On Solar System and Cosmic Rays Nucleosynthesis and Spallation Processes

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ABSTRACT

A brief survey of nuclide abundances in the solar system and in cosmic rays and of the believed mechanisms of their synthesis is given. The role of spallation processes in nucleosynthesis is discussed. A short review of recent measurements, compilations, calculations, and evaluations of spallation cross sections relevant to nuclear astrophysics is given as well. It is shown that in some past astrophysical simulations, old experimental nuclear data and theoretical cross sections that are in poor agreement with recent measurements and calculations were used. New astrophysical simulations using recently measured and reliably calculated nuclear cross sections, further researches in obtaining better cross sections, and production of evaluated spallation cross sections libraries for astrophysics are suggested.

Subject headings: Nucleosynthesis, abundances — nuclear reactions, spallation cross sections, data libraries

1. Introduction

A considerable success was achieved over the last decades in determination of abundances of nuclides in the solar system and in cosmic rays as well as in understanding the mechanisms of their synthesis (see, e.g., Burbidge, Burbidge, Fowler, & Hoyle 1957; Crosas & Weisheit 1996; McWilliam 1997; Wallerstein et al. 1997; Ramaty et al. 1998; Käppeler, Thielemann, & Wiescher 1998; Cameron 1999; Bethe 1999; Busso, Gallino, & Wasserburg 1999; Ginzburg 1999; Hamann & Ferland 1999; Henley & Schiffer 1999; Käppeler 1999; Khlopov 1999; Salpeter 1999; Wolfenstein 1999). Nevertheless, many interesting questions still remain. So, the light-element abundances, especially that of beryllium, and the origin of low-energy cosmic rays and their role in the light-element production require a critical reexamination (Ramaty et al. 1998). Another open question on chemical evolution in galaxies is, e.g., the fact that plots of abundances relative to hydrogen, [Be/H] and [B/H] versus [Fe/H] in halo stars both exhibit a slope of +1, rather than the value +2 that is expected for normal supernova recycling of interstellar material (Crosas & Weisheit 1996; Duncan et al. 1992).
Another open question is related with the effect of hypothetical sources of non-equilibrium particles on the radiation-dominant (RD) stage of expanding hot Universe, like the effect of antiproton interaction with $^4$He on abundance of light elements (Khokhlov 1999). The abundance of light elements is much more sensitive to possible effects of non-equilibrium particles than to the spectrum of the thermal electromagnetic background, so more complete analysis of effects of non-equilibrium particles on the RD stage of the Universe is still to be performed in the future (Khokhlov 1999).

Note that in spite of a determinative role of nuclear astrophysics in understanding mechanisms of nucleosynthesis and of a great improvement of nuclear data over the past decades, some of the remaining questions about abundances of both stellar and interstellar elements are related with uncertainties of nuclear data used in astrophysics. So, one of the biggest remaining uncertainties in nuclear astrophysics today concerns the precise parameters of a pair of resonance levels in $^{16}$O, just below the thermonuclear energy range (Salpeter 1999). Also, some of the important for astrophysics nuclear reactions are either not measured yet, or the results of recent measurements and model calculations by nuclear physicists are little known and not widely used yet by astrophysicists.

At the same time, some questions about elemental abundances, especially of the interstellar light elements, are related more with the cosmology itself and with elementary particle physics (Khokhlov 1999; Salpeter 1999; Turner & Tyson 1999) rather than with the “old” nuclear physics. So, as mentioned by Salpeter (1999), to predict today’s interstellar abundances quantitatively we need to know how many stars of various masses were born and have already died, since only in old age (e.g., planetary nebulae) and death (supernovae) does the material from a star’s interior reach interstellar space. This mass distribution, the “initial mass function,” is still somewhat uncertain (Salpeter 1999).

The aim of the present paper is to review briefly the believed today mechanisms of nucleosynthesis and the elemental abundances of stellar and interstellar matter and to highlight places where nuclear spallation processes are important. Nuclear spallation is our field of research for decades, so we hope to find points where our experience and knowledge may help to a little better understanding some astrophysical questions.

2. The Solar System and Cosmic Rays Abundances of Elements

Let us briefly review in the beginning the believed today scenario of the origin of elements and of their abundances, so that we may discuss later a possible contribution to nucleosynthesis from spallation processes.

The abundance of the solar system elements is shown in Fig. 1. Data shown by the thick black curve are taken from Table 38 by Lang (1980) and are based upon measurements of Type I carbonaceous chondrite meteorites (meteorites containing carbon compounds with a minimum of stony or metallic chondrite metals, and are thought to be of a better representation than the
old Suess and Urey’s (1956) curve (thin, blue) which was based on measurements of terrestrial, meteoric, and solar abundances.

Fig. 1.— Abundances of solar system nuclides plotted as a function of mass number. The thin blue curves shows old data compiled in Table III by Suess and Urey (1956) which are based on measurements of terrestrial, meteoric, and solar abundances. These data were used by Burbidge, Burbidge, Fowler, and Hoyle (1957) in postulating the basic nucleosynthetic processes in stars in their seminal work which become widely known as “B2FH,” the “bible” of nuclear astrophysics. The thick black curve shows newer data from the compilation published in Table 38 by Lang (1980) which are based upon measurement of Type I carbonaceous chondrite meteorites, and are thought to be a better representation than Suess and Urey’s curve. The nuclear processes which are thought to be the main stellar mechanisms of nuclide production are shown as well in the figure.

An example of abundances of several light and medium elements in 70-280 MeV/nucleon cosmic
rays compared with the corresponding abundances of elements in the solar system is shown in Fig. 2. One can see that while abundances of the majority of elements in cosmic rays are very close to what we have for the solar system, there are groups of nuclides, like the one in the Sc-V-Mn region and, especially, the light LiBeB group, whose abundances in cosmic rays are many orders of magnitude lower than in the solar system.

![Graph showing relative elemental abundances of 70-280 MeV/nucleon cosmic rays compared to solar system abundances.](image)

Fig. 2.— The relative elemental abundances of 70-280 MeV/nucleon cosmic rays (closed circles, taken from Tab. 2 by Simpson, 1983) compared to the solar system abundances (open circles, taken from Tab. 38 by Lang, 1980) normalized to Si = 10^6.

It is natural that abundances shown in both Figs. 1 and 2 are not definitive. With development of better measurement methods and techniques and with increasing our general understanding of the astrophysics, more reliable data will be obtained in the future. As one can see from Table 1 (adopted from Schramm, 1995), not only the precision of measurements increases with time but even the objects of observation of elements and their presumed origins change considerably in the
course of time. Nevertheless, the two sets of data shown in Fig. 1 suggest us that one may expect no sweeping changes in the main features of already measured abundances of the solar system elements. So, even not definitive, these abundances can be used confidently to study and to understand the origin of elements.

Table 1: Twenty-five Years for the Light Elements (adopted from Schramm, 1995)

| Isotope | 25 YEARS AGO | PRESENT |
|---------|--------------|---------|
|         | Best Observation | Presumed Origin | Best Observation | Presumed Origin |
| D       | Sea Water      | T-Tauri Stars  | ISM (HST)        | BBN             |
| $^3$He  | Solar Flares   | Low Mass Stars | Galactic H-II Regions | BBN plus Low Mass Stars |
| $^4$He  | Indirect       | BBN          | Extragalactic   | BBN             |
| $^7$Li  | Pop I Stars    | T-Tauri Stars | Pop II Stars    | BBN (Pop I has Additional Sources) |
| $^6$Li  | Meteorites     | T-Tauri Stars | Pop II Stars    | Cosmic Ray Spallation |
| Be      | Pop I Stars    | T-Tauri Stars | Pop II Stars    | Cosmic Ray Spallation |
| B       | Meteorites     | T-Tauri Stars | Pop II Stars (HST) | Cosmic Ray Spallation (Possible Additional Source for $^{11}$B) |

It is believed today that the elements we observe at present have been generated mainly by three different processes (Reeves 1994): The first one is the primordial nucleosynthesis, i.e., via thermonuclear reactions in the first few minutes after the Big Bang and prior to formation of stars (this concerns mainly D, $^3$H, $^3$He, $^4$He, $^7$Li, and perhaps some of the observed today Be and B; heavier elements could be produced by primordial nucleosynthesis, but were probably burned thereafter in nuclear reactions during the stellar era). The second mechanism generating most of the observed nuclei is nucleosynthesis in stars (most of elements heavier than Li). A third contribution to nucleosynthesis comes from spallation reactions in the interstellar medium (a part of the observed Li, Be, B, and some heavier nuclides). By convention, into the last group of nuclide production mechanisms can be included as well nuclear reactions induced by $\nu$ (see, e.g., Ryan et al. 1999; Khokhlov 1999), although $\nu$-process nucleosynthesis is considered every so often in the literature as a special mechanism (Woosley et al. 1990). Let us discuss briefly below all these processes in turn.
3. Big-Bang Nucleosynthesis (BBN)

According to modern concepts, at time $t \simeq 15$ s after the Big Bang the temperature of the Universe would have been decreased to $T \simeq 3 \times 10^9$ K and nucleosynthesis would then begin through the synthesis of deuterium from protons

$$p + p \rightarrow D + e^+ + \nu_e.$$ (1)

This would have been the end of the “radiative era,” when radiation existed separately from matter as hadrons and leptons, and the beginning of the “nucleosynthesis era”.

Note that the binding energy of the nucleons in deuterium is very small, of only 2.2 MeV, which corresponds to $T \sim 2.5 \times 10^{10}$ K. Therefore, at this stage, almost all deuterium produced is rapidly destroyed by high-energy photons and further synthesis of heavier nuclei by means of reactions

$$D + D \rightarrow ^3H + p,$$ (2)

$$^3H + D \rightarrow n + ^4He,$$ (3)

$$n + ^3He \rightarrow ^3H + p,$$ (4)

is not possible until the temperature of the Universe decreases to a value of $T \sim 10^9$ K. With further decrease in temperature the photodisintegration of deuterons practically ceases and deuterons begin to accumulate. At the same time almost all of the neutrons are utilized in the creation of helium through the reaction (4). By this time neutron decay would have shifted the neutron-proton balance to 13% of neutrons and 87% of protons (see, e.g., Fig. 3.13 by Tsipenyuk 1997). This moment of time corresponds approximately to the third minute after the Big Bang and to a temperature of $\sim 10^9$ K.

Beside reactions (1-4), there are other ways to get $^3$He and $^4$He from nucleons during the BBN. So, the following reactions are usually considered along with (1-4) to produce Helium from Hydrogen at the BBN stage:

$$p + n \rightarrow D + \gamma,$$ (5)

$$p + D \rightarrow ^3He + \gamma,$$ (6)

$$n + ^3He \rightarrow ^4He + \gamma,$$ (7)

$$D + ^3He \rightarrow ^4He + p,$$ (8)

$$n + D \rightarrow ^3H + \gamma,$$ (9)

$$p + ^3H \rightarrow ^4He + \gamma,$$ (10)

$$D + D \rightarrow ^3He + n.$$ (11)

Nuclei which are heavier than helium would not have been produced in significant quantities during this time interval as there are no stable nuclei in the Nature with the mass numbers 5 and 8.
Therefore two energy gaps would have appeared and synthesis of heavier nuclei would have stopped for some time. The gap at \( A = 5 \) is overcome and the production of \(^7\text{Li}, ^7\text{Be}, \) and \(^6\text{Li} \) together with their subsequent possible destruction proceed through:

\[
\begin{align*}
^3\text{H} + ^4\text{He} & \rightarrow ^7\text{Li} + \gamma, \\
^7\text{Li} + p & \rightarrow ^4\text{He} + ^4\text{He}, \\
^7\text{Li} + D & \rightarrow ^4\text{He} + ^4\text{He} + n, \\
^3\text{He} + ^4\text{He} & \rightarrow ^7\text{Be} + \gamma, \\
^7\text{Be} + n & \rightarrow ^7\text{Li} + p, \\
^7\text{Be} + D & \rightarrow ^4\text{He} + ^4\text{He} + p, \\
^4\text{He} + D & \rightarrow ^6\text{Li} + \gamma, \\
^6\text{Li} + p & \rightarrow ^7\text{Be} + \gamma, \\
^6\text{Li} + n & \rightarrow ^7\text{Li} + \gamma.
\end{align*}
\]

The gap at \( A = 8 \) prevents primeval production of heavier isotopes in any significant quantities. Generally, it should be mentioned that different models assume different numbers of chains considered in BBN calculations. So, while some authors limit themselves to only 12 most important reactions in their BBN calculations (see, e.g., Smith et al. 1993; Sarkar 1999), other recent works consider up to 22 possible chains (Lopez & Turner 1998), or even much more extended nuclear networks (see, e.g., Thomas et al. 1993) like the one shown in Fig. 3, kindly supplied by Keith Olive.

Usually, one tries to determine the primeval ratios of abundances of nuclei produced before the “star era” began, avoiding in observations regions where the remnant matter from the Big Bang was processed through stars. So, although all stars start on the main sequence and produce light elements in their interiors, it is believed that most of the observed today interstellar helium was already there when the galaxy was formed, i.e., most of it is primordial and not from stars (Salpeter 1999). One reason for this is that there is little mixing from a star’s center to its surface (and usually little mixing between stars and interstellar gas); another reason is that much of the interior helium is processed into heavier elements before a star dies.

The primordial abundances of \(^4\text{He}, \ D, \ ^3\text{He}, \ ^7\text{Li}, \) and other light elements measured in such a way are used further to fit the main parameters of the BBN. The “standard model” of the big bang nucleosynthesis, in which it is assumed that the baryon distribution was uniform and homogeneous during that period, is described by only one parameter, \( \eta \), the baryon to photon ratio, or by the baryon density, \( \rho_B \), related to \( \eta \) by \( \rho_B = 6.88\eta \times 10^{-22} \) g cm\(^{-3} \) (Burles et al. 1999). In practice, usually the baryon density is expressed not directly units of \( \rho_B \) but by a related parameter \( \Omega_B h^2 \), where \( \Omega_B \) is the baryon density in terms of the critical mass density, \( \rho_c \): \( \Omega_B = \rho_B / \rho_c \), where \( \rho_c = 1.88 \times 10^{-29}h^2 \) g cm\(^{-3} \) and \( h \) is related to the Hubble constant, \( H_0 \), by the relation \( H_0 = 100h \) km s\(^{-1} \) Mpc\(^{-1} \) (see, e.g., Lang 1999).
Fig. 3.— The nuclear chain considered in the largest network of the Homogeneous BBN calculations by Thomas, Schramm, Olive, and Fields (1993), with kind permission from Keith Olive.
As one can see from Fig. 4 (Turner 1999), a reasonable agreement between predicted by the BBN abundances of $^4$He, D, $^3$He, $^7$Li and recent measurements may be achieved only in a narrow range of values for the baryon density, namely, $\Omega_B h^2 = 0.019 \pm 0.0024$.

When we go beyond the Standard Model, there is another fundamental parameter which affects the BBN abundances, namely, the number of massless neutrino species in the Universe, $N_\nu$, which affects the expansion temperature-time relation and hence the way in which nuclear reactions go out of thermal equilibrium. The presence of additional neutrino flavors (or of any other relativistic species) at the time of nucleosynthesis increases the energy density of the Universe and hence the expansion rate, leading to a larger value of the temperature at the freeze-out of the weak-interaction rates, $T_f$, to a larger value of n/p ratio, and ultimately, to a higher value of the primeval $^4$He abundance, $Y_p = 2(n/p)/(1 + n/p)]$. By means of a likelihood analysis on $\eta$ and $N_\nu$ based on $^4$He and $^7$Li it was found that the 95% CL range are $1.7 \leq N_\nu \leq 4.3$ (Cassco 1998). As one can see from Fig. 5, adapted from Copi, Schramm, & Turner (1997), a recent analysis of the deuterium abundance in high-redshift hydrogen clouds helps to sharpen this limit to $N_\nu \leq 3.4(3.2)$, for $Y_p = 0.242$, and to $N_\nu \leq 3.8(4.0)$, for $Y_p = 0.252$, that is in a good agreement with the Standard Model’s value of $N_\nu = 3$. This fact can be treated as one more confirmation of the dramatic success of the Big Bang model, which provides agreement with the observed element abundances only if the number of massless neutrino species is three, which correspond exactly to the three species (electron, muon, and tau) we know to exist.

Besides the mentioned above two fundamental parameters, the BBN calculations involve also a number of “working” parameters, namely, the cross sections for processes considered in the BBN nuclear networks. More exactly, traditionally, in astrophysics are used not directly nuclear cross sections but the so called “nuclear reaction rates” derived from measured or evaluated cross sections of relevant reactions convoluted with a thermal (Maxwell-Boltzmann) relative velocity distribution. Useful references on reaction rates works performed before 1993 can be found in Smith, Kawano, & Malaney (1993). The last and most complete compilation of reaction rates involving light (1 $\leq Z \leq$ 14), mostly stable, nuclei, called NACRE (Nuclear Astrophysics Compilation of REaction rates), have been published recently by a big consortium of nuclear physics and astrophysical European laboratories (Angulo et all. 1999), where further detailed references may be found (see the recent work by Vangioni-Flam, Coc, Casse, & Oberto (2000), where NACRE have been already used in an updated BBN model to study primordial abundances of light elements up to $^{11}$B).

When we have already fixed the two fundamental parameters of the BBN, $\eta$ and $N_\nu$, and have chosen the “working horses”, the needed thermonuclear reaction rates, we can perform BBN calculations to study how abundances of different light elements have changed with the time (or temperature) after the big bang, like shown in Fig. 6, adapted from Burles, Nollett, & Turner (1999).
Fig. 4.— Predicted abundances of $^4$He (mass fraction), D, $^3$He, and $^7$Li (number relative to hydrogen) as a function of the baryon density; widths of the curves indicate “2σ” theoretical uncertainty. The dark band highlights the determination of the baryon density based upon the recent measurement of the primordial abundance of deuterium (Burles & Tytler, 1998a,b), $\Omega_B h^2 = 0.019 \pm 0.0024$ (95% cl); the baryon density is related to the baryon-to-photon ratio by $\rho_B = 6.88 \eta \times 10^{-22}$ g cm$^{-3}$ (Burles et al, 1999). [From Turner 1999, with kind permission from Michael Turner].
Fig. 5.— Marginal likelihood for $\tilde{N} \equiv N_\nu - \Delta Y/0.016$ with different Bayesian priors for the primeval deuterium abundance: $(D/H)_P \leq 1.0$ (solid line); $[(D + ^3\text{He})/H]_P \leq 2 \times 10^{-4}$ (short-dashed line); extreme model of $^3\text{He}$ chemical evolution (from Turner et al. 1996) (long-dashed line); $(D/H)_P = (2.5 \pm 0.5) \times 10^{-5}$ (dashed-dotted line). In each case we have assumed the $^7\text{Li}$ abundance that results in the least stringent limit to $\tilde{N}$. The fact that $\tilde{N} = 3$ is well within the 95% credibility interval is indicative of the consistency of big-bang nucleosynthesis with three massless neutrino species. [From Copi, Schramm, and Turner, Phys. Rev. C55, 3389 (1997), with kind permission from Michael Turner.]
Fig. 6.— Mass fraction of primordial nuclei as a function of temperature for $\eta = 5.1 \times 10^{-10}$, from Burles, Nollett, & Turner (1999), with kind permission from Kenneth Nollett.
Our knowledge of the observed primordial abundances is still uncertain, allowing and involving different models for primordial nucleosynthesis. Though the standard cosmology tells us that all nuclei heavier than carbon were produced in stellar interiors after the galaxy formation, recent observations in the sub-giant CD-38°245, one of the oldest stars in first generation which were born a few million years after the galaxy formation, as well as recently observed absorption lines in quasi stellar objects (QSO) with red-shift factor $z = 2$ (see, e.g., Kajino 1992) suggest that there were some production activities of medium and heavy elements (up to Ba) before or during the galaxy formation. At present, there are no definite measurements of the primordial abundances for carbon and heavier elements, therefore all such observations should be interpreted only as an upper, possible limit.

At the end of this section, let us note one more point of interest in context with the aim of the present paper. Even if the standard BBN explains the origin of light elements D, $^3$He, $^4$He, and $^7$Li and their primordial abundances, it is hopelessly ineffective in generating $^6$Li, $^9$Be, $^{10}$B, $^{11}$B (see, e.g., Vangioni-Flam, Casse, & Audoze 1999). Due to their low binding energy, these nuclei are not produced significantly in the BBN or in stellar nuclear burning, and are, in fact, destroyed in stellar interiors. Instead, it is believed today that LiBeB are made mostly by spallation processes due to energetic nuclei and neutrinos (see Fields, Olive, Vangioni-Flam, & Olive 1999 and references therein). We will return to this question again in Section 5. Let us also mention that a new, good, and useful review on BBN nucleosynthesis and primordial abundances will be published shortly in Physica Scripta by Tytler, O’Meara, Suzuki, & Lubin (2000).

4. Nucleosynthesis in Stars

After the Big Bang, the story of nucleogenesis is considered mostly with the physics of stellar evolution and nucleosynthesis in stars (see, e.g., McWilliam 1997). In the $^3$FH paper, the “bible” of nuclear astrophysics, to describe all features of the abundance curve known as of 1957, eight separate processes were necessary to be taken into account: 1) Hydrogen Burning; 2) Helium Burning; 3) $\alpha$ Process; 4) $e$ Process; 5) $r$ Process; 6) $p$ Process; 7) $s$ Process; and 8) $x$ Process. Today, 43 years later, nearly the same processes are still considered to be as fundamental ones for stellar nucleosynthesis (Wallerstein et al. 1997). For completeness sake, let us briefly list bellow in turn processes shown in Fig. 1 which are believed today to be of the main importance for stellar nucleosynthesis.

4.1. Hydrogen Burning

Hydrogen burning starts in stars with the proton-proton and deuteron-proton reactions (1) and (6) discussed in Section 3. Other reactions of the hydrogen burning chain suggested and discussed half a century ago by many prominent physicists (see detailed references in Lang 1999) are (13)
and (15), as well as:

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + p + p, \quad (21) \]
\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e, \quad (22) \]
\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma, \quad (23) \]
\[ ^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu_e, \quad (24) \]
\[ ^8\text{Be} \rightarrow ^4\text{He} + ^4\text{He}. \quad (25) \]

The energy released in each of these and other reactions discussed may be found in Lang 1999. For stars more massive than the Sun, hydrogen will be fused into helium by the fast C-N cycle provided that carbon, nitrogen, or oxygen are present to act as a catalyst:

\[ ^{12}\text{C} + p \rightarrow ^{13}\text{N} + \gamma, \quad (26) \]
\[ ^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu_e, \quad (27) \]
\[ ^{13}\text{C} + p \rightarrow ^{14}\text{N} + \gamma, \quad (28) \]
\[ ^{14}\text{N} + p \rightarrow ^{15}\text{O} + \gamma, \quad (29) \]
\[ ^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu_e, \quad (30) \]
\[ ^{15}\text{N} + p \rightarrow ^{12}\text{C} + ^4\text{He}. \quad (31) \]

Additional proton capture reactions, which may take place to form the complete C-N-O bi-cycle (see references in Lang 1999) are:

\[ ^{15}\text{N} + p \rightarrow ^{16}\text{O} + \gamma, \quad (32) \]
\[ ^{16}\text{O} + p \rightarrow ^{17}\text{F} + \gamma, \quad (33) \]
\[ ^{17}\text{F} \rightarrow ^{17}\text{O} + e^+ + \nu_e, \quad (34) \]
\[ ^{17}\text{O} + p \rightarrow ^{14}\text{N} + ^4\text{He}. \quad (35) \]

It is possible that the CNO cycle produces most of the \(^{14}\text{N}\) found in nature. During supernovae explosions, a rapid CNO cycle might take place in which the (n,p) reactions replace the beta decays in the cycle.
4.2. Helium Burning

It is believed now that helium burning results in the production of approximately equal amount of $^{12}\text{C}$ and $^{16}\text{O}$ in stars of masses from 0.5 to 50 $M_{\odot}$. The reactions assigned to be the triple alpha process, $^4\text{He} + ^4\text{He} + ^4\text{He} \rightarrow ^{12}\text{C} + \gamma$, are (see references in Lang 1999):

$$^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be},$$

$$^8\text{Be} + ^4\text{He} \rightarrow ^{12}\text{C}^*,$$

$$^{12}\text{C}^* \rightarrow ^{12}\text{C} + \gamma.$$  

Once $^{12}\text{C}$ is formed, and with increasing temperature in the stellar core, $^{16}\text{O}$ and other heavier nuclei up to the very stable, double magic, $^{40}\text{Ca}$, or even a little further will be produced by successively $\alpha$-capture:

$$^{12}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O} + \gamma,$$

$$^{16}\text{O} + ^4\text{He} \rightarrow ^{20}\text{Ne} + \gamma,$$

$$^{20}\text{Ne} + ^4\text{He} \rightarrow ^{24}\text{Mg} + \gamma,$$

$$^{24}\text{Mg} + ^4\text{He} \rightarrow ^{28}\text{Si} + \gamma,$$

$$^{28}\text{Si} + ^4\text{He} \rightarrow ^{32}\text{S} + \gamma,$$

$$^{32}\text{S} + ^4\text{He} \rightarrow ^{36}\text{Ar} + \gamma,$$

$$^{36}\text{Ar} + ^4\text{He} \rightarrow ^{40}\text{Ca} + \gamma.$$  

As suggested by Cameron about half a century ago (see references in Cameron 1999 and Lang 1999), $\alpha$-capture reactions on products of the C-N-O cycle might play a role of neutron producer in stars:

$$^{13}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O} + \text{n},$$

$$^{14}\text{N} + ^4\text{He} \rightarrow ^{18}\text{F} + \gamma,$$

$$^{18}\text{F} \rightarrow ^{18}\text{O} + \text{e}^+ + \nu_e,$$

$$^{18}\text{O} + ^4\text{He} \rightarrow ^{22}\text{Ne} + \gamma,$$

$$^{18}\text{O} + ^4\text{He} \rightarrow ^{21}\text{Ne} + \text{n},$$

$$^{22}\text{Ne} + ^4\text{He} \rightarrow ^{25}\text{Mg} + \text{n}.$$
4.3. Carbon and Oxygen Burning

At the condition of helium burning, the predominant nuclei are $^{12}$C and $^{16}$O (Lang 1999). When temperatures greater than $8 \times 10^8$ K are reached, carbon will begin to react with itself according to the reactions:

$$^{12}C + ^{12}C \rightarrow ^{24}Mg + \gamma,$$  \hspace{1cm} (52)

$$^{12}C + ^{12}C \rightarrow ^{23}Na + p,$$  \hspace{1cm} (53)

$$^{12}C + ^{12}C \rightarrow ^{20}Ne + ^4He,$$  \hspace{1cm} (54)

$$^{12}C + ^{12}C \rightarrow ^{23}Mg + n,$$  \hspace{1cm} (55)

$$^{12}C + ^{12}C \rightarrow ^{16}O + ^4He + ^4He.$$  \hspace{1cm} (56)

At about $2 \times 10^9$ K, oxygen will also react with itself according to the reactions:

$$^{16}O + ^{16}O \rightarrow ^{32}S + \gamma,$$  \hspace{1cm} (57)

$$^{16}O + ^{16}O \rightarrow ^{31}P + p,$$  \hspace{1cm} (58)

$$^{16}O + ^{16}O \rightarrow ^{31}S + n,$$  \hspace{1cm} (59)

$$^{16}O + ^{16}O \rightarrow ^{28}Si + ^4He,$$  \hspace{1cm} (60)

$$^{16}O + ^{16}O \rightarrow ^{24}Mg + ^4He + ^4He.$$  \hspace{1cm} (61)

The $\alpha$ particles, protons, and neutrons which are produced via reactions (52-61) will interact with the other products of the burning to form many other nuclides with $16 \leq A \leq 28$.

It is now thought that most of the carbon, oxygen, and silicon burning, which account for the observed solar system abundances for $20 \leq A \leq 64$, occurs during fast explosions, and these explosive burning processes are discussed briefly in Section 4.7.

4.4. Silicon Burning

At the completion of carbon and oxygen burning, the most abundant nuclei will be $^{32}$S and $^{28}$Si with significant amount of $^{24}$Mg (Lang 1999). Because the binding energies for protons, neutrons, and $\alpha$ particles in $^{32}$S are smaller than those in $^{28}$Si, the nuclide $^{32}$S will be the first to photodisintegrate according to the reactions:

$$^{32}S + \gamma \rightarrow ^{31}P + p,$$  \hspace{1cm} (62)

$$^{31}P + \gamma \rightarrow ^{30}Si + p,$$  \hspace{1cm} (63)

$$^{30}Si + \gamma \rightarrow ^{29}Si + n,$$  \hspace{1cm} (64)

$$^{29}Si + \gamma \rightarrow ^{28}Si + n.$$  \hspace{1cm} (65)
The resulting reactions will leave little but $^{28}\text{Si}$. Silicon will then begin to photodisintegrate at temperatures greater than $3 \times 10^9$ K according to the reactions:

\[
^{28}\text{Si} + \gamma \rightarrow ^{27}\text{Al} + p, \quad (66)
\]
\[
^{28}\text{Si} + \gamma \rightarrow ^{24}\text{Mg} + ^4\text{He}. \quad (67)
\]

As the ($\gamma$, $^4\text{He}$) reaction has the lower threshold, it is the dominant reaction at low temperatures $T < 2 \times 10^9$ K; whereas the ($\gamma$, $p$) reaction has the shorter lifetime at higher temperatures. Further photodisintegrations lead to the build-up of lighter elements according to the reactions:

\[
^{24}\text{Mg} + \gamma \rightarrow ^{23}\text{Na} + p, \quad (68)
\]
\[
^{24}\text{Mg} + \gamma \rightarrow ^{20}\text{Ne} + ^4\text{He}, \quad (69)
\]
\[
^{20}\text{Ne} + \gamma \rightarrow ^{16}\text{O} + ^4\text{He}, \quad (70)
\]
\[
^{16}\text{O} + \gamma \rightarrow ^{12}\text{C} + ^4\text{He}. \quad (71)
\]

The abundances of most of the nuclei in the range $28 \leq A \leq 60$ are thought to be determined by equilibrium or quasi-equilibrium processes in which the importance of many individual reaction rates is diminished (see references in Lang 1999). Most nuclear species between $^{28}\text{Si}$ and $^{59}\text{Co}$, except the neutron-rich species ($^{36}\text{S}$, $^{40}\text{Ar}$, $^{43}\text{Ca}$, $^{46}\text{Ca}$, $^{48}\text{Ca}$, $^{51}\text{Ti}$, $^{54}\text{Cr}$, and $^{58}\text{Fe}$), are generated by a quasi-equilibrium process in which the only important thermonuclear reaction rates are thought to be those of $^{44}\text{Ca}$, $^{45}\text{Sc}$, and $^{45}\text{Ti}$ (Lang 1999). The abundances of the neutron-rich species could be determined by the $s$ or $r$ processes discussed briefly below.

### 4.5. $s$, $r$, and $p$ Processes

Because the binding energy per nucleon decreases with increasing $A$ for nuclides beyond the iron peak ($A \geq 60$), and because these elements have large Coulomb barriers, they are not likely to be formed by fusion or alpha and proton capture (Lang 1999). It is thought that most of these elements are formed by neutron capture reactions which start with the iron group nuclei (Cr, Mn, Fe, and Ni). If the flux of neutrons is weak, most chains of neutron capture will include only a few capture before the beta decay of the product nucleus. As the neutron capture lifetime is slower ($s$) than the beta decay lifetime, this type of neutron capture is called the $s$ process. This process can continue all the way up to lead and bismuth; beyond bismuth the resulting nuclei alpha decay back to Pb and Tl isotopes (Wallerstein et al. 1997). Good reviews on laboratory measurements, stellar models, and abundance studies of the $s$-process elements may be found in Secs. X and XI of the recent comprehensive surveys by Wallerstein et al. (1997) and in Käppeler (1999).

When there is a strong neutron flux, as it is believed to occur during a supernovae explosion, the neutron-rich elements will be formed by the rapid ($r$) neutron capture process, in which the
sequential neutron captures take place on a time scale which is much more shorter than for beta decay of the resulting nuclei. This process produces much more neutron-reach progenitors that are required to account for the second set of abundance peaks that are observed about 10 mass units above the s-process abundance peaks corresponding to the neutron magic numbers, \( N = 50 \) and 82. We forward readers interested in more details about both the physics and astrophysical scenario of the rapid neutron capture to the Sec. XII of the mentioned above review by Wallerstein et al. (1997) and to a more recent and useful work by Cowan et al. (1999).

The proton rich medium and heavy elements are much less abundant than the elements thought to be produced by \( r \) and \( s \) processes, and are thought to be formed by a proton capture (\( p \) process) at high enough temperature to overcome the coulomb barrier. Burbidge, Burbidge, Fowler, & Hoyle (1957) described in their “bible”, two possible mechanisms by which \( p \)-nuclides could be formed: proton radiative captures, \((p, \gamma)\), in a hot \((T \sim 2 \sim 3 \times 10^9 \, ^\circ K)\) proton-rich environment, or photon-induced \( n, p, \) and \( \alpha \)-particle removal reactions, also in a hot environment. A possible occasion for this process is the passage of a supernova shock wave through the hydrogen outer layer of a pre-supernova star. The separate mechanisms that are believed today as contributing to \( p \)-process nucleosynthesis, as well as their strengths and weaknesses are discussed in details in Sec. XIV of the review by Wallerstein et al. (1997).

It is believed today that some nucleosynthesis of the lighter \( p \)-nuclides is provided by the so called \( rp \) process. The \( rp \)-process is very similar to the \( r \)-process, except it goes by a successive rapid proton absorption and \( \beta^+ \) decay. At present, it is believed that the \( rp \)-process can provide contributions to the nucleosynthesis of proton rich isotopes after the hot C-N-O cycle up through \(^{65}\text{As}\), to as high as \(^{68}\text{Se}\), or even to \(^{96}\text{Ru}\) (see details and references in Wallerstein et al. 1997).

4.6. Equilibrium Processes

Another type of processes of nucleosynthesis in stars discussed intensively in the literature since the pioneering work by Hoyle (1946) and reviewed in B\(^2\)FH are the equilibrium processes, called in B\(^2\)FH as “\( e \) processes”. Such processes are possible only if the matter is in equilibrium with the radiation, and if every nucleus is transformable into any other nucleus. Hoyle (1946) showed that matter is in equilibrium with radiation at temperatures \( T \approx 10^9 \, ^\circ K \), and that all known nuclei may be transformed into any other nucleus by nuclear reactions at \( T \gtrsim 2 \times 10^9 \, ^\circ K \). Though statistical equilibrium requires that the entropy of a system should be at the maximum, that may be a too strong requirement, not fulfilled exactly for real systems (Lang 1999; Wallerstein et al. 1997), this method proved to be very successful for the description of abundances of nuclei in the iron group and around \((28 \leq A \leq 60)\) (see detailed references in Lang 1999). What is more, if to assume a thermodynamic equilibration in a star, than its composition (elemental abundances) may be calculated without determining individual reaction rates, and only the binding energies and partition functions of the various nuclear species need to be specified.
Under conditions of statistical equilibrium, the number density, \( N_i \), of particles of the \( i \)th kind is given by (Lang 1999):

\[
N_i = \frac{1}{V} \sum_r \mu_i [\pm \mu_i + \exp(\varepsilon_{ir}/kT)]^{-1},
\]

(72)

where \( V \) is the volume, \( \mu_i \) is the chemical potential of the \( i \)th particle, the plus and minus signs refer to Fermi-Dirac and Bose-Einstein statistics, respectively, and the summation is over all energies, \( \varepsilon_{ir} \), which includes both internal energy levels and the kinetic energy. If an internal level has spin, \( J \), then \( 2J + 1 \) states of the same energy must be included in the sum. When the nuclides are non-degenerate and non-relativistic, Maxwellian statistics can be employed to give (Lang 1999):

\[
N_i = \mu_i \omega_i \left( \frac{2\pi M_i kT}{\hbar^2} \right)^{3/2} \int_0^p p^2 \exp \left( -\frac{p^2}{2M_i kT} \right) dp
\]

(73)

where \( p \) is the particle momentum, \( M_i \) is its mass, the partition function \( \omega_i = \sum (2J_r + 1) \exp(-\varepsilon_r/kT) \), and here \( \varepsilon_r \) refers to internal states only. For particles \( p_i, p_j, \cdots \) which react according to

\[
\alpha p_i + \beta p_j + \cdots \rightleftharpoons \xi p_r + \eta p_s + \cdots,
\]

(74)

the chemical potentials are related by the equation

\[
\mu_i^\alpha \mu_j^\beta \cdots = \mu_i^\xi \mu_j^\eta \cdots \exp(-Q/kT),
\]

(75)

where

\[
Q = c^2[\alpha M_i + \beta M_j + \cdots - \xi M_r - \eta M_j - \cdots].
\]

(76)

Hoyle (1946) and Burbidge, Burbidge, Fowler, & Hoyle (1957) considered the condition of statistical equilibrium between the nuclei, \((A, Z)\), and free protons, p, and neutrons, n. For a nucleus, there are \( Z \) protons and \((A - Z)\) neutrons and the statistical weight of both protons and neutrons is two. It then follows from Eqs. (73) to (76) that for equilibrium between nuclides, protons, and neutrons, the number density, \( N(A, Z) \), of the nucleus, \((A, Z)\), is given by:

\[
N(A, Z) = \omega(A, Z) \left( \frac{AM_\mu kT}{2\pi \hbar^2} \right)^{3/2} \left( \frac{2\pi h^2}{M_\mu kT} \right)^{3A/2} N_p^{(A-Z)} N_n^Z \exp \left[ \frac{Q(A, Z)}{kT} \right],
\]

(77)

where the partition function, \( \omega(A, Z) \), of the nucleus, \((A, Z)\), is given by

\[
\omega(A, Z) = \sum_r (2I_r + 1) \exp \left( -\frac{E_r}{kT} \right).
\]

(78)
where \( I_r \) and \( E_r \) are, respectively, the spin and energy of the \( r \)th excited level, the binding energy, \( Q(A, Z) \), of the nucleus, \((A, Z)\), is given by

\[
Q(A, Z) = e^2[(A - Z)M_n + ZM_p - M(A, Z)],
\]

(79)

where \( M_n, M_p, \) and \( M(A, Z) \) are, respectively, the masses of the free neutron, free proton, and the nucleus, \((A, Z)\), the factor

\[
\left( \frac{2\pi\hbar^2}{M\mu kT} \right)^{3/2} \approx 1.6827 \times 10^{-34}T_9^{-3/2} \text{ cm}^{-3},
\]

(80)

where \( T_9 = T/10^9 \), the atomic mass unit is \( M\mu \), and \( N_n \) and \( N_p \) denote, respectively, the number densities of free neutrons and protons. As one can see, Eq. (77) contains indeed only the binding energy \( Q(A, Z) \) and does not require any cross sections or nuclear rates. Further details, more references, and newer and more general notions on equilibrium processes may be found, e.g., in Lang 1999 and Wallerstein et al. 1997.

There is an allied process to the equilibrium nucleosynthesis, the so called “quasi-equilibrium” process, when the total number of nuclei in different ranges of atomic number or mass number might be slowly varying and we may see only a quasi-equilibrium between nuclides of some separate groups, but not between different groups. So, Michaud and Fowler (1972) showed that with an initial neutron enhancement of \( 4 \times 10^{-3} \) the natural abundances for nuclei with \( 28 \leq A \leq 59 \) may be accounted for by quasi-equilibrium burning. In this case, a quasi-equilibrium between elements with \( 24 \leq A \leq 44 \) and a separate equilibrium for elements with \( 46 \leq A \leq 60 \) is assumed, and detailed nuclear reactions are given for the “bottleneck” at \( A = 45 \) (see further details and references on quasi-equilibrium processes in Lang 1999 and Wallerstein et al. 1997). This quasi-equilibrium silicon burning process must have taken place in a short time, \( t \lesssim 1 \text{ sec} \), and at high temperatures, \( T \gtrsim 4.5 \times 10^9 \text{ K} \), suggesting the explosive burning processes discussed briefly in the next subsection.

### 4.7. Explosive Burning Processes

As explained by Burbidge, Burbidge, Fowler, and Hoyle (1957), the successive cycles of static nuclear burning and contraction, which successfully account for much stellar evolution, must end when the available nuclear fuel is exhausted (Lang 1999). B^3FH showed that the unopposed action of gravity in a helium exhausted stellar core leads to violent instabilities and to rapid thermonuclear reactions in the stellar envelope. Later, Arnett (1968) showed that when cooling by neutrino emission in a highly degenerate gas is considered, the \(^{12}\text{C} + ^{12}\text{C}\) reaction will ignite explosively at core density of about \( 2 \times 10^9 \text{ g cm}^{-3} \). The stellar material is instantaneously heated and then expands adiabatically so that the density, \( \rho \), and temperature, \( T \), are related by

\[
\rho(t) \propto [T(t)]^3,
\]

(81)
for a $\Gamma_3 = 4/3$ adiabat, and a time variable, $t$. The appropriate time is the hydrodynamic time scale, $\tau_{HD}$, given by (Lang 1999)

\[
\tau_{HD} \approx 446 \rho^{-1/2} \text{ sec.} \tag{82}
\]

The initial temperature and density must be such that the mean lifetime, $\tau_R$, for a nucleus undergoing an explosive reaction, $R$, must be close to $\tau_{HD}$. For the interaction of nucleus 1 with a nucleus 2,

\[
\tau_R = \tau_2(1) = [N_2 < \sigma v>]^{-1} = \left[ \rho N_A \frac{X_2}{A_2} < \sigma v > \right]^{-1}, \tag{83}
\]

where the mass density is $\rho$, the $X_2$, $A_2$, and $N_2$ are, respectively, the mass fraction, mass number, and number density of nucleus 2, and $N_A < \sigma v >$ is the reaction rate. Arnett (1969) used a mean carbon nucleus lifetime,

\[
\log \tau_{12C} \approx 37.4 T_9^{-1/3} - 25.0 - \log_{10} \rho \approx \log_{10} \tau_{HD} \tag{84}
\]

for carbon burning to determine the initial condition of explosive carbon burning. Knowing the reaction rates, Eqs. (81) and (84) allow us to calculate expected abundances using the corresponding abundance equations discussed briefly below. Abundance rations which closely approximate those of the solar system were found for $^{20}\text{Ne}$, $^{23}\text{Na}$, $^{24}\text{Mg}$, $^{25}\text{Mg}$, $^{26}\text{Mg}$, $^{27}\text{Al}$, $^{28}\text{Si}$, and $^{30}\text{Si}$, when it was assumed that a previous epoch of helium burning produced equal amounts of $^{12}\text{C}$ and $^{16}\text{O}$, and that

\[
T_p = 2 \times 10^9 \text{ K} \quad \rho_p = 1 \times 10^5 \text{ g cm}^{-3} \quad \eta = 0.002 . \tag{85}
\]

Here $T_p$ and $\rho_p$ denote, respectively, the peak values of temperature and mass density in the shell under consideration, and the neutron excess, $\eta$, is given by

\[
\eta = \frac{N_n - N_p}{N_n + N_p}, \tag{86}
\]

where $N_n$ and $N_p$ denote, respectively, the number density of free neutrons and protons (Lang 1999).

Similarly, many works by different authors were dedicated to study explosive oxygen and silicon burning. Useful references and more details on explosive nucleosynthesis may be found in the comprehensive monograph by Lang (1999) and in the recent reviews by Arnett (1995) and Woosley and Weaver (1995).

In a general case, the equation governing the change in the number density, $N(A, Z)$, of the nucleus $(A, Z)$ is of the form (Lang 1999):

\[
\frac{d}{dt} (N_i) = - \sum_j N_i N_j < \sigma v >_{ij} + \sum_{kl} N_k N_l < \sigma v >_{kl}, \tag{87}
\]
where \( N_i \) is the number density of the \( i \)th species, \(< \sigma v >_{ij} \) is the product of cross section and the relative velocity for an interaction involving species \( i \) and \( j \), the \( N_mN_n \) is replaced by \( N_n^2/2 \) for identical particles, and the summation is over all reactions which either create or destroy the species, \( i \). The probabilistic interpretation of this equation is obvious: the number density, \( N_i \) of the species \( i \) at a given time \( t \) is built by all processes resulting in the species of interest minus the contribution of all processes destroying these species. In practice, for numerical calculations, instead of \( N_i \) one usually uses the following parameter (Lang 1999):

\[
Y_i = \frac{N(A, Z)}{\rho N_A} = \frac{N_i}{\rho N_A},
\]  

(88)

where \( \rho \) is the mass density of the gas under consideration and \( N_A \) is the Avogadro’s number. Then, Eq. (87) can be rewritten as:

\[
\frac{d}{dt}(Y_i) = - \sum_j f_{ij} + \sum_{kl} f_{kl},
\]  

(89)

where the vector flow, \( f_{ij} \), which contains nuclei \( i \) and \( j \) in the entrance channel, is given by

\[
f_{ij} = \frac{N_iN_j < \sigma v >_{ij}}{\rho N_A} = Y_iY_j\rho N_A < \sigma v >_{ij},
\]  

(90)

The real, explicit view of this equation in a concrete calculation depends on processes we like to take into account. So, in a general case when we take into account negative and positive \( \beta \)-decays, electron and neutron captures, alpha decay, photodisintegration, as well as all possible reactions between two interacting nuclei, Eq. (89) becomes (Lang 1999):

\[
\frac{dY(A, Z)}{dt} = - \left[ \lambda_{\beta^-}(A, Z) + \lambda_{\beta^+}(A, Z) + \lambda_K(A, Z) + \lambda_{\alpha}(A, Z) + \lambda_{\gamma}(A, Z) + 2.48 \times 10^8 \sigma_T N_n + \sum_j Y(A_j, Z_j)\rho N_A < \sigma v >_{ij}Y(A, Z) + \lambda_{\beta^-}(A, Z - 1)Y(A, Z - 1) + \lambda_{\beta^+}(A, Z + 1)Y(A, Z + 1) + \lambda_K(A, Z + 1)Y(A, Z + 1) + \lambda_{\alpha}(A + 4, Z + 2)Y(A + 4, Z + 2) + \lambda_{\gamma}(A, Z)Y(A, Z) + 2.48 \times 10^8 \sigma_T N_n Y(A - 1, Z) + \sum_{ik} Y(A_i, Z_i)Y(A_k, Z_k)\rho N_A < \sigma v >_{ik} \right],
\]  

(91)

(92)

where the symbol \( \lambda \) denotes the decay rate or the inverse mean lifetime, the subscripts \( \beta^- \), \( \beta^+ \), \( K \), \( \alpha \), and \( \gamma \) denote, respectively, negative beta decay, positive beta decay, electron capture, alpha decay, and photodisintegration, \( \sigma_T \) is the cross section for neutron capture in cm\(^2\), \( N_n \) is the number density of neutrons, the summation \( \sum_j \) denotes all reactions between the nucleus \( (A, Z) \) and any other nucleus, the summation \( \sum_{ik} \) denotes all reactions between two nuclei which have \( (A, Z) \) as a product, \( \rho \) is the gas mass density, and \( N_A < \sigma v > \) is the reaction rate.
Numerical solution of such complex set of nuclear reaction networks requires a number of approximations and assumptions. Details on abundance equations for s, r, equilibrium, and quasi-equilibrium processes as well as useful references can be found in Lang (1999).

5. Li-Be-B Generation and Spallation Processes

The observed today rare light nuclei, lithium, beryllium, and boron, are not products of the BBN or stellar nucleosynthesis, and are, in fact destroyed in hot stellar interiors. This condition is reflected in the comparatively low abundances of these nuclei (see Figs. 1 and 2). In contradiction with measurements, the primordial $^6\text{Li}$, $^9\text{Be}$, $^{10}\text{B}$, and $^{11}\text{B}$ abundances calculated using the best of the available today evaluations for the reaction rates are many orders of magnitude below compared to $^7\text{Li}$, so, the standard BBN is ineffective in generating $^6\text{Li}$, $^9\text{Be}$, $^{10}\text{B}$, and $^{11}\text{B}$ (Vangioni-Flam, Cassé, & Audouze 1999).

Up to recently, the most plausible formation agents of LiBeB were thought to be Galactic Cosmic Rays (GCRs) interactions with interstellar medium (ISM), mainly C, N, and O nuclei. (The most abundant and energetic cosmic-ray particles are protons and $\alpha$-particles.) Other possible origins have been also identified: primordial and stellar ($^7\text{Li}$) and supernova neutrino spallation (for $^7\text{Li}$ and $^{11}\text{B}$), while $^6\text{Li}$, $^9\text{Be}$, and $^{10}\text{B}$ are thought to be pure spallation products (Vangioni-Flam, Cassé, & Audouze 1999).

Recent measurements in a few halo stars with the 10 meter KECK telescope and the Hubble Space Telescope indicate a quasi linear correlation between Be and B vs Fe, at least at low metallicity, contradictory at first sign to a dominating GCRs origin of the light elements which predicts a quadratic relationship (see the appendix in Vangioni-Flam, Cassé, & Audouze 1999). As a consequence, the theory of the origin and evolution of the LiBeB nuclei has yet to be reassessed Vangioni-Flam, Cassé, & Audouze (1999). Aside GCRs, which are thought to be accelerated in the general interstellar medium and which create Li-Be-B through the break up of interstellar C-N-O nuclei by their fast protons and alphas, Wolf-Rayet stars (WR) and core collapse supernovae (SNIa) grouped on superbubbles could produce copious amount of light elements via the fragmentation in flight of rapid carbon and oxygen nuclei (called hereafter low energy component, LEC) colliding with H and He in the ISM (Vangioni-Flam, Cassé, & Audouze 1999). In this case, Li-Be-B would be produced independently of the interstellar medium chemical composition. As noted by Vangioni-Flam, Cassé, & Audouze (1999), more spectroscopic observations (specifically of O, Fe, Li, Be, B) in halo stars are required for a better understanding of the relative contribution of various mechanisms.

New measurements of Be/H and B/H, together with [Fe/H] (see detailed references in Vangioni-Flam, Cassé, & Audouze 1999) in very low metallicity halo stars came to set strong constrains on the origin of light isotopes. Recent compilations of Be and B data are presented in Figs. 7 and 8. The most striking point is that log(Be/H) and log(B/H) are both quasi proportional to [Fe/H].
Concerning lithium, as one can see from Fig. 7, the flat portion of the lithium abundance, usually referred to as the Spite plateau (after the original work of Francois and Monique Spite in 1982) expends up to $[\text{Fe/H}] \sim -1$. It is believed that it represents the abundance of Li generated by the BBN nucleosynthesis. Beyond, Li/H is strongly increasing until its solar value of $2 \times 10^{-9}$. This increase in the Li/H ratio is believed to be related with nucleosynthesis in a variety of Galactic objects, including Type II supernovae, novae and giant stars, as well as production by cosmic rays (Ramaty, Kozlovsky, & Lingenfelter 1998). A stringent constraint on any theory of Li evolution arises from such a form of Li/H curve: it should avoid to cross the Spite’s plateau below $[\text{Fe/H}] = -1$. Accordingly, the Li/Be production ratio should be less than about 100 (Vangioni-Flam, Cassé, & Audouze 1999).
Galactic cosmic rays represent the only sample of matter originating from beyond the Solar System. They are constituted by bare nuclei stripped from their electrons. Their energy density (about 1 eV cm\(^{-3}\) similar to that of stellar light and that of galactic magnetic field), indicate that they are an important component in the dynamics of the Galaxy (Vangioni-Flam, Cassé, & Audouze 1999). A key point for us is that, as can be seen from Fig. 2, GCRs are exceptionally LiBeB rich (LiBeB/CNO \(\sim 0.25\)) compared to the Solar System matter (LiBeB/CNO \(\sim 10^{-6}\)).

![Graph](image)

**Fig. 8.**— Beryllium and Boron evolution vs [Fe/H]. The halo evolution, ([Fe/H] \(<-1\)), is dominated by the LEC component linked to massive stars. As far as B is concerned, there is room for a small contribution for \(\nu\) spallation. This figure is reproduced from Vangioni-Flam, Cassé, & Audouze (1999) with kind permission by Elisabeth Vangioni-Flam.

For detailed calculations of LiBeB production by the GCR mechanism, the formation rate of a light isotope (i.e., Li, Be, or B, noted here as \(L\)) from the spallation of a medium isotope (e.g., \(^{12}\)C, \(^{14}\)N, \(^{16}\)O, and \(^{20}\)Ne, noted as \(M\)) by a flux of protons with energy spectrum, \(\varphi(E)\), is given by (Lang 1999):

\[
\frac{dN_L}{dt} = \sum_M N_M \int \sigma(M, L, E)\varphi(E)dE,
\]  

(93)
where $M$ denotes any of “medium” elements and $L$, any of “light” nuclei, the number densities of the $M$ and $L$ elements are, respectively, $N_M$ and $N_L$, the time variable is $t$, the proton energy is $E$, and the spallation reaction cross section is $\sigma(M, L, E)$. For the low energy cosmic (LEC) rays mechanism, where LiBeB are produced by interaction of low energy (less than 100 MeV/A) interactions of “medium” nuclei with interstellar H and $^4$He, we have just a similar formula. The main difference is in the energy dependence of fluxes of the projectiles, while the values of cross sections are the same, for identical bombarding energies per nucleon. For spallative nucleosynthesis calculations, cross sections at energies from $\sim 1$ MeV to $\sim 100$ GeV are required, in contrast with the stellar nucleosynthesis that occur at low energies, from $\sim 1$ keV to $\sim 100$ keV. Current assumptions about energy dependences of the GCR and LEC fluxes, as well as further interesting points of the LiBeB story may be found in Vangioni-Flam, Cassé, & Audouze (1999) and in proceedings of the recent special conference on LiBeB held in December 1998 in Paris (Ramaty, Vangioni-Flam, Cassé, & Olive 1999). Spallation cross sections are discussed in the next section.

According to modern concepts (see, e.g., Woosley et al. 1990; Woosley & Weaver 1995), neutrino spallation (NS) is also a source of $^7$Li and $^{11}$B via the interaction of neutrinos (predominantly $\nu_\mu$ and $\nu_\tau$) on nuclei, specifically on $^4$He and $^{12}$C (Vangioni-Flam, Cassé, & Audouze 1999). Recently, $\nu$-process nucleosynthesis was incorporated into a model of galactic chemical evolution (Olive et al. 1994) and Vangioni-Flam et al. (1996) which had included as well the LEC component) with the primary purpose of augmenting the low value for $^{11}$B/$^{10}$B produced by standard GCR nucleosynthesis. To fit the observed ration of 4, it was found that the yields of NS predicted by Woosley & Weaver (1995) had to be turned down by a factor of about 2 to 5, to avoid the overproduction of $^{11}$B. Turning down the NS yields ensured as well that the production of $^7$Li was insignificant, in accordance with the Spite plateau (Vangioni-Flam, Cassé, & Audouze 1999).

Note that if taking the full NS yield, all galactic boron would be produced by $\nu$ spallation. This could be a problem since $^9$Be is not coproduced and $^7$Li overproduced. Thus, the NS mechanism acts as a complement to nuclear spallation at a level estimated to at most 20 percent concerning $^{11}$B, if one wants to fulfill the observational constraints of LiBeB discussed by Vangioni-Flam et al. (1999).

An example of contribution from primordial, galactic cosmic rays, and $\nu$-nucleosynthesis to the total Li abundance, as calculated by Ryan, Beers, Olive, Fields, & Norris (1999) is shown in Fig. 9. Although these results were obtained not without fitting parameters (therefore are not completely definitive), they may help us to understand the relative role of different production mechanisms of light elements. One can see that the primordial contribution to Li abundance decreases at high metallicity due to astration, but other components increase with metallicity as discussed by Ryan, Beers, Olive, Fields, & Norris (1999). The main conclusion from these results as well as from recent works by other authors (see details and references in Ryan, Beers, Olive, Fields, & Norris 1999) is that LiBeB evolution may be understood only if we take into account a combination of BBN, cosmic ray, and $\nu$-process nucleosyntheses, but the $\nu$-process scenario seems to not play a major role.
Fig. 9.— Contributions to the total lithium abundance from different reaction mechanisms shown on the plot, as predicted by the one-zone (closed box) GCE model (Fields & Olive 1999) compared with available experimental data for low metallicity and high metallicity stars (Ryan, Beers, Olive, Fields, & Norris 1999). The solid curve is the sum of all components; $^6$Li is thought to be produced only by spallation reactions (Fields & Olive 1998). This figure is taken with the kind permission of authors from Ryan, Beers, Olive, Fields, & Norris (1999), where further details may be found.

The $\nu$-process may contribute as well to production of some other of the lowest abundance $p$-nuclei, like $^{11}$B and $^{19}$F (Boyd 1999). Generally, the process is thought to occur in the neutrino wind generated by stellar collapse in supernovae. The nuclides synthesized clearly depend on the shell in which the $\nu$-process occurs. For example, $^{11}$B and $^{19}$F would be expected to be made in
shells in which the dominant constituents were $^{12}$C and $^{20}$Ne respectively, both by processes in which a neutrino would excite the target nucleus via the neutral-current interaction (Boyd 1999).

The $\nu$-process could also make two of the rarest stable nuclides in the periodic table: $^{138}$La and $^{180}$Ta (Boyd 1999). The latter would be made by the $^{181}$Ta($\nu$,n)$^{180}$Ta (neutral current) reaction, which appears to produce an abundance consistent with what observed. Similarly, the $^{139}$Ta($\nu$,n)$^{138}$La (neutral current) reaction, together with the $^{138}$Ba($\nu$,e)$^{138}$La (charge current) reaction, appear capable of synthesizing roughly the observed $^{138}$La abundance. Thus, the $\nu$-process seems to provide a natural mechanism for synthesis of $^{138}$La and $^{180}$Ta, which has evaded description for several decades, as well as some other nuclides (Boyd 1999). However, it should be noted that such results are somewhat uncertain due to questions about the neutrino spectrum resulting from a Type II supernova and many questions on neutrino processes have yet to be solved in the future (see, e.g., Woosley, Hartmann, R.D. Hoffman, & Haxton 1990, Boyd 1999, Ginzburg 1999, Henley & Schifer 1999, Lang 1999, Khlopov 1999, Turner & Tyson 1999, Wolfenstein 1999, and references therein).

6. Spallation Cross Sections

Precise nuclear spallation cross sections are needed in astrophysics not only to calculate abundances of light elements with formulas of the type (93) but also for many other tasks. So, it is believed today that low energy cosmic ray interactions with ISM are responsible not only for a part of LiBeB-production discussed in the previous section, but also for the production of some of the now extinct radioisotopes that existed at the time of the formation of the solar system and found recently in meteorites, like $^{26}$Al, $^{41}$Ca, and $^{53}$Mn (see Ramaty, Kozlovsky, & Lingenfelter 1996a and references therein). To estimate the abundances of these extinct radioisotopes in the solar system one uses formulas similar to (93) and one needs reliable cross sections for interaction of a variety of nuclei from the LEC with H and $^4$He, the most abundant constituents of the ambient medium (see details in Ramaty, Kozlovsky, & Lingenfelter 1996a).

Generally, a lot more spallation cross sections are needed to study meteorites besides the ones related with the extinct radioisotope production. During the recent years, large number of meteorites were found on Antarctic icefields and in hot deserts, in particular in the Sahara. These meteorite finds have increased the interest in the investigation of cosmogenic nuclides. Besides direct measurements of radionuclide composition performed for some of the found meteorites, such investigations usually involve theoretical calculations of production rates of cosmogenic nuclides in meteoroids by folding depth- and size-dependent spectra of primary and secondary cosmic-ray particles with the cross sections of the underlying reactions. The quality and reliability of the calculated production rates exclusively depend on the accuracy of the available spallation cross sections. A serious progress in interpretation the cosmogenic nuclide production in meteorites by galactic and solar cosmic rays and in understanding the cosmic radiation itself was achieved during the last years by the group of Prof. Rolf Michel at Hannover (see, e.g., Michel, Leya, & Borges
Another problem on cosmogenic nuclide production study requiring reliable spallation cross sections from interactions of protons and alphas up to about 200 MeV with a variety of nuclei-targets is the investigation of solar cosmic ray (SCR) exposure of the lunar surface material, as well as of the earth atmosphere (see, e.g., Bodemann et al. 1993 and references therein). The survey by Reedy and Marti (1990) may serve as a good review on this subject and a source for further references.

As mentioned by Tsao, Barghouty, & Silberberg (1999), it is believed today that the elements Li, Be, B, Cl, K, Sc, Ti, V, Mn and much of N, Al, and P in cosmic rays (see Fig. 2) are produced by nuclear spallation of the more abundant elements of the cosmic-ray source component, i.e., C, O, Ne, Mg, Si, Ca, and Fe. Studies of the composition, propagation, and origin of galactic cosmic rays are still to a large degree model dependent and conclusions made from such works depend essentially on nuclear cross sections used in calculations, therefore as precise as possible estimates of the relevant cross sections are needed.

Let us mention just one more particular problem in astrophysics requiring reliable cross sections. Recently, the gamma-ray line at 0.511 MeV has been observed from a variety of astrophysical sites, including solar flares (see references in Kozlovsky, Lingenfelter, & Ramaty 1987). It is thought that this line is due to positron annihilation on a electron \( (e^+ + e^- \rightarrow \gamma + \gamma) \), where one photon will have a high energy and, if the electron is at rest, the other photon will have an energy on the order of \( m_e c^2 = 0.511 \text{ MeV} \) from decay of radioactive nuclei and pions. One possibility of positron emitters production in a solar flare is via interactions of particles accelerated in the flare with the ambient solar atmosphere. To estimate the annihilation of positrons from such radioactive nuclei one need to know a great variety of proton- and \( \alpha \)-induced spallation cross sections for the production of such positron emitters (see details in Kozlovsky, Lingenfelter, & Ramaty 1987).

The list of astrophysical tasks requiring reliable cross sections can be continued further and further. As mentioned recently by Waddington (1999), it appears that the most serious limitation to deducting abundances of energetic nuclei in the cosmic radiation arises not from our lack of astrophysical measurements and observations, but just from our lack of the appropriate nuclear cross sections. Let us also note, that such spallation cross sections are of great importance as well both for fundamental nuclear physics and for many nuclear applications, e.g., for accelerator transmutation of waste (ATW), accelerator-based conversion (ABC), accelerator-driven energy production (ADEP), accelerator production of tritium (APT), for the optimization of commercial production of radioisotopes used in medicine, mining, and industry, for solving problems of radiation protection of cosmonauts, aviators, workers at nuclear facilities, and for modeling radiation damage to computer chips, etc. (see details and references, e.g., in Mashnik, Sierk, Bersillon, & Gabriel 1997). In the following subsections, we present a short survey of available experimental, calculated, and evaluated spallation cross sections for astrophysics and other fields together with our thought of how to possibly improve the present status of this problem.
6.1. Experimental Data

Cosmic rays consist of all the elements in the periodic table, up to uranium, therefore reactions induced by any projectile are of interest for astrophysics. However, since hydrogen is the dominant element, followed by helium, spallation cross sections from reactions induced by protons and alphas are of the first priority, while we do mention as well the importance of nucleus-nucleus reactions for many astrophysics problems, as surveyed recently by Tsao, Barghouty, & Silberberg (1999). Thousands of measurements of spallation cross sections relevant to astrophysics (mainly, proton-induced) have been performed over the last half a century.

A good survey of experimental cross sections for proton induced spallation reactions measured before 1966, was done by Bernas, Gradsztajn, Reeves, & Schatzman (1967) and included thereafter in Chapter 9 by Audoze, Epherre, & Reeves (1967) and Chapter 8 by Gradsztajn (1967) of the well known book High-Energy Nuclear Reactions in Astrophysics edited by B. S. P. Shen and published by W. A. Benjamin, Inc. in 1967 in New York. In a way, this survey was like a “bible” of nuclear cross sections in astrophysics, as it was widely known and used, to our knowledge, without questions in almost all astrophysical simulations, up to very recent years. A short but comprehensive review of experimental results obtained by 1976 may be found in Hudis (1976). Another known in astrophysics paper serving as a survey of both proton- and alpha-induced experimental spallation cross sections was published 11 years later (only figures, as a by-product) by Kozlovsky, Lingenfelter, & Ramaty (1987). The last published short astrophysical survey on spallation cross sections measurements was, to our knowledge, the work by Tsao, Barghouty, & Silberberg (1999). Meanwhile, many other reliable measurements were performed that are not covered by these compilations, and, as one can see from Fig. 10, not all old cross sections agree well with the new data.

Many efforts have been previously made as well by nuclear physicists to compile experimental spallation cross sections from proton and heavier projectiles induced reactions. So, very good and comprehensive reviews of experimental excitation functions from proton-, deuteron-, and alpha-induced reactions on a number of light and medium nuclei-targets from Carbon to Chlorine, as well as on Cu and Au, were published by Tobailem and co-authors from 1971 to 1983 at CEA, Saclay, France, in a convenient form of Reports (in French) with tables and figures (Tobailem et al. 1971, 1972, 1975, 1977, 1981a, 1981b, 1982, and 1983). But to the best of our knowledge, the most complete compilation (ever published, in any fields of nuclear cross sections data) was performed by Sobolevsky and co-authors at INR, Moscow, Russia, and was published by Springer-Verlag from 1991 to 1996 in eight separate subvolumes (Sobolevsky et al. 1991, 1992, 1993, 1994a, 1994b, 1995, 1996a, and 1996b). Sobolevsky and co-authors have performed a major work and compiled all data available to them for target elements from Helium to transuransics for the entire energy range from thresholds up to the highest energy measured. For example, for proton-induced reactions, this compilation contains about 37,000 data points published in the first four Subvolumes, I/13a-d, (the following Subvolumes, I/13e-h, concern pion, antiproton, deuteron, triton, \(^4\)He, and alpha induced reactions). This rich compilation is also currently available in an electronic version as an IBM PC code named NUCLEX, published only a month ago by Springer-Verlag in a hardcover format.
Fig. 10.— Examples of cross sections used in astrophysical simulations (solid lines) compared with the presently available data (open circles) compiled in the LANL T-2 library (Mashnik et al. 1998). On the two top plots, the cross sections for production of $^7$Be from interaction of protons with $^{14}$N and $^{16}$O compiled in 1967 by Bernas, Gradsztajn, Reeves, & Schatzman and used thereafter in most of the following astrophysical simulations are shown together with available at present data (see text). The bottom plot shows the $^{27}$Al(p,n)$^{27}$Si cross section used by Kozlovsky, Lingenfelter & Ramaty (1987) to evaluate the role of this reaction as a positron-emitter in their interpretation of the observed 0.511 MeV line from solar flares. The 0.511 MeV line was interpreted in a model of annihilation of positrons from the decay of radioactive nuclei produced from interaction of particles accelerated in the flare with the ambient solar atmosphere. For comparison, data from the LANL T-2 library are shown in this plot together with the recent HMS-ALICE (Blann & Chadwick 1998) calculations by Chadwick (dashed line) from the LA150 transmutation/activation libraries (Koning, Chadwick, MacFarlane, Mashnik, & Wilson 1998).
accompanied by a CD-ROM with the NUCLEX code, as the ninth subvolume of this series and
a supplement to previous eight subvolumes (Sobolevsky et al. 2000; see a detailed description of
NUCLEX in Ivanov, Sobolevsky, & Semenov (1998)).

Unfortunately this valuable compilation is either not known yet by astrophysicists (we do
not know any citations on it in astrophysical papers) or is too expensive for individual users and
small libraries (Springer Verlag sells, e.g., the single subvolume I/13g (Sobolevsky et al. 1996a) for
$1647.00, the subvolume I/13f, (Sobolevsky et al. 1995) for $2020.00, and the last subvolume with
the CD-ROM, I/13i (Sobolevsky et al. 2000), for $2386.00; interested buyers may find information
on the Web, at pages: http://www.springer-ny.com/catalog/np/nov96np/DATA/3-540-61045-6.html,
http://www.springer-ny.com/catalog/np/oct95np/DATA/3-540-59049-8.html, and, for the
CD-ROM, on http://www.springer-ny.com/catalog/np/feb00np/3-540-63646-3.html). Of more im-
mediate concern is the fact that NUCLEX does not contain a large volume of data obtained during
recent years, especially for proton-induced reactions.

Due to the increasing interest in intermediate-energy data for ATW, ABC, ADEP, APT, astro-
physics, and other applications, precise and voluminous measurements of proton-induced spallation
cross sections have been performed recently, and are presently in progress, by the group of Prof.
Michel from Hannover University (see, e.g., Michel et. al. 1997, Michel, Leya, & Borges 1996, Gi-
labert et al. 1998, and the Web page
http://sun1.rrzn-user.uni-hannover.de/zsr/survey.htm#url=overview.htm), Yu. E. Titarenko et al.
at ITEP, Moscow (Titarenko 1999a, 1999b, and references therein), Yu. V. Aleksandrov et al. at
JINR, Dubna (Aleksandrov et al. 1995 and references therein), B. N. Belyaev et al. at B. P.
Konstantinov St. Petersburg Institute of Nuclear Physics (Belyaev, Domkin, & Mukhin 1994 and
references therein), N. I. Venikov et al. at Kurchatov Institute, Moscow (Venikov, Novikov, &
Sebiakin 1993), A. S. Danagulyan et al. at JINR, Dubna (Danagulyan et al. 2000 and references
therein), H. Vonach et al. at LANL, Los Alamos (Vonach et al. 1997), S. Sudar and S. M. Qaim
at KFA, Jülich (Sudar & Qaim 1994), D. W. Bardayan et al. at LBNL, Berkeley (Bardayan et
al. 1997), J. M. Sisterson et al. at TRIUMF and other accelerators (Sisterson et al. 1997), etc.
Finally, we note another, “new” type of nuclear reaction intensively studied in recent years, which
provides irreplaceable data both for nuclear astrophysics and nuclear physics itself. These are from
reactions using reverse kinematics, when relativistic ions interact with hydrogen targets and they
often provide the only way to obtain reliable data for interaction of intermediate energy protons
with separate isotopes of an element with a complex natural isotopic composition. Good data for
this type of reactions have been recently obtained, e.g., by W. R. Webber et al. at the LBL Bevalac
(Webber, Kish, & Schrier 1990, Chen 1997, and references therein) and L. Tassan-Got et al. at GSI,
Darmstadt (Tassan-Got et al. 1998, Wlazlo et al. 2000). Further references on several more such
“new” type of measurements, as well as on recent spallation cross sections from nucleus-nucleus
interactions may be found in Silberberg, Tsao, & Barghouty (1998) and Tsao, Barghouty, & Sil-
berberg (1999). These new data, as well as a number of other new and old measurements have not
been covered by NUCLEX.
Let us note that for our needs, we compiled in the T-2 Group at LANL also an experimental data library of spallation cross sections, referred below as LANL T-2 Library (Mashnik, Sierk, Van Riper & Wilson 1998). Our library is only for proton-induced reactions and was completed so far only for 33 elements-targets: C, N, O, F, Ne, Na, Mg, Al, P, S, Cl, Ar, K, Ca, Fe, Co, Zn, Ga, Ge, As, Y, Zr, Nb, Mo, Sn, Xe, Cs, Ba, La, Ir, Au, Hg, and Bi. But for the 91 targets (separate isotopes or natural composition) of these elements, our library is the most complete, as far as we know, and contains 23,439 data points covering 2,562 reactions, in comparison with NUCLEX, having only 13,703 data points and 1594 reactions for the same 33 elements. For these elements, we produced also a calculated cross section library both for proton- and neutron-induced reactions up to 5 GeV, as well as an evaluated library, discussed briefly in the next subsection.

In developing our experimental LANL T-2 library, we did not confine ourselves solely to NUCLEX as a source of experimental cross sections; instead, we compile all available data for the targets in which we are interested, searching first the World Wide Web, then any other sources available to us, including the compilation from NUCLEX. We also have begun to store in our library data for intermediate energy neutron-induced reactions, but so far we have only 95 data points for Bi and C targets covering 14 reactions induced by fast neutrons. (Extensive neutron-induced experimental and evaluated activation libraries at energies below 150 MeV have been produced, validated, and used by many authors; see, e.g., Muir & Koning (1997), Korovin et al. (1999), Chadwick et al. (1999), Fessler et al. (2000) and references therein.) Our library is still in progress, we permanently update it when new data for our elements are available, and we hope to extend it, depending on our needs, and to make it available public through the Web.

Note, that many data (especially, recent) on experimental spallation cross sections are already included in the Experimental Nuclear Reaction Data Retrievals (EXFOR) compilation, available to users from the Web through the international nuclear data banks (see, e.g., the Web page of the NEA/OECD, Paris at http://www.nea.fr/html/dbdata/dbexfor.html).

From our point of view, it would be useful for the astrophysical community to merge the NUCLEX data library (Sobolevsky et al. 1991-2000), our LANL T-2 compilation (Mashnik, Sierk, Van Riper, & Wilson 1998), and the data permanently updated in the EXFOR database with already existing data libraries, considered by the Nuclear Astrophysics Data Effort Steering Committee (Smith, Cecil, Firestone, Hale, Larson, & Resler 1996) as Nuclear Data Resources for Nuclear Astrophysics, CSIRS (The Cross Section Information Storage and Retrieval System), ECSIL (The LLNL Experimental Cross Section Information Library), and ECSIL2 (a LANL/LLNL extension of ECSIL) as well as to make available this information through the recent powerful NASA Astrophysical Data System (Krutz, Eichhorn, Accomazzi, Grant, Murray, & Watson 2000).
6.2. Calculated and Evaluated Cross Sections

Experiments to measure all data necessary for astrophysics and other fields are costly and there are a limited number of facilities available to make such measurements (Blann et al. 1994, Nagel et al. 1995). In addition, most measurements have been performed on targets with the natural composition of isotopes for a given element and, what is more, often only cumulative yields of residual product nuclei are measured. In contrast, for astrophysical simulations and other applications, as well as to study the physics of nuclear reactions, independent yields obtained for isotopically separated targets are needed. Furthermore, only some 80–100 cross section values of residual product nuclei are normally determined by the γ spectrometry method in the experiments with heavy nuclei, whereas, according to calculations, over 1000 residual product nuclei are actually produced. Therefore, it turns out that reliable theoretical calculations are required to provide the necessary cross sections (Blann et al. 1994, Nagel et al. 1995, Koning 1993).

In some cases, it is more convenient to have fast-computing semiempirical systematics for various characteristics of nuclear reactions instead of using time-consuming, more sophisticated nuclear models. Therefore, to our knowledge, in most astrophysical simulations one uses predictions of different semiempirical systematics (see, e.g., Silberberg, Tsao, & Barghouty 1998, Tsao, Barghouty, & Silberberg 1999 and references therein). After many years of effort by many investigators, many empirical formulae are now available for spallation cross sections and excitation functions. Many current systematics on excitation functions have been reviewed by Koning (1993); most of the old systematics available in 1970 were analyzed in the comprehensive monograph by Barashenkov and Toneev (1972); the majority of systematics for mass yields, charge dispersions, energy and angular distributions of fragments produced in pA and AA collisions at relativistic energies available in 1985 are presented in the review by Hufner (1985); useful systematics for different hadron-nucleus interaction cross sections may be found in our review (Gabriel & Mashnik 1996); improved parametrizations for fragmentation cross sections were recently published by Summerer and Blank (2000); the last update of the well known and widely used in astrophysics code YIELD together with further references may be found in Silberberg, Tsao, & Barghouty (1998) and Tsao, Barghouty, & Silberberg (1999). Let us mentioned as well the old but widely used in the past in astrophysical simulations systematics by Rudstam (1966), Gupta, Das, & Biswas (1970), Silberberg & Tsao (1973a, 1973b), Foshina, Martins, & Tavares (1984), and direct readers interested in references on other phenomenological systematics to surveys by Koning (1993), Barashenkov & Toneev (1972), Hufner (1985), Gabriel & Mashnik (1996), Tsao, Barghouty, & Silberberg (1999), as well as to the recent work by Michel et al. (1995). Michel with co-authors (1995) have performed a special analysis of predictabilities of different semiempirical systematics and have concluded that “Semiempirical formulas will be quite successful if binding energies are the crucial parameters dominating the production of the residual nuclides, i.e. for nuclides far from stability. In the valley of stability, the individual properties of the residual nuclei, such as level densities and individual excited states, determine the final phase of the reactions. Thus, the averaging approach of all semiempirical formulas will be inadequate.” In this case, one has to perform calculations in the
Products in 59-Co irradiated with 0.07GeV protons

Fig. 11.— Product comparison between the new experimental (filled symbols) and simulated (opaque symbols) yields in $^{59}$Co irradiated with 70-MeV protons (Titarenko et al. 1999a). Results labeled as YIELDX and “Foshina et al.” are obtained with the updated systematics by Silberberg, Tsao, & Barghouty (1998) and using the semiempirical formulas by Foshina, Martins, & Tavares (1984), respectively, that are often used in astrophysical simulations. Results labeled as CEM95, LAHET, INUCL, and HETC were calculated with Monte Carlo codes by Mashnik (1995), Prael & Lichtenstein (1989), Stepanov (1989), and Armstrong & Chandler (1972), respectively. One can see discrepancies more than an order of magnitude for spallation cross sections of some isotopes.

As an example, Fig. 11 shows a comparison between the new data for isotope production from interaction of 70-MeV protons with $^{59}$Co by Titarenko et al. (1999a) and results obtained with the systematics by Silberberg, Tsao, & Barghouty (1998), noted in figure as YIELDX, with semiempirical formulas by Foshina, Martins, & Tavares (1984), together with calculations using the Monte Carlo codes CEM95 (Mashnik 1995), LAHET (Prael & Lichtenstein 1989), INUCL (Stepanov
1989), and HETC (Armstrong & Chandler 1972). One can see that for these reactions, neither the phenomenological systematics by Silberberg, Tsao, & Barghouty (1998), nor the semiempirical formulas by Foshina, Martins, & Tavares (1984), both widely used in astrophysics, provide a good description of all data, therefore we can not rely exclusively on them in astrophysical and other simulations.

In such situations, one has to perform calculations in the framework of reliable Monte Carlo models of nuclear reactions and to use available experimental data. As was mentioned by Mashnik, Sierk, Van Riper, & Wilson (1998), ideally, it would be desirable to have for applications a universal evaluated library that includes data for all nuclides, projectiles, and incident energies. At present, neither the measurements nor any of the current models or phenomenological systematics can be used alone to produce a reliable evaluated activation library covering a large area of target nuclides and incident energies. As one can see from Fig. 11, some of the best Monte Carlo codes also have big difficulties in describing part of the data. The problem is to find out the predictive power of different models, codes, and phenomenological systematics, and to identify the regions of projectiles, targets, incident energies, and produced nuclides where each model or systematics works better. When we know this, we can create a reliable evaluated library as we did in our medical isotope production study (Van Riper, Mashnik, & Wilson 1998; 2000). We think, a similar library would be very useful for astrophysical simulations as well, therefore let us remind here our main concept. We chose to create our evaluated library (Mashnik, Sierk, Van Riper & Wilson 1998) by constructing excitation functions using all available experimental data along with calculations using some of the more reliable codes, employing each of them in the regions of targets and incident energies where they are most applicable. When we had reliable experimental data, they were taken as the highest priority for our approximation as compared to model results, and wherever possible, we attempted to construct a smooth transition from one data source to another.

The recent International Code Comparisons for Intermediate Energy Nuclear Data organized by NEA/OECD at Paris (Blann et al. 1994, Michel & Nagel 1997), our own comprehensive benchmarks (Van Riper et al. 1997, Mashnik, Sierk, Van Riper & Wilson 1998, Van Riper, Mashnik, & Wilson 1998 and 2000), several studies by Titarenko et al. (1999a, 1999b, and references therein), and the recent Ph.D. thesis by Batyaev (1999), specially dedicated to benchmark currently available models and codes, have shown that a modified version of the Cascade-Exciton model (CEM) as realized in the code CEM95 (Mashnik 1995) and the LAHET code system (Prael & Lichtenstein 1989) generally have the best predictive powers for spallation reactions at energies above 100 MeV as compared to other available models.

Therefore, we choose CEM95 (Mashnik 1995), the recently improved version of the CEM code, CEM97x, (Mashnik & Sierk 1998), and LAHET (Prael & Lichtenstein 1989) above 100 MeV to evaluate the required cross sections. The same benchmarks have shown that at lower energies, the HMS-ALICE code (Blann & Chadwick 1998) most accurately reproduces experimental results as compared with other models. We therefore use the activation library calculated by Chadwick (M. B. Chadwick 1998, private communication) with the HMS-ALICE code (Blann & Chadwick 1998)
for protons below 100 MeV and neutrons between 20 and 100 MeV. In the overlapping region, between 100 and 150 MeV, we use both HMS-ALICE and CEM95 and/or LAHET results. For neutrons below 20 MeV, we consider the data of the European Activation File EAF-97, Rev. 1 (Muir & Koning 1996, Sublet, Kopecky, Forrest, & Niegro 1997) with some recent improvements by Herman (1996), to be the most accurate results available; therefore we use them as the first priority in our evaluation.

Measured cross-section data from our LANL T-2 compilation described in the previous subsection (Mashnik, Sierk, Van Riper & Wilson 1998), when available, are included together with theoretical results and are used to evaluate cross sections for study. We note that when we put together all these different theoretical results and experimental data, rarely do they agree perfectly with each other, providing a smooth continuity of evaluated excitation functions. Often, the resulting compilations show significant disagreement at energies where the available data progresses from one source to another. These sets are thinned to eliminate discrepant data, providing data sets of more-or-less reasonable continuity defining our evaluated cross sections.

An examples with typical results of evaluated activation cross sections for both proton- and neutron-induced reactions is shown in Fig. 12. by broad gray lines. 51 similar color figures for proton-induced reactions and 57 figures for neutrons, can be found on the Web, in our detailed report (Van Riper, Mashnik, & Wilson 1998). We think that constructing and using similar evaluated libraries in astrophysical calculations (at least for the most important reactions) would significantly improve the reliability of final results and would help us, for instance, to better understand the origin of some light and medium elements, their abundances, and the role of spallation processes in nucleosynthesis.

New reliable measurements, in particular, on separate isotopes of (enriched) targets or using reverse kinematics as mentioned above, and further development of nuclear reaction models and phenomenological systematics are necessary to produce a reliable evaluated library of spallation cross sections. Excitation functions, i.e., spallation cross sections as functions of the kinetic energy of projectiles, are a very “difficult” characteristic of nuclear reactions as they involve together the different and complicated physics processes of spallation, evaporation, fission, and fragmentation of nuclei. A lot of work is still necessary to be done by theorists and code developers before a reliable complex of codes able to satisfactorily predict arbitrary excitation functions in a wide range of incident energies/projectiles/targets/final nuclides will be available. At present, we are still very far from the completion of this difficult task (Mashnik, Sierk, Bersillon, & Gabriel 1997).

In the meantime, to evaluate excitation functions needed for astrophysics, nuclear science, and applications, it is necessary to use and analyze together the available experimental data, and for each region of incident energies/projectiles/targets/final nuclides, the predictions of phenomenological systematics, and the results of calculations with the most reliable codes, and not to limit ourselves just to one source of data, as was practiced in many past astrophysical simulations.
Fig. 12.— Examples of data and evaluations for $(p,x)$ and $(n,x)$ reactions from the LANL T-2 library (Garland, Schenter, Talbert, Mashnik, & Wilson 1999). Experimental data for protons from the LANL T-2 compilation (Mashnik, Sierk, Van Riper, & Wilson 1998) are shown by triangles, and for neutrons, from the European Activation File EAF-97 (Sublet, Kopecky, Forrest, & Niegro 1997), by the magenta line marked with “E”. Calculations with the HMS-ALICE code (Blann & Chadwick 1998) are shown by blue lines marked with “A”, and with the CEM95 code (Mashnik 1995), by red lines marked with “C”. Evaluated cross sections are shown by broad gray lines.
7. Summary

We have performed a brief review of nuclide abundances in the solar system and in cosmic rays and of the believed today mechanisms of their production. We have shown on a number of examples that nuclear spallation processes play an important role in synthesis not only of the light nuclei, Li-Be-B, but also in production of other elements in the solar system, in cosmogenic nucleosynthesis, in production of most energetic nuclei in cosmic rays, in cosmic ray exposure of the lunar (and planets) surface material and of meteorites, as a source of positron emitters, etc.

To study and understand these processes, reliable spallation cross sections for a variety of reactions are needed. We have performed a brief review of recent measurements, compilations, calculations, and evaluations of spallation cross sections relevant to astrophysics. We have shown on several examples that in some past astrophysical simulations old experimental cross sections were used that are in poor agreement with recent measurements and calculations with reliable modern models of nuclear reactions.

We suggest to not limit in astrophysical calculations only to one source of spallation cross sections as was done in some previous works but to use and analyze together all available experimental data, and for each region of incident energies/projectiles/targets/final nuclides, the predictions of phenomenological systematics, and the results of calculations with the most reliable models and codes. Even better it would be to produce an universal evaluated library of spallation cross sections needed for astrophysics, using together available experimental data and calculations with the most reliable codes, as was done before in the group T-2 at LANL for a number of reactions of interest for our medical isotope production study. Such an evaluated data library would be very useful not only for astrophysical simulations, but also for fundamental nuclear physics itself and a number of important applications, like ATW, ABC, ADEP, APT, medical isotope production, etc. New reliable measurements on separate isotopes of (enriched) targets or using reverse kinematics, extending and updating already created compilations of spallation cross sections by nuclear physicists, like NUCLEX and the LANL T-2 library, as well as merging these data libraries with astrophysical libraries, like CSIRS, ECSIL, and ECSIL2, and, finally, further development of nuclear reaction models and phenomenological systematics are necessary to successfully complete this goal.

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REFERENCES

Aleksandrov, Yu. V., et al. 1995, Bull. Russian Acad. Sci.: Physics, 59, 895

Angulo, C., et al. 1999, Nucl. Phys. A., 656, 3

Armstrong, T. W., & Chandler, K. C. 1972, Nucl. Sci. Eng., 49, 110

Arnett, W. D. 1968, ApJ, 153, 341

Arnett, W. D. 1969, Ap&SS, 5, 180

Arnett, W. D. 1969, ApJ, 137, 1369

Arnett, W. D. 1995, ARA&A, 33, 115

Audouze, J., Epherre, M., & Reeves, H. 1967, in: High-Energy Nuclear Reactions in Astrophysics, ed. B. Shen (New York: W. A. Benjamin), 255

Barashenkov, V. S., & Toneev, V. D. 1972, Interaction of High Energy Particles and Nuclei with Atomic Nuclei (Moscow: Atomizdat)

Baradaran, D. W., et al. 1997, Phys. Rev., C55, 820

Belyaev, B. N., Domkin, V. D., & Mukhin, V. S. 1994, Phys. At. Nucl., 57, 1163

Bernas, R., Gradsztajn, E., Reeves, H., & Schtzman, E. 1967, Ann. Phys. (N.Y.), 44, 426

Bethe, H. A. 1999, Rev. Mod. Phys., 71, S6

Blann, M., Gruppelar, H., Nagel, P., & Rodens, J. 1994, International Code Comparison for Intermediate Energy Nuclear Data, (Paris: NEA OECD)

Blann, M., & Chadwick, M. B. 1998, Phys. Rev. C, 57, 233

Bodemann, R., et al. 1993, Nucl. Instr. Meth. B, 82, 9

Boyd, R. N. 1999, Chapter 22 in Heavy Elements and Related New Phenomena, Vol. 2, eds. W. Greiner and R. K. Gupta (Singapore: World Scientific), 893

Burbidge, E. M., Burbidge, G. R., Fowler, W. A., & Hoyle, F. 1957, Rev. Mod. Phys., 29, 547

Batyaev, V. F. 1999, Ph.D. thesis, ITEP, Moscow

Burles, S., & Tytler, D. 1998a, ApJ, 499, 699

Burles, S., & Tytler, D. 1998b, ApJ, 507, 732

Burles, S., Nollett, K. M., Truran, J. W., & Turner, M. S. 1999, Phys. Rev. Lett., 82, 4176

Busso, M., Gallino, R., & Wasserburg, G. J. 1999, ARA&A 37, 239

Cameron, A. G. W. 1999, ARA&A, 37, 1

Caso, C, et al. 1998, European Physical Journal C3, 1; Revised September 1999 update “16. Big-Bang Nucleosynthesis,” by K. A. Olive, available on the PDG WWW page: http://pdg.lbl.gov

Chadwick, M. B., et al. 1999, Nucl. Sci. Eng., 131, 293

Chen, C.-Z., et al. 1997, Phys. Rev. C, 56, 1536
Copi, C. J., Schramm, D. N., & Turner, M. S. 1997, Phys. Rev. C, 55, 3389
Cowan, J. J., Pfeiffer, B., Kratz, K.-L., Thielemann, F.-K., Sneden, C., Burles, S., Tytler, D., & Beers, T. C. 1999, ApJ, 521, 194
Crosas, M., & Weisheit, J. 1996, ApJ, 465, 659
Danagulyan, A. S., et al. 2000, Phys. At. Nucl., 63, 151
Duncan, D. K., Lambert, D. L., & Lemke, M. 1992, ApJ, 401, 584
Duncan, D. K., et al. 1997, ApJ, 488, 338
Fessler, A., et al. 2000, Nucl. Sci. Eng., 134, 171
Fields, B. D., & Olive, K. A. 1998, preprint (astro-ph/9811183)
Fields, B. D., Olive, K. A., Vangioni-Flam, E., & Casse, M. 1999, preprint (astro-ph/9911320)
Foshina, M., Martins, J. B., & Tavares, O. A. P. 1984, Radiochim. Acta, 35, 121
Gabriel, T. A., & Mashnik, S. G. 1996, JINR Preprint E4-96-43, Dubna
Garland, M. A., Schenter, R. E., Talbert, R. J., Mashnik, S. G., & Wilson, W. B. 1999, Proc. 3rd Int. Conf. on Isotopes, Vancouver, Canada, September 6-10, 1999, in press, preprint LA-UR-99-4898 (physics/9909021)
Gilabert, E., et al. 1998, Nucl. Instr. Meth. B, 145, 293
Ginzburg, V. L. 1999, Physics-Uspekhi, 42, 353
Gradsztajn, E. 1967, in: High-Energy Nuclear Reactions in Astrophysics, ed. B. Shen (New York: W. A. Benjamin), 247
Gupta, B. K., Das, S., & Biswas, M. M. 1970, Nucl. Phys. A, 155, 49
Hamann, F. & Ferland, G. 1999, ARA&A 37, 487
Henley, E. M., & Schiffer, J. P. 1999, Rev. Mod. Phys., 71, S205
Herman, M. 1996, LANL Report LA-UR-96-4914
Hoyle, F. 1946, Mon. Not. R. Astron. Soc., 106, 343
Hudis, J. 1976, in Spallation Nuclear Reactions and Their Applications, Astrophysics and Space Science Library, vol. 59, ed. B. S. P. Shen and M. Merker, (Dordrecht-Holland: D. Reidel Pub. Comp.), 9
Hüfner, J. 1985, Phys. Rep., 125, 129
Ivanov, V. I., Sobolevsky, N. M., & Semenov, V. G. 1998, in Proc. 3d Specialists Meeting on Shielding Aspects of Accelerators, Targets and Irradiation Facilities (SATIF-3), Tohoku University, Sendai, Japan, May 12-13, 1997, (Paris: NEA/OECD), 277
Kajino, T. 1993, in Proc. Int. Symp. on Origin and Evolution of the Elements, Tokyo, Japan, 16-17 October 1992, Ed. S. Kubono & T. Kajino (Singapore: World Scientific), 15
Käppeler, F., Thielemann, F.-K., & Wiescher, M. 1998, Annu. Rev. Nucl. Part. Sci., 48, 175
Käppeler, F. 1999, Prog. Part. Nucl. Phys., 43, 419

Khlopov, M. Yu. 1999, Cosmoparticle Physics, (World Scientific; Singapore)

Koning, A. J. 1993, ECN-C-93-005 Report, Petten

Koning, A. J., Chadwick, M. B., MacFarlane, R. E., Mashnik, S. G., & Wilson, W. B. 1998, ECN-R-98-012 Report, Petten

Korovin, Yu., et al. 1999, in Proc. 3rd Int. Conf. on Accelerator-Driven Transmutation Technologies and Applications (ADTTA’99), Praha, Czech Republic, June 7-11, 1999, (Paper # P-C29 on the Web page http://www.fjfi.cvut.cz/con_adtt99/)

Kozlovsky, B., Lingenfelter, R. E., & Ramaty, R. 1987, ApJ, 316, 801

Krauss, L. M., & Romanelli, P. 1990, ApJ, 358, 47

Kurtz, M. J., Eichhorn, G., Accomazzi, A., Grant, C., Murray, S. S., & Watson, J. M. 2000, The NASA Astrophysical Data System: Overview, in press, (arXiv:astro-ph/0002104)

Lang, K. R. 1980, Astrophysical Formulae (2d ed.; Berlin: Springer-Verlag)

Lang, K. R. 1999, Astrophysical Formulae, 2 volumes (3d enlarged and revised ed.; Berlin: Springer-Verlag)

Lassus St-Genies, C. H., & Tobailem, J. 1972, Note CEA-N-1466(2), Saclay

Mashnik, S. G. 1995, User Manual for the Code CEM95, Joint Institute for Nuclear Research, Dubna, Russia; see the Web page http://www.nea.fr/abs/html/iae1247.html

Mashnik, S. G., Sierk, A. J., Van Riper, K. A., & Wilson, W. B. 1998, in Proc. 4th Workshop on Simulating Accelerator Radiation Environments, Sept. 14-16, 1998, Knoxville, TN, ed. T. A. Gabriel (Oak Ridge: ORNL), 151

Mashnik, S. G., & Sierk, A. J. 1998, in Proc. 4th Workshop on Simulating Accelerator Radiation Environments, Sept. 14-16, 1998, Knoxville, TN, ed. T. A. Gabriel (Oak Ridge: ORNL), 29

Mashnik, S. G., Sierk, A. J., Bersillon, O., & Gabriel, T. A. 1997, Cascade-Exciton Model Detailed Analysis of Proton Spallation at Energies from 10 MeV to 5 GeV, LANL Report LA-UR-97-2905, http://t2.lanl.gov/publications/publications.html.

McWilliam, A. 1997, ARA&A 35, 503

Michaud, G., & Fowler, W. A. 1977, ApJ, 173, 157

Michel, R. et al. 1997, Nucl. Instr. Meth. B, 129, 153

Michel, R., & Nagel, P. 1997, International Codes and Model Intercomparison for Intermediate Energy Activation Yields, NSC/DOC(97)-1, (Paris: OECD)

Michel, R., Leya, I., & Borges, L. 1996, Nucl. Instr. Meth. B, 113, 434

Michel, R. et al. 1995, Nucl. Instr. Meth. B, 93, 183

Muir, D. W., & Koning, A. J. 1997, in Proc. 2d Int. Conf. on Accelerator-Driven Transmutation Technologies and Applications, Kalmar, Sweden, June 3-7, 1996, ed., H. Condé, (Stokholm: Gotab), 469

Nagel, P., Rodens, J., Blann, M., & Gruppelar, H., 1995, Nucl. Sci. Eng., 119, 97
Olive, K. A., Prantzos, N., Scully, S., & Vangioni-Flam, E. 1994, ApJ, 424, 666
Olive, K. A. 1999, preprint UMN-TH-1735/99, TPI-MINN-98/30 (astro-th/99011231)
Prael, R. E., & Lichtenstein, H. 1989, LANL Report LA-UR-89-3014
Ramaty, R., Kozlovsky, B., & Lingenfelter, R. E. 1996a, ApJ, 456, 525
Ramaty, R. 1996b, A&AS, 120, 373
Ramaty, R., Kozlovsky, B., Lingenfelter, R. E., & Reeves, H. 1997, ApJ, 488, 730
Ramaty, R., Kozlovsky, B., & Lingenfelter, R. E. 1998, Phys. Today, 51, 4, 30
Ramaty, R., Scully, S. T., Lingenfelter, R. E., & Kozlovsky, B. 1999, ApJ, in press (astro-ph/9909021)
Ramaty, R., Vangioni-Flam, E., Cassé, M., & Olive, K. 1999, eds., Proc. Conf. on LiBeB Cosmic Rays and Gamma-Ray Line Astronomy, Paris, December 1998, ASP Conf. Series, 171 (San Francisco: ASP)
Reedy, R. C., & Marti, K. 1990, in The Sun in Time, eds. C. P. Sonett, M. S. Giampapa, & M. S. Matthews (Tucson: Univ. of Arizona Press), 260
Reeves, H. 1994, Rev. Mod. Phys., 66, 193
Reames, D. V. 1967, in: High-Energy Nuclear Reactions in Astrophysics, ed. B. Shen (New York: W. A. Benjamin), 273
Rudstam, G. 1966, Zs. f. Naturforsch. A, 21, 1027
Ryan, S. G., Beers, T. C., Olive, K. A., Fields, B. D., & Norris, J. E. 1999, preprint (astro-ph/9905211)
Salpeter, E. E. 1999, Rev. Mod. Phys., 71, S220
Sarkar, S. 1999, preprint (astro-th/9903183)
Schramm, D. N. 1995, in The Light Element Abundances, Proc. of an ESO/EIPC Workshop Held in Marciana Marina, Isola d’Ebla, May 21–26, 1994, ed. P. Crane (Berlin: Springer), 50
Schramm, D. N., & Turner M. S. 1998, Rev. Mod. Phys., 70, 303
Silberberg, R., Tsao, C. H., & Barghouty, A. F. 1998, ApJ, 501, 911
Silberberg, R., & Tsao, C. H. 1973a, ApJS, 220, 315
Silberberg, R., & Tsao, C. H. 1973b, ApJS, 220, 335
Silberberg, R., Tsao, C. H., & Shapiro, M. M. 1976, in Astrophysics and Space Science Library, Vol. 59, eds. B. S. O. Shen, & M. Merker (Dordrecht: D. Reidel Publ. Comp.), 49
Simpson, J. A. 1983, Ann. Rev. Nucl. Part. Sci., 33, 323
Sisterson, J. M., et al. 1997, Nucl. Instr. Meth. B, 123, 324
Smith, M. S., Cecil, F. E., Firestone, R. B., Hale, G. M., Larson, D. C., & Resler, D. A. 1996, U.S. Nuclear Data Resources for a Coordinated U.S. Effort in Nuclear Data for Nuclear Astrophysics, http://www.dne.bnl.gov/ burrows/usnrdn/astrodata.html
Smith, M. S., Kawano, L. H., & Malaney, R. A. 1993, ApJS, 85, 219

Sobolevsky, N. M. et al., 1991, Production of Radionuclides at Intermediate Energies, Subvolume A: Interaction of Protons with Targets from He to Br, Landolt-Börnstein, New Series, I/13a, ed. H. Schopper, (Berlin, Heidelberg: Springer Verlag)

Sobolevsky, N. M. et al., 1992, Production of Radionuclides at Intermediate Energies, Subvolume B: Interaction of Protons with Targets from Kr to Te, Landolt-Börnstein, New Series, I/13b, ed. H. Schopper, (Berlin, Heidelberg: Springer Verlag)

Sobolevsky, N. M. et al., 1993, Production of Radionuclides at Intermediate Energies, Subvolume C: Interaction of Protons with Targets from I to Am, Landolt-Börnstein, New Series, I/13c, ed. H. Schopper, (Berlin, Heidelberg: Springer Verlag)

Sobolevsky, N. M. et al., 1994a, Production of Radionuclides at Intermediate Energies, Subvolume D: Interaction of Protons with Nuclei (Supplement to I/13a, b, c), Landolt-Börnstein, New Series, I/13d, ed. H. Schopper, (Berlin, Heidelberg: Springer Verlag)

Sobolevsky, N. M. et al., 1994b, Production of Radionuclides at Intermediate Energies, Subvolume E: Interaction of Pions and Antiprotons with Nuclei, Landolt-Börnstein, New Series, I/13e, ed. H. Schopper, (Berlin, Heidelberg: Springer Verlag)

Sobolevsky, N. M. et al., 1995, Production of Radionuclides at Intermediate Energies, Subvolume F: Interaction of Deuterons, Tritons and 3He-nuclei with Nuclei, Landolt-Börnstein, New Series, I/13f, ed. H. Schopper, (Berlin, Heidelberg: Springer Verlag)

Sobolevsky, N. M. et al., 1996a, Production of Radionuclides at Intermediate Energies, Subvolume G: Interaction of α-Particles with Targets from He to Rb, Landolt-Börnstein, New Series, I/13g, ed. H. Schopper, (Berlin, Heidelberg: Springer Verlag)

Sobolevsky, N. M. et al., 1996b, Production of Radionuclides at Intermediate Energies, Subvolume H: Interaction of α-Particles with Targets from Sr to Cf, Landolt-Börnstein, New Series, I/13h, ed. H. Schopper, (Berlin, Heidelberg: Springer Verlag)

Sobolevsky, N. M., et al. 2000, Production of Radionuclides at Intermediate Energies, Subvolume I: Interaction of Protons, Deuterons, Tritons, 3He-nuclei, and α-particles with Nuclei, (Supplement to volumes I/13 a-h), Landolt-Börnstein, New Series, I/13i, ed. H. Schopper, (Berlin, Heidelberg: Springer Verlag)

Steigman, G. 1998, preprint (astro-th/9803055)

Stepanov, N. V. 1988, ITEP Preprint ITEP-55, Moscow

Sublet, J.-Ch., Kopecky, J., Forrest, R. A., & Niegro, D. 1997, The European Activation File: EAF-97 Report file-Rev. 1, UKAEA, Culham, Abigdon, Oxfordshire OX 14 3DB, United Kingdom

Suess, H. E., & Urey, H. C. 1956, Rev. Mod. Phys., 28, 53

Sudar, S. & Qaim, S. M. 1994, Phys. Rev. C, 50, 2408

Sümmerer, K. & Blank, B. 2000, Phys. Rev. C, 61, 034607

Tassan-Got, L., et al. 1998 in Proc. Int. Conf. on the Phys. of Nucl. Sci. and Techn., October 5-8, 1998, Long Island, New York, vol. 2 (LaGrange Park, IL: ANS Inc.), 1334

Thomas, D., Schramm, D. N., Olive, K. A., & Fields, B. D. 1993, ApJ, 406, 579
Titarenko, Yu. E. et al. 1999a, in Proc. 3rd Int. Conf. on Accelerator-Driven Transmutation Technologies and Applications (ADTTA’99), Praha, Czech Republic, June 7-11, 1999, (Paper # P-C27 on the Web page http://www.fjfi.cvut.cz/con_adtt99/)

Titarenko, Yu. E. et al. 1999b, in Proc. 3rd Int. Topical Meeting on Nuclear Applications of Accelerator Technology (AccApp’99), Long Beach, CA, November 14-18, 1999, (LaGrange Park, IL: ANS, Inc.), 212

Tobailem, J., Lassus St-Genies, C. H., & Leveque, L. 1971, Note CEA-N-1466(1), Saclay

Tobailem, J., & Lassus St-Genies, C. H. 1975, Note CEA-N-1466(3), Saclay

Tobailem, J., & Lassus St-Genies, C. H. 1977, Note CEA-N-1466(4), Saclay

Tobailem, J. 1981a, Note CEA-N-1466(5), Saclay

Tobailem, J. 1981b, Note CEA-N-1466(6), Saclay

Tobailem, J. 1982, Note CEA-N-1466(7), Saclay

Tobailem, J. 1983, Note CEA-N-1466(8), Saclay

Tsao, C. H., Barghouty, A. F., & Silberberg R. 1999, in Horizons in World Physics Series, vol 230, Topics in Cosmic-Ray Astrophysics, (Commack, New York: Nova Science Publishers, Inc.), 141

Tsipenyuk, Yu. M. 1997, Nuclear Methods in Science and Technology, Fundamental and Applied Nuclear Physics Series, ed. D. A. Bradley, (Bristol, UK: Institute of Physics Publishing)

Turner, M. S. et al. 1996, Astrophys. J. Lett., 466, L59

Turner, M. S. 1999, in The Proc. of Particle Physics and the Universe (Cosmo-98), edited By O. Caldwell (AIP, Woodbury, NY), to be published

Turner, M. S. & Tyson, J. A. 1999, Rev. Mod. Phys., 71, S145

Tytler, D., O’Meara, J. M., Suzuki, N., & Lubin, D. 2000, Physica Scripta, in press, preprint (arXiv:astro-ph/0001318)

Vangioni-Flam, E., Cassé, M., Fields, B. D., & Olive, K. A. 1996, ApJ, 468, 199

Vangioni-Flam, E., Cassé, M., & Audouze, J. 1999, preprint (astro-th/9907171)

Vangioni-Flam, E., Coc, A., Cassé, M., & Oberto, Y. 2000, preprint (arXiv:astro-th/0002248)

Van Riper, K. A., et al. 1997, LANL Report LA-UR-97-5068

Van Riper, K. A., Mashnik, S. G., & Wison, W. B. 1998, LANL Report LA-UR-98-5379 (a 684 page detailed report with 37 tables and 264 color figures is available at the Web page http://t2.lanl.gov/publications/publication.html)

Van Riper, K. A., Mashnik, S. G., & Wison, W. B. 2000, Nucl. Instr. Meth. A, in press (nucl-th/9901073)

Venikov, N. I., Novikov, V. I., & Sebiakin, A. A. 1993, Appl. Radiat. Isot., 44, 751

Vonach, H., et al. 1997, Phys. Rev. C, 55, 2458
Waddington, C. J. 1999, in Horizons in World Physics Series, vol 230, Topics in Cosmic-Ray Astrophysics, (Nova Science Publishers, Inc., Commack, New York), 199

Wallerstein, E. et al. 1997, Rev. Mod. Phys., 69, 995

Webber, W. R., Kish, J. C., & Schrier, D. A. 1990, Phys. Rev. C, 41, 547

Weigel, A. et al. 1999, Geochimica et Cosmochimica Acta, 62, 175

Wlazlo, W., et al. 2000, Phys. Rev. Lett., in press (arXiv:nucl-ex/0002011)

Wolfenstein, L. 1999, Rev. Mod. Phys., 71, S140

Woosley, S. E., Hartmann, D. H., Hoffman, R. D., & Haxton, W. C. 1990, ApJ, 356, 272

Woosley, S. E., & Weaver T. A. 1995, ApJS, 101, 181