be well developed for the ^{12}C(n,n_2) experiment as well as a consideration of the necessitudes of further improvements to TexAT. The second experimental objective, to extract a direct decay branching ratio, is still on-going however with an estimated **80,000** Hoyle decays measured in an almost background-free environment, this allows for a sensitivity a factor of 40 lower than the previous experimental results which may be sufficient to measure an absolute value rather than an improved limit [9].

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