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Physics with post accelerated beams: nuclear astrophysics

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Abstract

In this article, recent studies so far conducted with post accelerated beams at the ISOLDE facility in the area of nuclear astrophysics are reviewed. Two experiments in particular are highlighted, that each feature novelty and innovation. Three future experiments are also briefly presented. Collectively, these works advance our understanding of big bang nucleosynthesis, quiescent and explosive burning in novae and x-ray bursts, and core-collapse supernovae, both in terms of the underlying explosion mechanism and gamma-ray satellite observable radioisotopes.

Keywords: ISOLDE, nuclear astrophysics, post accelerated beams

(Some figures may appear in colour only in the online journal)

1. Introduction: ISOLDE—a facility for nuclear astrophysics

A scientific highlight of the second half of the 20th century was the great advance made in understanding the nuclear physics processes through which stars are born, live and die, and in doing so, how they create the elements from which we are made. As this field matures, it looks to provide detailed understanding of all the elemental abundances observed, and of the physical mechanisms that lead to the diversity and breadth of the stellar structures seen.

The vast majority of a star's life is spent in quiescent phases, where pressure from gravitational attraction is balanced by thermal pressure from exothermic nuclear reactions. By implication, the nuclear reactions occurring in these periods must involve stable or very long-lived nuclei, and kinetic energies that are well below the Coulomb barrier. However, short-lived explosive phenomena such as novae, x-ray bursters and supernovae, demonstrate there are conditions in which rapid changes occur, that must be driven by nuclear reactions involving radioactive nuclei, and much higher kinetic energies. This makes the capabilities of the REX-ISOLDE facility particularly well matched to studies of nuclear reactions of importance in explosive astrophysical environments. In recent years, two such studies have been conducted, and are reviewed below. Accepted proposals for further studies in this area are also discussed.

2. Novae and x-ray bursters

Approximately half of all stars reside in binary (or even high multiplicity) stellar systems, a consequence of angular momentum conservation in the stellar formation process. In most cases, the stars are sufficiently far apart such that they have little impact on one another, and evolve independently. However, in systems where the separation between stars is comparable to their size, as the stars evolve, the outer layers of one star can become transferred to the other, with dramatic and explosive consequences.

Consider two main-sequence stars, in close orbit, one with a mass greater than the minimum required for the red giant phase $\sim$0.3 $M_\odot$ (solar masses) and one with a mass greater than the minimum for core helium burning to occur, $\sim$0.5 $M_\odot$. The heavier star evolves most rapidly, shedding its outer hydrogen layers to leave a carbon–oxygen, or if heavier, a carbon–oxygen–neon white dwarf (assuming it is not so massive to progress beyond helium burning, about 8 $M_\odot$). The second, lighter, star then also evolves. During its hydrogen shell burning phase, the outer layers of the star expand greatly, filling its Roche lobe, resulting in transfer of hydrogen to the surface of the companion. This scenario therefore results in hydrogen being accreted to a layer of degenerate material. For a range of accretion rates, this leads to the triggering of thermonuclear flashes, and is the mechanism for classical novae, of which there are approximately 40 yr^{-1} within the Milky Way. Classical novae contribute around 10^{-3} yr^{-1} $M_\odot$ of ejecta, enriched in carbon, nitrogen, or oxygen (CNO) and sometimes other intermediate-mass elements (e.g., Ne, Na, Mg, or Al, for ONe novae) to the Galactic interstellar medium [1].

Should one of the stars in the binary be sufficiently massive for core carbon burning to occur, it may ultimately evolve into a neutron star. Hydrogen transfer on to the surface of a neutron star provides an even more extreme environment within which thermonuclear flashes may occur. The nuclear physics trigger for such explosions is the ignition of the triple-α reaction and/or breakout from the hot CNO cycles into the rapid proton capture process (rp process). Rp-processing may proceed as far along the proton drip line as the Sb and Te isotopes, and may possibly be the origin of p-nuclei such as ^{92}Mo and ^{96}Ru [2]. In both the triple-α and CNO breakout mechanisms, energy generation increases rapidly as a function of temperature, such that the rate of energy release is faster than the rate of cooling, leading to runaway. The observational signature of these events is a sudden and enormous spike in x-ray emission, lasting a few seconds, with cycles repeating on a time scale of hours to days—so called Type-I x-ray bursts[1]. These spectacular astrophysical phenomena are now being studied in detail in a number of x-ray satellite observatories, including the NASA Chandra, XMM-Newton, and NuSTAR, and ESA's Integral a. For x-ray bursts, the depth of the neutron star gravitational potential is thought to preclude ejecta being released to the interstellar medium.

[1] Rarer, type-II x-ray bursts are not thought to be nuclear-driven events, but arise due to the in-fall of matter from an accretion disk into a deep potential well.

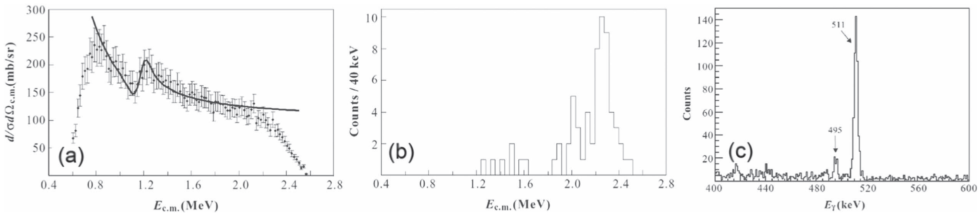

Figure 1. (a) Centre of mass energy spectrum for elastically scattered protons. The line is an *R*-matrix fit to the data, with the resonance due to a known 2^+ state in ^{18}Ne clearly visible. (b) As figure 1(a) but for protons in coincidence with 495 keV de-excitation γ rays detected in MINIBALL. (c) Energy spectrum of γ-rays measured by the MINIBALL array in coincidence with protons in the CD detector system. The marked peak indicates de-excitation from the 495 keV first excited state in ^{17}F. Reprinted figure with permission from [6], Copyright 2009 by the American Physical Society.

3. The ^{14}O(α, *p*)^{17}F reaction and its implications for explosive burning in novae and x-ray bursters

The ^{14}O$(\alpha, p)^{17}$F reaction is important both in the context of novae and x-ray bursters. In novae, in the period between bursts, energy is generated at a constant rate by the β-limited hot CNO cycles. As a consequence, novae ejecta are rich in the daughter products ^{14}N and ^{15}N. Thus for novae, knowledge of the rate of this reaction impacts estimates of key contributions to the interstellar medium. In x-ray bursts, higher temperatures bypass the waiting points, and the ^{14}O(α, *p*)^{17}F reaction may instead trigger the breakout from the hot CNO cycles via the ^{17}F(*p*, γ)^{18}Ne(α, *p*)^{21}Na sequence, and thus the reaction rate may be key to understanding the onset of the explosion.

A direct measurement of the ^{14}O(α, *p*)^{17}F reaction rate is difficult, due to the typically low cross sections at astrophysical energies and the possible beam-target combinations. However, the rate is expected to be dominated by capture to a single 1^- resonance, corresponding to a state in ^{18}Ne at 6.15 MeV [3], meaning that complete spectroscopic information for this state is likely sufficent for the astrophysical needs. Of key importance are the total and partial decay widths. Previous works using elastic scattering of ^{17}F ions on protons in inverse kinematics [4] had determined the total width of the state, which is dominated by proton emission, while the time reverse reaction, ^{17}F(*p*, α)^{14}O, was studied in inverse kinematics to obtain the first measurement of the much weaker partial α-decay width of the resonance [5]. Critically though, a limitation of this latter approach is that it cannot take into account the inelastic reaction channel corresponding to the production of the first excited state ($J^\pi = 1/2^+$, $E_x = 0.496$ MeV) in ^{17}F in the astrophysical reaction.

This final part of the picture has been provided by experiments studying the proton inelastic scattering reaction, ^{17}F(*p*, *p*′)^{17}F, at REX-ISOLDE and reported in He *et al* [6]. The experiment used fully stripped ^{17}F^{9+} ions to avoid intense isobaric contamination from ^{17}O. Around $(1.8 \pm 0.2) \times 10^{-3}$ pps were delivered with an integrated current of 8×10^8 ions on target. The beam energy, 44.2 MeV ($E_{\mathrm{c.m.}}$= 2.46 MeV), was chosen so ions entered just above the resonance energy and stopped inside a ~40 μm thick $(CH_2)_n$ target. Elastically and inelastically scattered protons were detected in a double-sided silicon strip detector (‘CD’) system [7]. The inelastic proton scattering branch from the 1^- resonance was tagged by measuring 495.33(10) keV γ-ray decays from the first excited state in ^{17}F with the MINIBALL array [8], (9.1% efficiency for 495 keV γ rays).

Figure 1(a) shows the centre of mass energy spectrum for protons detected in the CD array. The shape is characteristic of thick-target resonant proton elastic scattering, with a well known 2^+ state in ^{18}Ne clearly visible. An *R*-matrix fit to the data is shown. In figure 1(c), the MINIBALL energy spectrum of gamma rays detected within ~75 ns of protons registering in the CD array is shown. The β^+ decay of ^{17}F ions stopped in the target generates continuous annihilation radiation that may be in random coincidence with protons, leading to the most intense peak at 511 keV. The peak at 495 keV corresponds to de-excitaiton from the first excited state in ^{17}F. To identify genuine (p, p') inelastic scattering, and to remove events due to scattering of the ^{17}F beam on protons in the target, in figure 1(b) the proton centre of mass energy spectrum, gated on the 495 keV γ-decay peak, is shown. A peak is visible at an energy of 2.26(6) MeV, in agreement with the expected energy of the resonance of 2.22(1) MeV.

Guided by an *R*-matrix estimate of the angular distribution, a total angle-integrated cross section was estimated. This led to a value of 22 ± 7 keV for $\frac{\Gamma_{p0} \times \Gamma_{p'}}{\Gamma_{\rm tot}}$, where Γ_{p_0} represents the resonant elastic scattering width. In [4], a value for $\Gamma_{\rm tot}$ of 50(5) keV was obtained by an *R*-matrix fit to proton elastic scattering data. Since $\Gamma_{\rm tot} \approx \Gamma_p + \Gamma_{p'}$, the largest allowed value for $\frac{\Gamma_{p0} \times \Gamma_{p'}}{\Gamma_{\rm tot}}$ would be 12.5 keV. Given the uncertainties, the value found by He *et al* is reasonably consistent, and suggests $\Gamma_p \sim \Gamma_{p'}$, with significant uncertainty. This updated previous work by Blackmon *et al* [9] where a value for $\Gamma_{p'}/\Gamma p_0 = 2.4$ was reported. Subsequent to the experiment at ISOLDE, Bardayan *et al* [10] have reanalysed the elastic scattering data of Blackmon *et al* [9] and, incorporated results from [11], concluding the ratio $\Gamma_{p'}/\Gamma p_0$ to be reduced further to a value of 0.42. More ercently still, Hu *et al* have firmly determined the spin-parity of the 6.15 MeV state to be 1^-, and summarised the most recent resonant parameters from the literature, where the parameters from [10] were adopted. This most recent work confirms the finding from ISOLDE that that it is unlikely that the ^{14}O$(\alpha, p)^{17}$F reaction can bypass the β^+ decay of ^{14}O in the hot CNO cycles in the temperature and density conditions found in novae explosions.

4. Core-collapse supernovae

Core-collapse supernovae are remarkable astronomical events, exhibiting a combination of temperature, density and energy seen nowhere else in nature. They are likely central to the formation of many heavy elements, and are now known to be the engines behind many, if not all, gamma-ray bursts. Not surprisingly, there is immense interest in attempting to understand the physics that drives them. However, this is made extremely difficult, both by the complexity of the explosion, and the fact that the key processes are occurring deep beneath the surface. Remaining fundamental uncertainties include whether the explosion mechanism is a neutrino driven delayed detonation [12], or perhaps is mediated or assisted by gravitational effects as recently suggested [13, 14].

Stars $\gtrsim 8$ $M_\odot$ have nuclear burning phases that continue through to the production of iron and nickel in the core. With binding energy per nucleon maximised, nuclear fusion proceeds no further, and an inevitable collapse ensues. Intense nucleosynthesis occurring in the subsequent explosion produces significant amounts of radioactive nuclear material, some of which is ejected. Of particular interest is the isotope ^{44}Ti, as its decay powers the thermal emission of supernova remnants on timescales of years to centuries.

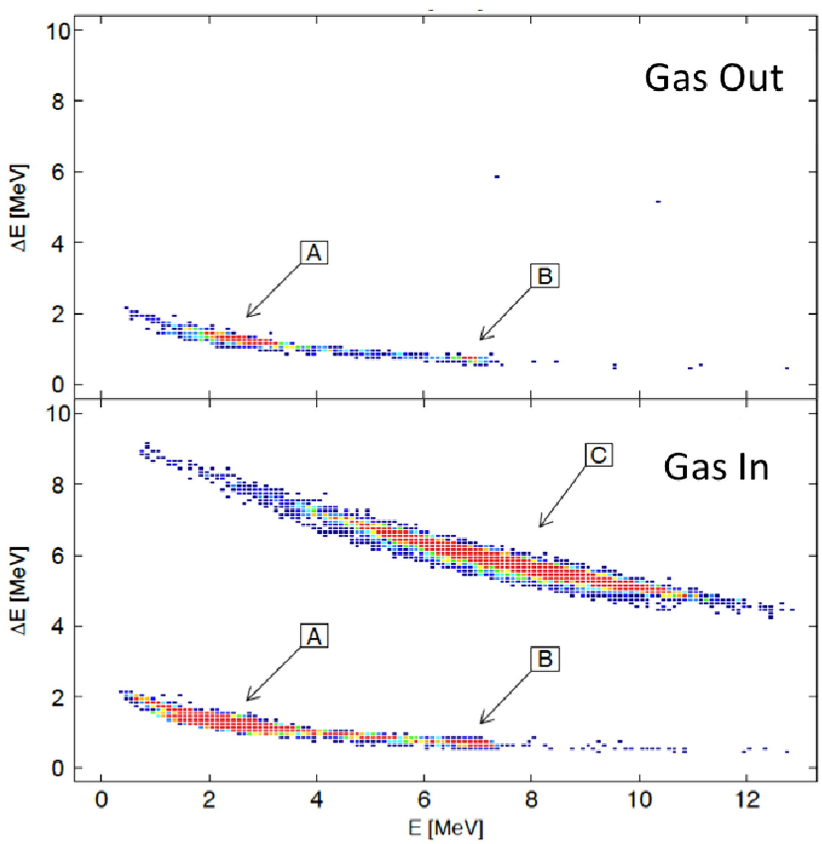

Figure 2. Plots of the energy deposited in a $\Delta E - E$ silicon detector telescope. Data in the upper panel were accrued with the gas cell open to the vacuum system, while in the lower panel the gas cell contained helium at 50 Torr. Features A and B are protons, arising from scattering of beam with hydrogen contaminants on the gas cell windows. The locus labelled C corresponds to elastic scattering of helium gas. Reprinted from [24], Copyright 2014, with permission from Elsevier.

5. The ^{44}Ti(α, p)^{47}V reaction and its implications for core collape supernovae

Recent observations of hard x-rays and γ-rays, from supernova remnants have revealed amounts of ^{44}Ti that are difficult to reproduce with present models. Since its launch in 2012, the NuSTAR satelite has deduced a yield of $1.25 \pm 0.3 \times 10^{-4}\,M_\odot$ from Cassiopeia-A [15] (and an unexpected lack of spatial correlation between ^{44}Ti and iron x-rays), and a yield of $1.5 \pm 0.3 \times 10^{-4}\,M_\odot$ in the ejecta of SN1987A [16].

The ^{44}Ti is thought to be mainly produced in a silicon layer just above the collapsing core. Two works [17, 18] have explored the sensitivity of the ^{44}Ti yield on the nuclear physics inputs, finding that the reaction to which the final ^{44}Ti abundance uncertainty is most sensitive is ^{44}Ti(α, p)^{47}V. The previous experimental constraints on this reaction come from a single study [19] that measured the cross section at four energies between 5.6 and 9 MeV in the centre of mass. A significant fraction of the produced material is beyond the mass cut, that is, it is successfully ejected. Although the location of the mass cut is sensitive to the details of the explosion mechanism, it is difficult to eject more than $1 \times 10^{-4}\,M_\odot$, even assuming a wide

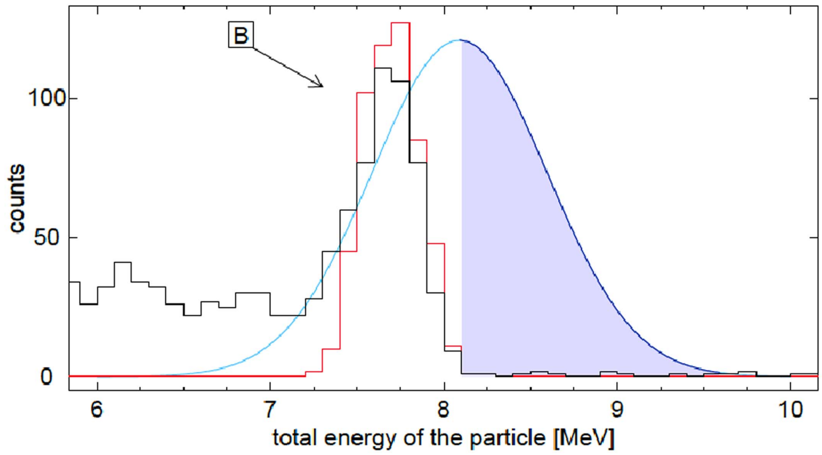

Figure 3. Data and simulation of total ($E + \Delta E$) energies of protons from gas-in data. The black line shows data. The red line shows the simulation of the scattering of ^{44}Ti beam ions with hydrogen deposits on the upstream surface of the gas cell, and reproduces the data adequately. The blue line indicates the location where protons from ^{44}Ti(α, p)^{47}V reactions would be expected to appear, for an arbitrarily large cross section. An upper limit for the cross section for this reaction was derived through a statistical analyisis of the events in the shaded region. Reprinted from [24], Copyright 2014, with permission from Elsevier.

range of progenitor models and masses [17, 20, 21]. Hence the observed amounts of ^{44}Ti ejecta present a problem for models.

To constrain the cross section at relevant energies a new direct measurement of this reaction has been conducted at REX-ISOLDE [22], with findings published by Margerin *et al* [23]. A beam of ^{44}Ti was produced in a novel way. As part of the ERAWAST initiative [24], highly irradiated components from the SINQ spallation neutron source of the Paul Sherrer Institute (PSI) were chemically separated. Around 50 MBq atoms of ^{44}Ti was obtained and dissolved in HNO_3. This sample was then dried on a molybdenum foil, and shipped from PSI to CERN. It was inserted in a standard target container in the ISOLDE Class A target laboratory, connected to a VADIS FEBIAD ion source in the VD5 configuration, and equipped with a large CF_4 gas leak to allow for the production of Ti beams as TiF_x molecular ions [25]. The unit was then installed on the GPS Front End and a TiF^{3+} molecular beam extracted. This was then dissociated during charge breeding in REX-ISOLDE before acceleration. $^{44}Ti^{13+}$ beams of around 5×10^5 to 5×10^6 pps, with no apparent isobaric contamination, and at centre of mass energies of 4.0 and 4.3 MeV, were provided for 4 days.

The beam was then incident on a 2 cm long ^{4}He-filled gas cell at a pressure of 50 Torr. Beam ions reached the target by traversing an entrance window consisting of a 12 mm diameter, 5.65 μm thick light-tight aluminium foil. Energy loss of the beam in this window meant the facility-delivered beam energy had to be significantly higher than the energy needed for the reaction being studied. An unwanted contribution from fusion-evaporation reactions of the beam and entrance window was avoided by using as thin a window as possible, thus minimising the initial beam energy. By design, beam ions were stopped in the exit foil of the gas cell, preventing direct exposure of downstream silicon detectors to beam flux, and allowing a more robust 15 μm window to be used. An additional benefit was that stopped ions became located at a well defined position, allowing a high-purity germanium detector, placed close by, to observe 1.157 MeV ^{44}Ti decay γ-rays. Counting of these allows an independent measurement of the integrated beam on target to be made.

Protons and alpha particles emanating from the gas cell were detected downstream in segmented silicon detectors [26] in a telescope configuration, allowing E–ΔE particle identification. All heavier ions were stopped in the exit window. Figure 2 shows a comparison of ΔE–E experimental data from runs with the gas cell empty of helium to runs with the gas cell filled (shown are the $E_{\rm cm} = 4.3$ MeV data). A detailed Monte Carlo simulation of the experiment was performed, demonstrating that features labelled A and B corresponded to protons from elastic scattering of the beam with hydrogen contamination (i.e. in water and oil) residing on the surfaces of the gas cell windows, and that band C arises from elastic scattering of the beam with helium in the gas cell, and indeed it is absent for gas-out data sets. The thus-validated Monte Carlo suggests events of interest from ^{44}Ti(α, p)^{47}V reactions would appear to the right of feature B, as shown in figure 3. No such feature was seen and an upper limit on the cross section at this energy of 40 μb (1σ) was established. The value for the cross section presently used in nucleosynthesis codes is from the NON-SMOKER code [27, 28], and would have been 88 μb given the experimental effects. The possible astrophysical impact of this reduced cross section has been explored by Perego *et al* [29], using a spherically symmetric 1-D hydrodynamical simulation of 18–21 $M_\odot$ progenitors. Assuming that the reduction in cross section is typical for all energies within the Gamow window, the yield of ejected ^{44}Ti rose by 43%. Including both the new cross section and a correction to include homogeneous mixing that results from convective overturn, the amount of ^{44}Ti in the ejecta is 3.99 10^5 $M_\odot$. This value is only marginally below the observational expectation.

6. The future programme at ISOLDE

The future ISOLDE programme is certain to feature a number of experiments primarily motivated by astrophysical needs. Three are briefly discussed here.

6.1. IS543: The ^{44}Ti(α, p)^{47}V reaction and its implications for core collape supernovae

The first is simply a more complete study of the ^{44}Ti(α, p)^{47}V reaction and its implications for core collape supernovae. The previous work led to an upper limit at a single energy, albeit well within the Gamow window. The result hints at a possible solution to the discrepancy between models and observations of ^{44}Ti production, but confirming this requires measurements, not upper limits, and at several energies, not just one. Consequently, this study is a high priority for the future astrophyscs programme at ISOLDE, and an approved experiment is awaiting scheduling. There is confidence that definitive results will be obtained, as post-run analysis of the ion source used in the previous work indicated that a leak had severely compromised the delivered beam intensity. Moreover, even at the reduced intensity, cross sections at the level expected would have resulted in measureable strength, so increased intensity is confidently expected to give positive results. Ample ^{44}Ti remains available at PSI from which the ion beam may be developed. Possible modifications to the previous experimental apparatus include alternative gas cell window materials to improve energy resolution and thus the separation of events of interest from those resulting from surface contaminents.

6.2. IS607: The ^{59}Cu(p, α) cross section and its implications for nucleosynthesis in core-collapse supernovae

The origin of the heavy elements remains uncertain. Most are believed to be produced by neutron capture reactions in the slow, 's-', and the rapid, 'r-', neutron capture processes. There are, however, several nuclei that lie on the proton rich side of stability, and which cannot therefore be produced by either of these processes; these nuclei are known as the '*p*-nuclei'. Despite their relatively low abundance, these nuclei, and the mechanism for their production, has attracted great attention over the years. In general, it has been thought that they are generated in the high temperature environment of core-collapse supernovae, where proton rich nuclei are produced by a series of photodisintegration reactions on existing heavy seeds. However, stellar models currently fail to reproduce the high solar system abundances of the lighter *p*-nuclei ^{92,94}Mo and ^{96,98}Ru [2].

Remarkably, some 99% of the energy emitted in a core-collapse is in neutrinos. Indeed, it is their escape, and the consequent loss of lepton degeneracy pressure, that allows the collapse to occur. The intense neutrino fluxes deposit sufficient energy to trigger a supersonic outflow of stellar material, called a neutrino driven wind. Relatively recently a new process has been proposed, the νp-process [30], in which antineutrino absorptions in the proton rich environment produce neutrons that are immediately captured by neutron-deficient nuclei. This speeds up the reaction flow by bridging slow charged-particle rates and long beta-decay lifetimes by (n, p) reactions, permitting element formation up to mass $A \sim 100$. Arcones *et al* [31] have identified an end point nuclear cycle that will limit the ability of the νp-process to form elements with $A > 64$. At high temperatures the ^{59}Cu$(p, \alpha)^{56}$Ni reaction dominates over ^{59}Cu(p, γ), preventing the synthesis of heavier elements by cycling material back to ^{56}Ni. However, the ^{59}Cu(p, α) reaction rate is presently unmeasured, so when this limitation begins is unknown.

The new proposal [32] aims to provide the first experimental cross section data for this reaction. This is only feasible because of the upgrade of the HIE-ISOLDE facility, offering for the first time an intense ^{59}Cu ($t_{\frac{1}{2}} = 81.5$ s) beam at beam energies of 5.0 MeV/u, well matched to the relevant temperature range in supernovae. The beam will be made incident on hydrogen within $(CH_2)_n$ PTFE foils, and alpha particles and heavy ions will be detected in coincidence in highly segmented silicon detectors. The experiment is approved and should hopefully run soon.

6.3. IS-554: Transfer reactions with ^{7}Be to study the cosmological lithium problem

The basic details of big bang nucleosynthesis (BBN) are well established, and give nucleosynthesis predictions that are in excellent agreement with the abundances of ^{2}H, ^{3}He and ^{4}He observed in metal-poor environments. However, the abundance of ^{7}Li has been a long-standing problem. Recent observations of metal-poor halo stars, and the high precision measurement of the baryon-to-photon ratio of the Universe by WMAP, show that the predicted abundance is higher by a factor of 3 than that observed.

This discrepancy is deeply concerning, attracting much attention. Possible nuclear physics solutions invoke a modified rate for one or more of the relevant reactions, such that the final abundance in ^{7}Li is reduced while maintaining the production of other nuclear species. Experimental searches to date, of which there have been many, have failed to support such a conjecture. In the absence of a nuclear physics solution, more exotic solutions have been propsed, invoking New Physics such as photon cooling, strongly interacting massive particles or primordial magnetic fields [33]. Clearly, it is important to fully explore remaining nuclear physics solutions.

One possible remaining solution is that ^{7}Be is destroyed more quickly in the early Universe than previously thought, resulting in less being available to decay to ^{7}Li, reducing the predicted BBN abundance. Enhanced ^{7}Be destruction may arise if the ^{7}Be(d, p)^{8}Be* reaction proceeds faster [34]. Earlier work has shown that resonant contributions from high-lying states can have significant contributions to the overall rate [35]. Experiment IS-554 at HIE-ISOLDE [36], will use a 35 MeV ^{7}Be beam on a $(CD_2)_n$ target to measure in greater detail the destruction of ^{7}Be through the ^{7}Be(d, p)^{8}Be* reaction. In particular, excitation energies in ^{8}Be up to about $E_x = 20$ MeV will be examined and the properties of the 16.7 MeV $\left(\frac{5}{2}^+\right)$ resonance in ^{9}B will be deduced from analysis of (d, d) data. The present expectaiton is that the scattering chamber installed on the second beamline of the HIE-ISOLDE facility will be instrumented with two sets of double-sided silicon strip detectors, covering laboratory angles from about 8°–150°, to detect protons and alpha particles in coincidence. The experiment is approved and awaiting beam time.

7. Summary

The recent ISOLDE science programme has included notable works contributing to nuclear astrophsyics, enabled by intense radioactive beams. In one study, inelastic scattering from protons using a ^{17}F beam determined the inelastic contribution of a key 1^- state in ^{18}Ne to the ^{14}O(α, p)^{17}F reaction rate, a possible trigger for breakout from the CNO cycles in x-ray bursts. Protons detected in a silicon array were tagged using γ-rays observed in MINIBALL. The study concluded that the inelastic contribution from the resonance was approximately equal to the ground-state. In another study, a sample of the long-lived isotope ^{44}Ti was extracted from highly irradiated materials, inserted in an ion source, and accelerated to produce an intense beam that could then be directed on to a helium-filled gas cell. This enabled a direct study of the ^{44}Ti(α, p)^{47}V reaction, at an energy corresponding to temperatures well within the range reached in core-collapse supernovae. An upper limit on the cross section was observed, providing a possible explanation for why satellite-based gamma-ray observations of ^{44}Ti in ejecta from supernovae are higher than models are able to produce. In the future, accepted proposals include a more complete study of the ^{44}Ti(α, p)^{47}V reaction, measurement of the ^{59}Cu(p, α) reaction to provide input to calculations of neutrino driven nucleosynthesis of certain p-process nuclei, and a measuremnt of the ^{7}Be(d, p)^{8}Be* reaction, which may provide a solution to the long-standing conundrum of the mismatch between BBN theory and the observed abundance of ^{7}Li in metal-poor stars.

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References

[1] Jose J, Halabi G M and El Eid M F 2016 *Astron. Astrophys.* **593** A54
[2] Arnould M and Goriely S 2003 *Phys. Rep.* **384** 1–84
[3] Hahn K I *et al* 1996 *Phys. Rev.* C **54** 1999
[4] del Campo J G *et al* 2001 *Phys. Rev. Lett.* **86** 43

[5] Harss B *et al* 2002 *Phys. Rev.* C **65** 035803
[6] He J J *et al* 2009 *Phys. Rev.* C **80** 042801R
[7] Ostrowski A N *et al* 2002 *Nucl. Instrum. Methods Phys. Res.* A **480** 448
[8] Eberth J 2001 *Prog. Part. Nucl. Phys.* **46** 389
[9] Blackmon J C *et al* 2003 *Nucl. Phys.* A **718** 127
[10] Bardayan D W, Blackmon J C, Kozub R L, Matos M and Smith M S 2012 *Phys. Rev.* C **85** 065805
[11] Almaraz-Calderon S *et al* 2012 *Phys. Rev.* C **86** 025801
[12] Bethe H A 1990 *Rev. Mod. Phys.* **62** 801
[13] Burrows A *et al* 2006 *Astrophys. J.* **640** 878
[14] Wang C H-T, Hodson A O, Murphy A S J, Davies T B, Tito Mendonca J and Bingham R 2013 *Phys. Lett.* B **726** 791
[15] Grefenstette B W *et al* 2014 *Nature* **506** 339
[16] Boggs S E *et al* 2015 *Science* **348** 670
[17] Magkotsios G, Timmes F X, Hungerford A L, Fryer C L, Young P A and Wiescher M 2010 *Astrophys. J. Suppl. Ser.* **191** 66–95
[18] The L S, Clayton D D, Jin L and Mayer B S 1998 *Astrophys. J.* **504** 500
[19] Sonzogni A A *et al* 2000 *Phys. Rev. Lett.* **84** 1651
[20] Tur C, Heger A and Austin S M 2010 *Astrophys. J.* **718** 357–67
[21] Timmes F X, Woosley S E, Hartmann D H and Hoffman R D 1996 *Astrophys. J.* **464** 332
[22] CERN INTC Proposal IS543 http://cds.cern.ch/record/2021518/files/INTC-CLL-022.pdf
[23] Margerin V *et al* 2014 *Phys. Lett.* B **731** 358
[24] Dressler R *et al* 2012 *J. Phys. G: Nucl. Part. Phys.* **39** 105201
[25] Penescu L, Catherall R, Lettry J and Stora T 2010 *Rev. Sci. Instrum.* **81** 02A906
[26] Micron Semiconductor Ltd. http://micronsemiconductor.co.uk
[27] Rauscher T and Thielemann F-K 1998 *Stellar Evolution, Stellar Explosions and Galactic Chemical Evolution* ed A Mezzacappa (Bristol: IOP) p 519
[28] Rauscher T and Thielemann F-K 2000 *At. Data Nucl. Data Tables* **75** 1
Rauscher T and Thielemann F-K 2001 *At. Data Nucl. Data tables* **79** 47
[29] Perego A *et al* 2015 *Astrophys. J.* **806** 275
[30] Fröhlich C *et al* 2006 *Phys. Rev. Lett.* **96** 142502
[31] Arcones A, Fröhlich C and Martinez-Pinedo G 2012 *Astrophys. J.* **750** 18
[32] CERN INTC Proposal 441 http://cds.cern.ch/record/2021520/files/INTC-P-441.pdf
[33] Yamazaki D G *et al* 2014 *Phys. Rev.* D **90** 023001
[34] Cyburt R H and Pospelov M 2012 *Int. J. Mod. Phys.* E **21** 1250004
[35] Angulo C *et al* 2005 *Astrophys. J.* **630** L105
[36] CERN INTC Proposal 350 http://cds.cern.ch/record/1482664/files/INTC-P-350.pdf