Nuclear Astrophysics

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Nuclear physics has a long and productive history of application to astrophysics which continues today. Advances in the accuracy and breadth of astrophysical data and theory drive the need for better experimental and theoretical understanding of the underlying nuclear physics. This paper will review some of the scenarios where nuclear physics plays an important role, including Big Bang Nucleosynthesis, neutrino production by our sun, nucleosynthesis in novae, the creation of elements heavier than iron, and neutron stars. Big-bang nucleosynthesis is concerned with the formation of elements with $A \leq 7$ in the early Universe; the primary nuclear physics inputs required are few-nucleon reaction cross sections. The nucleosynthesis of heavier elements involves a variety of proton-, $\alpha$-, neutron-, and photon-induced reactions, coupled with radioactive decay. The advent of radioactive ion beam facilities has opened an important new avenue for studying these processes, as many involve radioactive species. Nuclear physics also plays an important role in neutron stars: both the nuclear equation of state and cooling processes involving neutrino emission play a very important role. Recent developments and also the interplay between nuclear physics and astrophysics will be highlighted.

I. INTRODUCTION

This paper highlights some of the applications of nuclear physics to problems in astrophysics. There are two primary reasons why nuclear physics plays a fundamental role in astrophysics: (1) nuclear reactions are an important source of energy and (2) nuclear reactions alter the isotopic composition of matter. The close connection between these research areas has a long history. The fields of experimental and theoretical astrophysics have experienced considerable progress in recent years which in turn has contributed to the vitality of nuclear astrophysics.

We now have many probes of the Universe and it’s history. The photon spectrum contains a wealth of information, for example allowing measurements in optical and $\gamma$-ray astronomy as well as of the cosmic microwave background. Neutrinos from our sun and distant supernovae have now been detected; the prospects for future measurements from these and other sources are most promising. In addition important information comes from cosmic rays and measurements of the isotopic composition of objects found within our solar system.

Several areas of current interest in nuclear astrophysics have recently been reviewed at the Lake Louise Winter Institute by Hendrik Schatz (2003) and Richard Boyd (2000); this review will mostly focus on somewhat different topics. The considerable progress in this field which has taken place since the seminal work for Burbige, Burbige, Fowler, and Hoyle in 1957 is summarized in the review by Wallerstein et al. An important and common theme is that the observed elemental abundances in the universe can be understood to result from nuclear processing in Big-Bang, stellar, and cosmic-ray scenarios.

We will begin with a discussion of Big Bang nucleosynthesis, which is responsible for the synthesis of the lightest elements. Then some recent nuclear physics results relating to the production of neutrinos by our sun will be discussed. A discussion of explosive nucleosynthesis, such as takes place in novae and X-ray bursts, will follow next. We then cover some aspects of heavy-element nucleosynthesis and close out with a discussion of some aspects nuclear physics relevant to neutron stars.

II. BIG BANG NUCLEOSYNTHESIS

Observational evidence supporting the Big-Bang model of the universe comes primarily from four sources: (1) the Hubble expansion, (2) the age of the universe, (3) the properties of the Cosmic Microwave Background Radiations (CMBR), and (4) the relative abundances of the light elements $^1$H, $^2$H, $^3,^4$He, and $^7$Li. The field of Big Bang Nucleosynthesis (BBN) is concerned with the production of these light isotopes in the early Universe. The abundances of these isotopes can be measured in situations where they are believed to be primordial and compared to theoretical BBN calculations. The main ingredients of the calculations are the baryon density of the Universe and the rates of nuclear reactions between the light elements. This comparison can be used to determine the baryon density (or
TABLE I: Cosmological parameters deduced from CMBR measurements[5].

| Parameter           | Value       |
|---------------------|-------------|
| $\Omega_{\text{tot}}$ (total density) | 1.02(2)     |
| $\Omega_{\Lambda}$ (dark energy density) | 0.73(4)     |
| $\Omega_{m}$ (matter density) | 0.27(4)     |
| $\Omega_{b}$ (baryon density) | 0.044(4)    |
| $t_0$ (age of universe) | 13.7(2) Gyr |
| $\eta$ (baryon-to-photon ratio) | $6.1(3) \times 10^{-10}$ |

baryon-to-photon ratio) of the Universe. Nuclear physics clearly plays an important role here. Before further delving into the details it is worth discussing some of the exciting recent developments in the broader field of cosmology.

Measurements of the CMBR have reached a remarkable level of precision. Recent results from the Wilkinson Microwave Anisotropy Probe are reported by Bennett et al.[5]. The measurements provide a wealth of cosmological information including the age, matter density, and baryon density of the Universe; some of their key results are summarized in Table I. The data indicate that the baryon-to-photon ratio of $6.1^{+0.3}_{-0.2} \times 10^{-10}$ which will be compared to the BBN value below. Another exciting aspect of the measurements are the findings of a non-zero cosmological constant and non-baryonic dark matter. These findings almost certainly point to new physics beyond standard cosmological and particle physics models.

Another source of cosmological information which has recently become available are observations distant (high-$z$) Type Ia supernovae[6, 7]. These “standard candles” allow for an independent determination of the matter density and cosmological constant. The supernova data in fact preceded the high-precision CMBR measurements and were the first solid indication of a non-zero cosmological constant or dark energy. This “accelerating expansion” of the Universe indicates that our present understanding of gravity is incomplete.

The physics of BBN in the present “precision era” has been reviewed by Schramm and Turner[8]. The nuclear reaction network is shown in Figure 1 and Table II. There has been considerable recent progress in the observational determination of the primordial abundances of the light elements. Measurements of deuterium and $^7$Li are most useful for determining the baron-to-photon ratio. Recent determinations of the the primordial D/H ratio are carried out by measuring absorption in the direction of distant quasi-stellar objects[9] and the present status of primordial $^7$Li/H are summarized by Ryan et al.[10].

![Figure 1: The most important portion of the reaction network used to calculate BBN abundances. See Table II for the reactions corresponding to the numbered links.](image-url)
TABLE II: The most important reactions for BBN. The numbers correspond to the links in Figure [1]

|   |   |
|---|---|
| 1 | $p \leftrightarrow n$ |
| 2 | $p(n, \gamma)^2H$ |
| 3 | $^2H(p, \gamma)^3He$ |
| 4 | $^2H(d, n)^3He$ |
| 5 | $^2H(d, p)^3H$ |
| 6 | $^3H(d, n)^4He$ |
| 7 | $^3H(\alpha, \gamma)^7Li$ |
| 8 | $^3He(n, p)^3H$ |
| 9 | $^3He(d, p)^4He$ |
| 10 | $^3He(\alpha, \gamma)^7Li$ |
| 11 | $^7Li(p, \alpha)^4He$ |
| 12 | $^7Be(n, p)^7Li$ |

It is quite remarkable that the BBN reaction network is so simple and requires only about a dozen nuclear reaction inputs (in the scenarios discussed later the networks may have hundreds of links). The nuclear physics inputs into BBN have recently been reviewed by Nollett and Burles [11]; these authors also carefully considered how the nuclear physics uncertainties propagate in BBN calculations. The relevant energy ranges for BBN are also given for each reaction. Although there has been considerable work on the nuclear physics of the light elements over the past 50 years, these authors point out that more work needs to be done so that nuclear physics uncertainties do not limit cosmological conclusions. Recent calculations of the low-energy $^3H(\alpha, \gamma)^7Li$ and $^3He(\alpha, \gamma)^7Be$ cross sections have been carried out Nollett [12] using realistic nucleon-nucleon forces along with Monte Carlo techniques. These methods show considerable promise for the future. In Fig. 2 the calculations for the $^3H(\alpha, \gamma)^7Li$ reaction are compared to experimental data [13] (the $S$-factor is a reparametrization of the cross section which approximately removes the effect of the Coulomb barrier). The data and calculations are seen to be in reasonable agreement although there is some ambiguity in the calculations depending upon how the scattering states are constructed. Perhaps the comparison with the $^3H(\alpha, \gamma)^7Li$ data can be used to determine the best method for constructing the scattering states and it can then be applied to the $^3He(\alpha, \gamma)^7Be$ case where the data have larger errors and are more discrepant.

Further work remains to be done on BBN reactions. The $n + p \rightarrow \gamma + D$ reaction is particularly interesting. In the energy range of BBN ($\sim 100$ keV) there is very little data and the cross section is in a transition region from being primarily $M1$ at low energies to being primarily $E1$ at higher energies. Nollett and Burles [11] have also pointed out that the $^2H(d, n)^3He$ and $^2H(d, p)^3H$ reaction data needed improved accuracy.

Comparisons between BBN calculations and observed abundances have been performed by several recent workers [14, 15, 16]. For the most part the conclusions are in good agreement. Burles et al. [14] report a baryon-to-photon ratio of $(5.6 \pm 0.5) \times 10^{-10}$ which is in good agreement with the value deduced from the CMBR discussed in the beginning of this section. This concordance is considered a major triumph for cosmology. There is however one aspect to this story which is somewhat puzzling: the observations of primordial lithium are only marginally consistent with the other abundances and the CMBR. If the lithium observations are taken by themselves, they would indicate a baryon-to-photon ratio of $\sim 3 \times 10^{-10}$. Although the origin of this discrepancy is not presently known, it may be an indication of new physics or something as yet unknown mechanism which has universally depleted the lithium in the old stars where it is measured.

### III. SOLAR NEUTRINOS

Nuclear physics also plays an important role in the production and detection of solar neutrinos. Nuclear reactions in the core of our sun are both a source of energy and neutrinos. The relevant nuclear physics for neutrino production has been discussed in a recent review article [17]. While it is possible to analyze solar neutrino measurements in manner which is independent of nuclear cross section assumptions [18], more information (e.g. concerning neutrino properties) can be deduced if the cross sections are understood. In the case of the $^1H(p, e^+\nu_e)^2H$ reaction, we are dependent on theoretical calculations [19, 20, 21, 22, 23]. The $^3He(^4He, 2p)^4He$, $^3He(^4He, \gamma)^7Be$ and $^7Be(p, \gamma)^8B$ reactions are particularly important for calculating the flux of neutrinos from the $\beta$ decays of $^7Be$ and $^8B$ which in turn supply...
FIG. 2: The low-energy $^3\text{H}(\alpha, \gamma)^7\text{Li}$ S-factor. The experimental data are from Ref.\[13\] and the curves are theoretical calculations\[12\] using different assumptions to generate the scattering wavefunctions.

most of the signal measured at Homestake (chlorine), Super Kamiokande, and the Sudbury Neutrino Observatory. The $^3\text{He}(^3\text{He}, 2p)^4\text{He}$ reaction has been measured recently in the laboratory at the relevant energies\[24\]; in the cases of $^3\text{He}(^4\text{He}, \gamma)^7\text{Be}$ and $^7\text{Be}(p, \gamma)^8\text{B}$ the cross section measurements must be extrapolated to lower energies. A solid theoretical and experimental understanding of these reactions is thus required.

As discussed by Adelburger \textit{et al.}\[17\] our present understanding of the $^3\text{He}(^4\text{He}, \gamma)^7\text{Be}$ and $^7\text{Be}(p, \gamma)^8\text{B}$ cross sections have not reached the desired level of precision. It should be noted that the $^8\text{B}$ neutrino flux has been measured with an absolute uncertainty of less than 4%\[25\], while the predicted flux has a much greater uncertainty ($\approx 20\%$) primarily due to nuclear physics\[26\]. In the case of $^3\text{He}(^4\text{He}, \gamma)^7\text{Be}$, further experiments are planned, while the theoretical approach of Nollett\[12\] discussed in Sec. \textsc{I} helps to better understand the extrapolation to lower energies and the relationship to the mirror reaction. In the case of the $^7\text{Be}(p, \gamma)^8\text{B}$ reactions there have been several recent direct\[27, 28\] and indirect experiments\[29, 30\]. While these measurements have helped the situation, there are some disagreements between the various approaches – the indirect approaches seem to indicate a $\approx 10\%$ lower cross section than the direct measurements. It is hoped that additional experiments will clarify this situation. The reader is directed to the recent papers for further discussions and references to earlier experiments.

We will next briefly discuss the role of nuclear physics in the detection of neutrinos via reactions on deuterium. They Sudbury Neutrino observatory has now detected both charged-current and neutral-current events from solar neutrinos reacting on deuterium\[31, 32\] which provide strong evidence for neutrino oscillations. In order to determine the neutrino fluxes it is necessary to understand the $\nu + ^2\text{H}$ reaction cross sections. Calculations of the charged- and neutral-current cross sections have been carried out using two approaches. The first “traditional” method\[33\] uses non-relativistic nuclear wavefunctions generated from nucleon-nucleon potentials along with one- and two-body current operators. The second method approach utilizes effective field theory\[34, 35\]. The two approaches agree at the level of 1%, providing considerable confidence in the calculated cross sections.

\textbf{IV. EXPLOSIVE NUCLEOSYNTHESIS}

There is presently a high level of interest in understanding the nuclear processes which take place in explosive environments such as novae and X-ray bursts\[36\]. In explosive situations the nuclear reactions take place very quickly, often on a timescale much shorter than radioactive decay. It is then essential that nuclear reactions involving radioactive species be taken into account. In order to address these questions a number of radioactive-beam facilities have recently come on line and more are planned for the future.
Novae are understood to result in binary systems in which a white dwarf is accreting matter from its main-sequence companion star\[37\]. Once sufficient material has accumulated on the surface of the white dwarf a thermonuclear runaway ensues and the accreted material burns very quickly (\(\sim 10^3\) s). The luminosity of the system increases by a factor of \(\approx 10^5\) during this time. In addition convection is predicted to bring the long-lived \(\beta^+\)-emitting nuclei to the surface where they may perhaps be seen by \(\gamma\)-ray telescopes. X-ray bursters are a understood to result from a similar scenario in which the white dwarf is replaced by neutron star. In both scenarios the most important nuclear processes are proton- and \(\alpha\)-capture reactions and \(\beta^+\) decay. The rates of these processes are needed to understand the rate of energy production in novae and X-ray bursts as well as to understand the elements produced. We will now focus on novae; for more information regarding X-ray bursts the reader is referred to the review of Schatz\[1\].

It is thought that novae produce a significant fraction of certain elements with \(A < 30\), e.g. \(^{13}\)C, \(^{15}\)N and \(^{17}\)O\[38\]. In addition they may produce detectable fluxes of \(\gamma\) rays from the decays of \(^{7}\)Be, \(^{18}\)F, and \(^{22}\)Na. The nuclear processing starts with the accreted material as well material dredged up from the white dwarf. This dredge-up material consists primarily of \(^4\)He, \(^{12}\)C, and \(^{16}\)O in the case of a carbon-oxygen white dwarf and \(^{16}\)O, \(^{20}\)Ne, and \(^{24}\)Mg in the case of an oxygen-neon-magnesium dwarf\[36\]. The reaction network generally lies along the proton-rich side of stability. The extent of the network and the nature of the cycling depends on the seed material and the temperature profile.

Considerable attention has recently been focused on reactions involving the isotopes \(^{17}\)F and \(^{18}\)F. These reactions are important for determining fluxes of 511-keV \(\gamma\) rays from \(^{18}\)F and 1275-keV \(\gamma\) rays from \(^{22}\)Na. In addition beams of these isotopes have recently become available at Argonne National Laboratory and the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory (ORNL-HRIBF). The reaction \(^{17}\)F(\(p, \gamma\))\(^{18}\)Ne has been studied indirectly by measuring the \(^1^H(17^F,p)^{18}\)F and \(^{14}\)N(\(^{17}\)F,\(^{18}\)Ne) reactions. In the former case the excitation energy and proton width of an important s-wave resonance were determined for the first time\[39, 40\]. While these parameters do not completely determine the reaction rate, they are of great importance as the rate is exponentially dependent on the resonance energy. The \(^{14}\)N(\(^{17}\)F,\(^{18}\)Ne) proton transfer reaction provides important information about the structure of bound states in \(^{18}\)Ne which improves our understanding of the (non-resonant) direct capture process\[41\]. It now appears that the direct capture mechanism dominates the reaction rate for nova temperatures (\(< 5 \times 10^8\) K). It would be highly desirable to measure directly the \(^{17}\)F(\(p, \gamma\))\(^{18}\)Ne cross section, but the cross section very small. The first step of measuring this cross section at the peak of the aforementioned s-wave resonance appears feasible for the ORNL-HRIBF facility.
Proton-induced reactions of $^{18}$F have also been studied via the $^1$H($^{18}$F,$p$)$^{18}$F and $^1$H($^{18}$F,$\alpha$)$^{18}$F reactions. As shown in Figure 3, these measurements accurately determine the several properties of the observed resonance: the resonance energy $E_r = 664.7 \pm 1.6$ keV, the total width $\Gamma = 39.0 \pm 1.6$ keV, the proton width $\Gamma_p/\Gamma = 0.39 \pm 0.2$, and the $(p,\alpha)$ resonance strength $\omega_\gamma = 6.2 \pm 0.3$ keV. The reaction rate for the $^{18}$F$(p,\alpha)^{15}$O reaction is now known within 10% for $0.4 \leq T \leq 2.0$ GK, but is still uncertain for lower temperatures due to the uncertainties associated with low-energy resonances. Although $\Gamma$, for the 665-keV resonance has not yet been determined it can be concluded that the $^{18}$F$(p,\gamma)^{19}$Ne in both novae and X-ray bursters.

The best opportunity for observing a nuclear $\gamma$-ray line produced by a nova appears to be with the 1275-keV line from $^{22}$Na. The $\gamma$-ray flux prediction depends on several reaction rates, including the proton-induced reactions of fluorine isotopes mentioned above. In addition, the $^{21}$Na$(p,\gamma)^{22}$Mg reaction plays a very important role (note that $^{22}$Mg decays into $^{22}$Na). Model calculations of oxygen-neon-magnesium novae indicate the uncertainty in the $^{21}$Na$(p,\gamma)^{22}$Mg reaction rate is the dominant source of uncertainty in calculated 1275-keV $\gamma$-ray flux. Fortunately the strength of the key 206-keV resonance in this reaction was recently measured at the TRIUMF-ISAC facility. These measurements support the prediction that maximum detectability distance for the European Space Agency’s INTEGRAL spectrometer (SPI) is approximately 1 kpc.

V. NUCLEOSYNTHESIS OF ELEMENTS HEAVIER THAN IRON

The more abundant heavy nuclei are primarily synthesized by neutron capture reactions. These processes can be categorized into the “slow” and “rapid” neutron capture process, depending on how the neutron-capture timescale compares to the $\beta^-$ decay time. These mechanisms are dubbed the s-process and r-process, respectively. Some proton-rich isotopes are thought to be synthesized by a succession of rapid proton captures (rp-process). In addition other mechanisms including photodissociation and neutrino spallation also play a role. Although certain parameters can be deduced from the observed abundances, the sites of these nucleosynthetic processes is not always clear. Many of these scenarios are likely associated with core-collapse supernovae: however a unified description of these phenomena is still a work in progress.

A. S-Process

The main component of the s-process ($A > 90$) is relatively well-understood to occur in low-to-intermediate-mass ([1.5 – 8]$M_\odot$) thermally-pulsing asymptotic giant branch (AGB) stars. The so-called weak component is produced in heavier $\sim 25M_\odot$ stars which are burning helium in their cores. At the present time research in this area is focused on two major areas: (1) measurements of neutron capture cross sections and (2) better determinations of the neutron source reactions.

Particular attention is being focused on neutron capture cross sections on unstable isotopes in the s-process path. In some of these cases neutron capture can compete with $\beta^-$ decay. These branch points can provide important information about the neutron density during the s-process. The measurements are difficult because radioactive targets are involved, but efficient techniques for measuring cross sections with small samples are under development.

The neutrons for the s-process are produced via the $^{13}$C($\alpha,n)^{16}$O and $^{22}$Ne($\alpha,n)^{25}$Mg reactions. At the temperatures involved in the s-process [$T \approx (1 - 3) \times 10^8 K$] the corresponding energies of the colliding nuclei are far below the Coulomb barrier and the cross sections are very small very difficult if not impossible to measure directly. More experimental and theoretical work is needed to determine the rates of these reactions at astrophysical energies.

B. R-Process

The r-process is responsible for the peaks in the solar-system abundances seen at $A \approx 130$ and 160. These peaks are thought to result from the neutron shell closures and $N = 82$ and 126. Nuclei consisting of a closed neutron shell plus one neutron have very low neutron separation energies and are much more likely to undergo $(\gamma,n)$ reactions than further neutron captures. Considerations of statistical equilibrium thus favor the build-up of abundances at the closed neutron shells. As the high-temperature environment cools the reactions fall out of equilibrium and the nuclei $\beta^-$ decay back to the stability line. Although this general framework has been understood for a long time, the details concerning nuclear physics and the astrophysical site remain largely unknown.

Several possible sites for the r-process have been put forward, including neutron star mergers, the ejecta of core-collapse supernovae heated by neutrino wind, and in the accretion disks of neutron stars following core-collapse supernovae. At the present time the site remains an open question. Measurements of the abundances of several
r-process elements have recently been carried out in ultra-metal-poor halo stars. These stars show an r-process abundance pattern which closely matches the (scaled) solar r-process abundances, indicating that the r-process may be universal in nature.

Hardly any of the isotopes in the projected path of the r-process have been studied in the laboratory. Knowledge of the neutron separation energies and half-lives are critical for determining the nature of the statistical equilibrium. The emission of $\beta$-delayed neutrons, fission, and the neutron-capture cross sections will impact the final abundance pattern. Depending upon the site, neutrino oscillations may also have a very significant effect on the r-process. A new facility is has been proposed to be built in the United States, the Rare Isotope Accelerator, would be able to produce the majority of the isotopes expected to be involved in the r-process. In addition to measurements of $Q$-values and decay properties, other nuclear structure information such as level densities and $\gamma$-ray strength functions can be determined which are important for estimating neutron capture cross sections.

VI. NEUTRON STARS

Nuclear physics also plays an important role in neutron star interiors. Of particular interest are the equation of state and cooling by neutrino emission. The nuclear equation of state largely determines the mass versus radius curve for neutron stars. Since the core density of neutron stars is several times normal nuclear density, this environment provides unique tests of nuclear physics which cannot be carried out in terrestrial laboratories. In principle the mass and radius are measurable so that the equation of state can be tested. At present many neutron star masses are accurately known, but there are no radius determinations – although there is promise for future measurements. Interestingly the vast majority of measured neutron star masses are clustered around $1.4 M_\odot$ which may be an indication that neutron stars are usually formed with near-maximal mass. Theoretical calculations indicate that the maximum possible neutron star mass is in the range $(1.5 - 1.7)M_\odot$ even if rather exotic nuclear physics is allowed for. In light of the fact that radius determinations will soon be possible, the prospects for an observational constraint on the nuclear equation of state are good.

The ages and temperatures of neutron stars can be determined in many case by the morphology of the supernova remnant and x-ray spectra, respectively. The age versus temperature trajectory is closely related to cooling rate of neutron stars. Of particular interest here are the neutrino-producing processes.

\[
\begin{align*}
  n + n & \rightarrow n + p + e^- + \bar{\nu}_e \\
  n + p & \rightarrow p + p + e^- + \bar{\nu}_e, \\
  n + n & \rightarrow n + n + \nu_x + \bar{\nu}_x, \text{ and} \\
  n + p & \rightarrow n + p + \nu_x + \bar{\nu}_x.
\end{align*}
\]

Many-body effects are very important due to the extremely high densities in neutron star cores. It is very likely that the neutrons are in a superfluid state, and the effects of strong magnetic fields may be important. It is expected that the fruitful interplay between astronomy and few-nucleon dynamics will continue in the future as better observations and calculations become available.

VII. CONCLUSIONS

Some applications of nuclear physics to Big Bang Nucleosynthesis, solar neutrinos, explosive nucleosynthesis, the production of elements heavier than iron, and neutron stars have been reviewed. The future in all of these areas is very exciting as improved measurements of the elemental abundances, solar neutrino fluxes, galactic $\gamma$ rays, and neutron star properties are planned. On the nuclear physics side new facilities such as the Rare Isotope Accelerator will improve our understanding of the underlying nuclear physics. Together these efforts will lead to a greater understanding of both our Universe and nuclear physics.

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U. Greife, C. J. Gross, P. A. Hausladen, C. Iliadis, C. C. Jewett, R. L. Kozub, T. A. Lewis, F. Liang, B. H. Moazen, A. M. Mukhamedzhanov, C. D. Nesara, F. M. Nunes, P. D. Parker, D. C. Radford, L. Sahin, J. P. Scott, D. Shapiro, M. S. Smith, J. S. Thomas, L. Trache, R. E. Tribble, P. J. Woods, and C.-H. Yu, Nucl. Phys. A718, 587c-589c (2003).

[42] D. W. Bardayan, J. C. Blackmon, W. Bradfield-Smith, C. R. Brune, A. E. Champagne, T. Davison, B. A. Johnson, R. L. Kozub, C. S. Lee, R. Lewis, P. D. Parker, A. C. Shotter, M. S. Smith, D. W. Visser, and P. J. Woods, Phys. Rev. C 63, 065802, 6 pages (2001).

[43] S. Bishop, R. E. Azuma, L. Buchmann, A. A. Chen, M. L. Chatterjee, J. M. D’Auria, S. Engel, D. Gigliotti, U. Greife, M. Hernanz, D. Hunter, A. Hussein, D. Hutcheon, C. Jewett, J. J. José, J. King, S. Kubono, A. M. Laird, M. Lamey, R. Lewis, W. Liu, S. Michimasa, A. Olin, D. Ottewell, P. D. Parker, J. G. Rogers, F. Strieder, and C. Wrede, Phys. Rev. Lett. 90, 162501 (2003).

[44] J. Gómez-Gomar, M. Hernanz, J. J. José, J. Isern, Mon. Not. R. Astron. Soc. 296, 913 (1998).

[45] R. Gallino, E. Arnone, S. Cristallo, S. Masera, D. Travaglio, D. L. Lambert, M. Lugaro, F. Käppeler, H. Van Winckel, M. Reyniers, O. Straniero, A. M. Davis, Nucl. Phys A718, 181c (2003).

[46] F. Käppeler, A. Mengoni, R. Gallino, Nucl. Phys A718, 173c (2003).

[47] G. M. Hale, Nucl. Phys. A621, 177c (1997).

[48] M. Heil, A. Couture, J. Daly, R. Detwiler, J. Görres, G. Hale, F. Käppeler, R. Reifarth, U. Giesen, E. Stech, P. Tischhauser, C. Ugalde, and M. Wiescher, Nucl. Phys. A688, 499c (2001).

[49] M. Jaeger, R. Kunz, A. Mayer, J. W. Hammer, G. Staudt, K. L. Kratz, and B. Pfeiffer, Phys. Rev. Lett. 87, 202501 (2001).

[50] S. Rosswog, M. Liebendörfer, F.-K. Thielemann, M. B. Davies, W. Benz, and T. Piran, Astron. Astr. 341, 499 (1999).

[51] S. E. Woosley and R. D. Hoffman, Astrophys. J. 395, 202 (1992).

[52] A. G. W. Cameron, Astrophys. J. 562, 456 (2001).

[53] C. Sneden, J. J. Cowan, I. I. Evans, G. M. Fuller, S. Burles, T. C. Beers, and J. E. Lawler, Astrophys. J. 533, L139 (2000).

[54] I. V. Panov and F.-K. Thielemann, Nucl. Phys. A718, 647c (2003).

[55] G. M. Fuller, Nucl. Phys. A688, 322c (2001).

[56] S. Goriely, Nucl. Phys. A718, 287c (2003).

[57] J. M. Lattimer and M. Prakash, Astrophys. J. 550, 426 (2001).

[58] N. K. Glendenning, Phys. Rev. C 64, 025801 (2001).

[59] M. Prakash, J. M. Lattimer, A. W. Steiner, D. Page, Nucl. Phys. A715, 835c (2003).

[60] D. G. Yakovlev, A. D. Kaminker, O. Y. Gnedin, P. Haensel, Phys. Rep 354, 1 (2001).

[61] Ch. Schaab, F. Weber, and M. K. Weigel, Astron. Astrophys. 335, 596 (1998).

[62] E. N. van Dalen, A. E. L. Dieperink, A. Sedrakian, and R. G. E. Timmermans, Astron. Astrophys. 360, 549-558 (2000).