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Helium Burning in Steady State and Explosive Nucleosynthesis

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Auspices Statement

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FY08 LDRD Final Report

Helium Burning in Steady State and Explosive Nucleosynthesis

LDRD Project Tracking Code: 07-LW-006

Jason T. Burke, Principal Investigator

Abstract

For this research program we had proposed two experiments involved in the nuclear burning of helium stellar environments. The first measured the triple alpha reaction governing the production of carbon in the universe. The second measures a key cross section in the production of ^{44}Ti. The decay of ^{44}Ti is the principle observable signature at late times in supernova remnants such as Cassiopeia A.

Both measurements were successfully carried out during this LDRD project. The triple alpha reaction radiative width is in the final stages of uncertainty analysis and the manuscript is being prepared for publication. The potential impact this result will have on our understanding of stellar evolution and the difficult nature of the analysis has slowed the delivery of this paper. The ^{40}Ca(α,γ)^{44}Ti cross section has been compared to the thick target yield we have measured. We have found that the ^{40}Ca(α,γ)^{44}Ti cross section has been over estimated by approximately a factor of 1.71. The reduced cross section also directly impacts the yield of ^{44}Ti produced in supernova. We find that previous claims of 40% over production of ^{44}Ti by supernova to be incorrect.

One key result from this work has been the recognition by the scientific community that LLNL continues to play a leading role in the nuclear physics community. Secondly we have brought back the ability to perform accelerator based nuclear physics to LLNL on-site. The use of the CAMS tandem for the ^{40}Ca(α,γ)^{44}Ti experiment was the first time in approximately 15 years that a nuclear physics experiment has been performed on-site at LLNL.

The Triple Alpha Reaction

Helium burning is possibly the most important burning phase for stellar nucleosynthesis. The two main products are carbon, produced by the 3α reaction, and oxygen by $^{12}C(\alpha,\gamma)\ ^{16}O$. In concert, these two reactions affect not only their own nucleosynthesis, C and O being the 3rd and 4th most abundant elements in nature, but the future evolution of massive stars during carbon, neon, and oxygen burning. It is the only nuclear burning phase where two reactions compete so nearly equally for the consumption of a major fuel. Helium burning also produces the first neutron excess in the life of a massive star by converting ^{14}N (left over from the hydrogen burning CNO cycle) to make ^{22}Ne, which is the seed for the neutron source reaction that enables the s-process to operate in massive stars, synthesizing isotopes up to A = 88.

The triple alpha reaction is the breakout reaction is the origin for the creation of heavy elements in stars. A fortuitous resonance in ^{12}C, first proposed by Fred Hoyle is formed by $^{8}Be^{*}$ and an alpha particle allow the creation of $^{12}C^{*}$. Overwhelmingly $^{12}C^{*}$ decays by emitting an alpha particle breaking up into unstable ^{8}Be and alpha particles. Fortunately, there is a small radiative decay (approximately 4 x 10^{-4}) which allows the excited $^{12}C^{*}$ nucleus to decay to its ground state [1-5].

The radiative width can be measured directly by elastically scattering alpha particles off of the $^{12}C^{*}$ nucleus. The second excited state of $^{12}C^{*}$ (7.65MeV) is the state of interest in the triple alpha process. The radiative width is defined as the number of excited ^{12}C nuclei which decay from this state by radiating a gamma ray versus breaking up into alpha particles. The proposed experiment measures the scattered particles from the 7.65 MeV state ($J^{\pi} = 0^{+}$) as well as the small fraction of recoiling ^{12}C nuclei in coincidence. This has been done in the past with varying results to a precision of 12% [1-5]. Although no individual experiment disagrees greatly, none of them are precise enough on their own to check the result directly. We also have reason to believe a systematic error has been unaccounted for historically in the measurements.

In the past, experimenters were restricted to small angular regions of the scattered alpha particles and recoil ^{12}C because large area segmented silicon detectors, which could produce precise angle and energy information did not exist. The coincidence efficiency of the detector is measured by scattering from the $J^{\pi}=2^{+}$ 4.44 MeV state in ^{12}C and

subsequent detection of alpha particles and ^{12}C recoils. The recoil angle of the ^{12}C nuclei changes significantly, between the 7.65 MeV and 4.44 MeV state, and constitues a major source of uncertainty in the coincidence efficiency. This directly translates into the dominant uncertainty in the radiative width on the order of 10%.

We have at hand a unique detector system which eliminates both of these problems. Commercial silicon detectors can now be made with large areas and a high degree of segmentation. This allows large solid angle coverage while providing accurate angle and position information as well as particle identification. The uniqueness of the Lawrence Livermore National Laboratory STARS/LIBERACE experimental setup at the Lawrence Berkeley Laboratory 88 Inch Cyclotron is ideally suited to perform this experiment with a minimum of development time.

Results

The triple alpha experiment ran for 5 days and produced over 5 million events populated the Hoyle state at 4.44 MeV in ^{12}C, see figure 1. Assuming a radiative width of 0.0004 we expect to see 1500 coincident events. This will result in the most statistically precise measurement of the radiative width of the Hoyle state to date. The recoil detection efficiency for measuring alpha particles in coincidence with recoil ^{12}C nuclei was determined to be 58 ± 2%. This particle-recoil efficiency is an order of magnitude greater than any previous measurement to date. The last remaining work to do is to quantify the systematic uncertainties associated with the measurement. This process is well underway, however we a reluctant to quote a final value at this time until we can confirm all systematics are well understood.

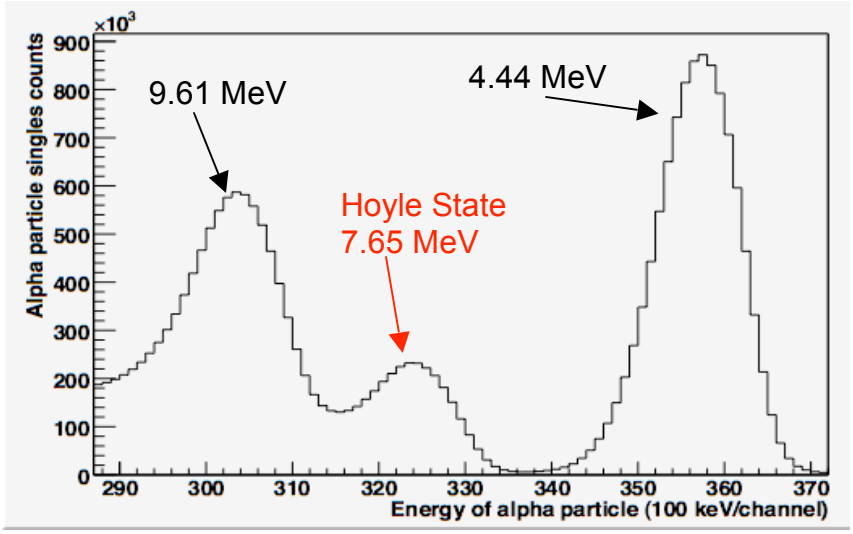

Figure 1. Particle singles events from the triple alpha experiment. Shown are the first excited state (4.44 MeV), second excited state (7.65 MeV) and third excited state (9.61 MeV).

The $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction

We have measured the $^{40}Ca(\alpha,\gamma)^{44}Ti$ cross-section which has been called for and is of great interest to the astrophysics community [6-7]. ^{44}Ti powers the late time light curves of Type II supernovae and is observable by its γ-ray emission. This serves as a probe of conditions extant prior to and during a supernovae explosion. Advances in observational astrophysics using satellite based γ-ray detectors have observed □-rays from the decay of ^{44}Ti.

The $^{40}Ca(\alpha,\gamma)^{44}Ti$ cross-section has been calculated by Woolsey [8] and also by Rauscher [9]. The cross-section has been measured recently by Nassar et. al. [10] using a novel technique in which the ^{44}Ti cross section is determined by bombarding a Helium target with a ^{40}Ca beam. The ^{44}Ti implants in a catcher foil and atomic mass spectroscopy is used to determine the amount of ^{44}Ti formed. They find an average cross section of 8.0 ± 1.1 μb which is approximately a factor of 2 greater than the calculated values of Rauscher. Previously, Cooperman had determined the cross section by examining the resonances in the $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction and they found an average cross section that was 0.5 of Woolsey's value [11].

This proposal would involve a two stage approach to determine the cross section. The experiment will consist of a prompt in-beam experiment and an activation type measurement. The prompt in beam experiment would be performed by bombarding an enriched ^{nat}CaO target with a 4.2 MeV beam of α particles from the CAMS 10 MV Tandem accelerator at a beam current of approximately 1 to 5 particle microamperes for a few days days.

We have designed and implemented our own chamber, 80% HPGe detectors and data acquisition system located at CAMS for this experiment. We determined the number of ^{44}Ti nuclei created by observing the 1083 keV transition following alpha capture. During the bombardment the beam current was integrated as part of the data stream. The cross section will be obtained by dividing the observed number of ^{44}Ti nuclei created by the integrated beam current divided by our γ-ray efficiency. We expect to obtain an average cross section with approximately a 5% uncertainty dominated by our experimental systematic uncertainties.

The second part of this cross section measurement required counting the target at a low background counting facility. This took place on-site at LLNL at the low background counting facility. It is important to note that the LLNL facility is currently the only one that can perform this measurement. During the bombardment we created approximately 10^7 atoms of ^{44}Ti. Using the half-life of ^{44}Ti is 62 ± 2 years [12] we would observe a decay rate of 0.0035 Hz. The observed γ-rays (68 keV and 78 keV) come from the decay of ^{44}Ti. The background in the region of the 68 keV and 78 keV γ-rays is 0.00146 Hz. In a 14 day run, we would observe a total of 4200 decays and approximately 700 background events under the γ-ray photopeak. A background run would be taken immediately following the measurement to perform a background subtraction. The expected average cross section should have a statistical uncertainty of approximately 3%. Having determined the number of atoms of ^{44}Ti produced we would calculate the thick target yield and use it to determine the cross section.

Comparison between the two determinations of the cross section would be performed and discrepancies looked for. This would be the first time that two methods were used simultaneously to verify the same experimental conditions for the ^{40}Ca(α,γ)^{44}Ti cross section.

Results

The $^{40}Ca(\alpha,\gamma)^{44}Ti$ experiment lasted a total of 2 days at the CAMS 10 MV tandem accelerator. The on-line γ-ray spectra clearly showed the 1083 keV line beam populated by the alpha capture reaction, see figure 2 below. The statistics of the reaction and detector efficiency allowed us to obtain sufficient statistics to run at three different beam energies (4.13, 4.54 and 5.36 MeV) instead of only one. This allowed us to make a much more precise comparison to the predicted cross section. The yield determined from this experiment is compared directly with the theoretical yield rescaled by a factor of 1/1.71, see figure 3. We produced enough ^{44}Ti only at the highest beam energy of 5.36 MeV, which was subsequently counted at the LLNL low background counting facility. The spectrum, resulting from the low background counting, is shown in figure 4. The on-line and off-line ^{44}Ti yields agree within the experimental uncertainties and are both plotted in figure 3 at 5.36 MeV.

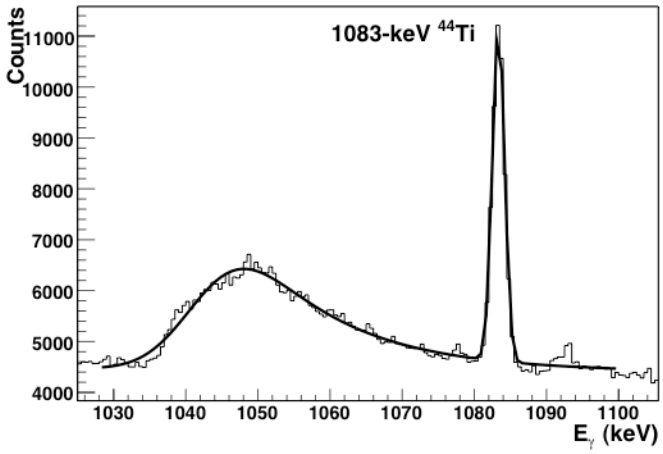

Figure 2. On-line gamma ray spectrum showing the 1083 keV gamma ray from the prompt gamma ray cascade in ^{44}Ti produced by the alpha capture reaction.

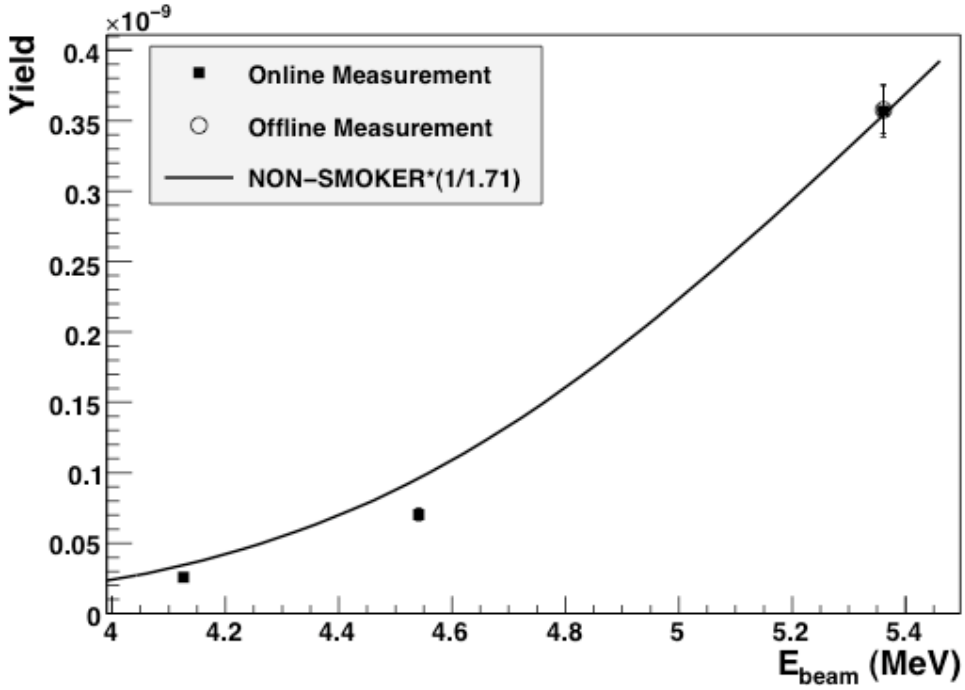

Figure 3. The yield of ^{44}Ti produced by alpha capture at three different beam energies is compared to the theoretical yield. Excellent agreement is obtained once the theoretical yield has been rescaled down by a factor of 1/1.71.

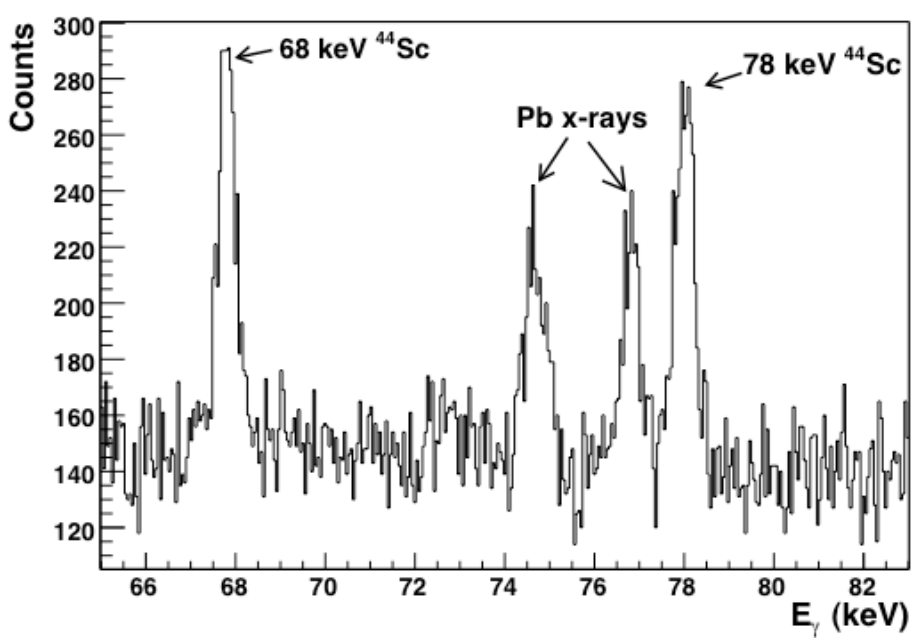

Figure 4. Results of 14 day low background count showing the 68 and 78 keV gamma rays from ^{44}Ti decay.

We have also carried out a sensitivity study for the production of radioactive ^{44}Ti using a one zone model. We assume an adiabatic expansion $\rho \propto T^3$ starting with pure ^{28}Si in an α-rich freeze out with T_9 =5.5, ρ_i = 1. × 10^7 g cm^{-3} (with the density declining on an e-folding timescale of 0.14 sec). The simulation was halted at charged-particle freeze-out (T_9=0.25) for a total freeze-out time of 1.31 s. This is identical to the study in [13] but we used a different reaction library [14].

The sensitivity of ^{44}Ti production in our α-rich freezeout simulation for five different ^{40}Ca(α,γ)^{44}Ti rates is shown in figure . The final amount of ^{44}Ti produced scales with the value of the reaction rate at T_9=2.4, where in the simulations ^{44}Ti reached half its final value. Our results suggests that reaction rates derived from the most recent experiments would over-estimate the amount of ^{44}Ti produced in this type of freeze-out. Interestingly, we agree most closely with the semi-empirical result of Rauscher [15], which takes into account the results of earlier experiments of $\alpha-$capture on self-conjugate nuclei.

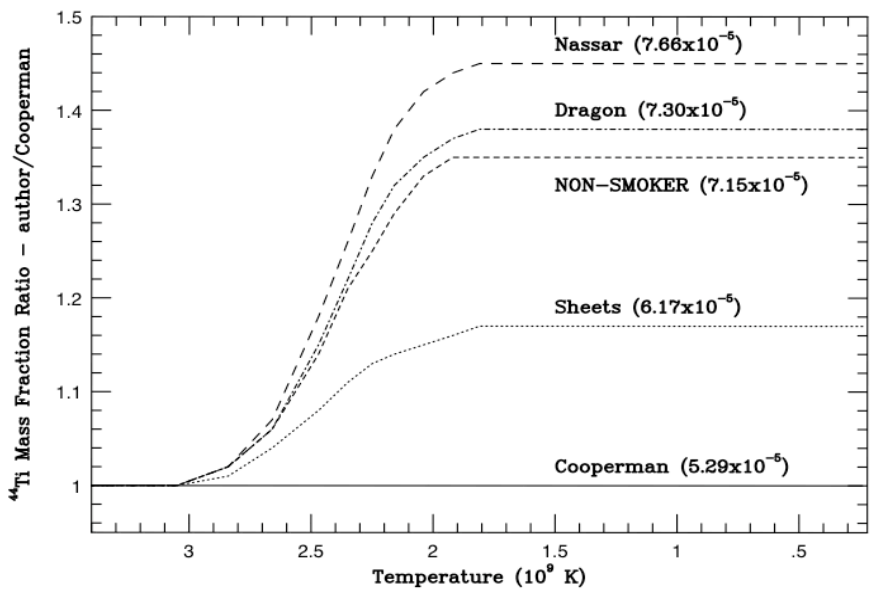

Figure 5. Results from the supernova models using old and new reaction rates for ^{40}Ca(α,γ)^{44}Ti. The result from the current work is designated by Sheets.

Exit Plan

We are currently aligning ourselves with the 100 day planning which is on-going at the laboratory. We intend to put in proposals relevant to the needs of NIF to explore low energy alpha cross sections of interest to aid in the understanding of the physics of NIF.

Summary

New capabilities for performing nuclear physics experiments have been developed through this LDRD that add to the overall capability of the LLNL. Two high impact papers are being prepared for publication. This LDRD has served to elevate LLNL in the basic scientific community and help us maintain our leadership role in performing cutting edge science and attracting top talent to LLNL.

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