ANL/TD/CP-95683

The submitted manuscript has been authored by a contractor of the U S Government under contract No W-31 109-ENG-38. Accordingly the U S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

Nuclear data evaluation for explosive hydrogen burning on A = 30-50 nuclei

RECEIVED
SEP 21 1999
OSTI

D L Smith

TD Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

L A Van Wormer

Department of Physics, Hiram College, Hiram, Ohio 44234, USA

Abstract. A research program to develop a reaction-rate (RR) data base for stellar explosive hydrogen burning via (p,γ) and (p,α) reactions involving stable-isotope target elements in the mass range A = 30-50 (phosphorus to titanium) is described. This project includes: 1) a survey of the literature; 2) preparation of written summaries for pertinent contributions; 3) compilation of alpha-numeric information into computer-platform-independent data files; 4) tabulation of reaction resonance parameters (and uncertainties); 5) determination of resonance RRs (and uncertainties) for Maxwellian-distributed reactant energies corresponding to temperatures in the range T_9 = 0.01-10 GK (1 GK = 10^9 degrees Kelvin); 6) fitting of these calculated RRs with an empirical formula, thereby converting the basic data into a form that is convenient for astrophysical network calculations; 7) examination of deviations between fitted curves and these RRs in the context of the uncertainties. The results of this work are made available to the nuclear astrophysics community through formal laboratory reports and computer files which are distributed to data centers. The procedures used in this work are discussed and some representative examples of products from the activity are given.

1. Introduction

The nuclear data needs for analysis of stellar evolution are extensive. Without comprehensive, accurate nuclear data even the most sophisticated models of stellar nucleosynthesis will yield unreliable results. There exist ~280 stable isotopes and > 2500 radioactive isotopes that may be involved. For each of these, two-body nuclear reactions such as (n,γ), (n,p), (n,α), (p,γ), (p,n), (p,α), (α,γ), (α,p), (α,n), *etc.*, should be considered. The relative importance of these materials and reactions depends on stellar temperature, cross sections, radioactive decay half lives, stellar condition, and other factors [1-3]. In very hot, explosive environments such as novae and supernovae, the rp-process is an important mechanism for processing matter from lower-mass to higher-mass species [3]. The present program examines stable-isotope targets in the mass range A = 30-50 (phosphorus to titanium), focusing on competition between the hydrogen-

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

burning reactions (p,γ) and (p,α). The properties of (p,n) reactions form a topic for another investigation so they will not be discussed here. When (p,γ) dominates, mass transfer to heavier elements tends to be rapid. However, at certain points in the Chart of the Nuclides where the (p,α) reaction is competitive, matter processing toward higher-A elements can be halted or severely impeded by the onset of reaction cycles. Competition between these two processes for various stellar conditions is influenced by several factors, including the Q-value, the Coulomb and angular momentum barriers, and details of nuclear structure [4,5]. Table 1 lists some of the influential parameters for stable targets in the mass range A = 30-50.

Table 1: Properties of proton reactions on stable targets with masses in the range A = 30-50 [4]

Target	C-N [a]	Half Life [b]	Decay Mode [c]	$Q_{p\gamma}$ (keV) [d]	$Q_{p\alpha}$ (keV) [d]
^{31}P	^{32}S	Stable	None	8864	1916
^{32}S	^{33}Cl	2.511 s	ϵ	2277	-4200
^{33}S	^{34}Cl	1.5264 s (32.00 m)	ϵ (IT,ϵ)	5143	-1522
^{34}S	^{35}Cl	Stable	None	6371	-627
^{36}S	^{37}Cl	Stable	None	8387	538
^{35}Cl	^{36}Ar	Stable	None	8506	1867
^{37}Cl	^{38}Ar	Stable	None	10242	3034
^{36}Ar	^{37}K	1.226 s	ϵ	1858	-4363
^{38}Ar	^{39}K	Stable	None	6381	-837
^{40}Ar	^{41}K	Stable	None	7808	1586
^{39}K	^{40}Ca	Stable	None	8328	1288
^{40}K [f]	^{41}Ca	1.03×10^5 y	ϵ	8891	2277
^{41}K	^{42}Ca	Stable	None	10277	4020
^{40}Ca	^{41}Sc	596.3 ms	ϵ	1085	-5183
^{42}Ca	^{43}Sc	3.891 h	ϵ	4930	124
^{43}Ca	^{44}Sc	3.927 h (58.6 h)	ϵ (IT,ϵ)	6696	-9
^{44}Ca	^{45}Sc	Stable (318 ms)	None (IT)	6889	-1046
^{46}Ca	^{47}Sc	3.3492 d	β^-	8486	-1678
^{48}Ca	^{49}Sc	57.2 m	β^-	9627	-2743
^{45}Sc	^{46}Ti	Stable	None	10345	2342
^{46}Ti	^{47}V	32.6 m	ϵ	5168	-3074
^{47}Ti	^{48}V	15.9735 d	ϵ	6832	-2252
^{48}Ti	^{49}V	330 d	ϵ	6758	-2554
^{49}Ti	^{50}V [e]	1.4×10^{17} y	ϵ,β^-	7949	-1935
^{50}Ti	^{51}V	Stable	None	8061	-2230

[a] C-N = Compound-nucleus system consisting of (proton + target).
[b] Half life of ground state of C-N is usually given; values in (...) corresponds to an isomeric state.
[c] Decay mode of ground state of C-N is given; mode in (...) is for an isomeric state. Decay modes: ϵ = electron capture and/or positron emission; β^- = beta (electron) emission; IT = isomeric transition.
[d] Ground-state reaction Q-value rounded to the nearest whole keV.
[e] ^{40}K (1.277×10^9 y) and ^{50}V (1.4×10^{17} y) are, for present purposes, effectively stable.

A quick glance at Table 1 suggests that, on the basis of Q-value alone, the probability that (p,α) might compete significantly with (p,γ) is probably the greatest for ^{31}P, ^{36}S, ^{35,37}Cl, ^{40}Ar, ^{39,40,41}K, and ^{45}Sc. However, a careful analysis of other factors which affect these reactions is required to understand the role of specific nuclear processes in various stellar environments. Among these additional factors is the half life of the product nucleus from a (p,γ) reaction. If the reaction product is stable or long-lived, a subsequent proton capture reaction on the product nucleus can fuel the rp-process. However, if the reaction product decays with a short half life this can slow down the rp-process, unless the stellar hydrogen density is extremely high.

2. Scope of this program

A large amount of new information pertinent to stellar nucleosynthesis has been accumulated from recent astronomical observations. Proper interpretation of these data demands sophisticated modeling techniques and a reliable data base of basic physical parameters, including nuclear ones. The work of Caughlan and Fowler $\leq$ 1988 (*e.g.*, [6]) attempted to provide the astrophysics community with a consistent set of nuclear reaction data. Their widely used results are limited to reactions with $Z \leq 14$ and $A \leq 30$. This work needs to be updated to incorporate new nuclear data. More recently (1996), Angulo *et al.* [7] have provided nuclear-reaction information for light elements up to Si. The goal of the present program is to complement these and other related nuclear data compilation activities, extending the target mass range to A = 30-50, but focusing, for the present, only on the hydrogen-burning reactions (p,γ) and (p,α). The present investigation is limited to reactions involving stable targets in their ground states, since very few experimental data are available for targets that are radioactive or reside in excited states. This program includes the following components: a survey of the literature on nuclear properties relevant to these reactions; preparation of written summaries of documents from the literature; compilation of pertinent nuclear parameters from these sources and storage of this information in a computer data base; calculation of stellar nuclear reaction rates (RRs) and estimation of their uncertainties; preparation of parameterized fits to these RRs and critical assessment of the quality of these numerical recipes. The results from this work are documented in formal laboratory reports and are transmitted to nuclear data centers.

3. Stellar nuclear reaction rates and their uncertainties

For analyses of stellar evolution, it is necessary to know the RRs for pertinent two-body nuclear reactions as a function of stellar temperature T, which is often expressed as T_6 MK (1 MK = 10^6 °K) or T_9 GK (1 GK = 10^9 °K) [1-3]. Under stellar conditions, the reactant energies are non-relativistic, to a good approximation, and are distributed according to a Maxwell-Boltzmann function characterized by κT (κ is Boltzmann's constant). The factor κT, in energy units, can be deduced easily from the fact that T_9 = 1 GK corresponds to κT = 86.173 keV. In such environments, the RR per interacting particle pair is related to cross section σ and relative velocity v of the reacting particles by the formula

$$\langle \sigma v \rangle = (8/\pi\mu)^{1/2}(\kappa T)^{-3/2} \int \sigma(E)\, E \exp(-E/\kappa T) dE, \qquad (1)$$

where E is the center-of-mass energy and μ is the reduced mass of the reacting particles. Integration extends from 0 to ∞ [2]. Eq. (1) represents an average of the energy-dependent reaction cross section, using the weighting function $w(E) \propto E \exp(-E/\kappa T)$. For small E, $w(E) \propto E$, while for large E, $w(E) \propto \exp(-E/\kappa T)$. It is instructive to examine the energy ranges that are

influential for various values of stellar temperature. The first observation is that 73.57% of the strength of this weighting function lies at energies above $E = \kappa T$. Proceeding further, we can define the 90%-response range (E_5, E_{95}) as that range of energies such that 5% of the strength of w(E) lies below E_5 while 5% lies above E_{95}. Let E_{99} be that energy such that only 1% of the strength of w(E) extends to higher energies. It is easy to show that for stellar temperature $T_9 =$ 1 GK, $E_5 = 30.60$ keV, $E_{95} = 408.7$ keV, and $E_{99} = 572.0$ keV. For other values of stellar temperature, these characteristic energies scale linearly with κT. Temperatures as high as $T_9 =$ 10 GK may occur in supernova explosions, but lower temperatures tend to prevail for other stellar environments. This approach to understanding the relative importance of different energies must be modified somewhat to account for the behavior of σ vs. E. However, the picture which emerges from the preceding analysis is basically correct. Consequently, the important interaction-energy region for nucleosynthesis in stars is generally below a few MeV.

The cross section σ from threshold (if applicable) to a few MeV must be known in order to calculate the RR, according to Eq. (1). Due to Coulomb repulsion, the cross sections for charged-particle (C-P) reactions in the mass range A = 30-50 are usually small, and often are very difficult, if not impossible, to measure directly at the relatively low energies encountered in stellar environments. Additional problems emerge when considering reactions that involve radioactive targets. So, indirect measurement techniques and/or nuclear-model calculations may have to be employed in estimating RRs. Therefore, it is important to have an understanding of the reaction mechanisms involved. Protons are captured to form a compound-nucleus (C-N) system (proton + target). The C-N can decay through particle-emission channels, *e.g.*, (p,n), (p,p), or (p,α), or by a radiative transition, (p,γ). From the shell-model point of view, C-N states formed in the mass range A = 30-50 are likely to be configurations of one or more valence nucleons in the $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$, $1f_{7/2}$, and $2p_{3/2}$ shells. The proton capture process, and subsequent decay of C-N states, can exhibit strong energy dependence, characteristic of resonance behavior, or milder energy dependence indicative of direct interactions or, most likely, a combination of both. When the density of C-N states is very high, statistical (Ericson) fluctuations in the cross section can occur. The details are governed by the particular target isotope, reaction process, interaction energy, and nuclear structure.

The reaction cross sections are typically enhanced near sharp resonances and decrease to much smaller values between these resonances, or in the wings of broad resonances. For this reason, the discrete-resonance contributions tend to dominate the RR when there are numerous narrow, isolated, and relatively weakly interfering resonances in the C-N, *i.e.*, when $\langle\Gamma\rangle \leq \langle D\rangle$. Here, $\langle\Gamma\rangle$ denotes average level width while $\langle D\rangle$ is the average level spacing. If the level density in the C-N is low, *i.e.*, if $\langle\Gamma\rangle \ll \langle D\rangle$, then the effects of direct processes or broad resonances can be more significant. Another extreme case involves very high level densities, *i.e.*, $\langle\Gamma\rangle \geq \langle D\rangle$. Then, it is not feasible to analyze the reaction process in terms of isolated resonances since these resonances tend to interfere. Statistical model calculations employing Hauser-Feshbach formalism (H-F) may then be required to estimate the energy-dependent cross section σ and associated RR. In the mass range A = 30-50, resonances tend to be relatively narrow because the E-M process governing decay by (p,γ) is relatively weak while, at the same time, the Coulomb barrier inhibits decay by the strong interactions associated with proton or α-particle emission. Irrespective of detailed nuclear-structure considerations, the level density increases steadily with the C-N excitation energy E_x. Since E_x is related to the (p,γ) reaction Q-value by the simple expression $E_x = E + Q_{p\gamma}$, one can surmise from an inspection of Table 1 which stable-target reactions are likely *a priori* to involve low or high C-N level densities.

When (p,γ) and (p,α) reaction strengths are strongly dominated by discrete, narrow, and weakly interacting resonances, Eq. (1) for RR can be expressed to a good approximation [2] by the formula

$$<\sigma v> \approx (2\pi/\mu\kappa T)^{3/2}(h/2\pi)^2 f\, \Sigma_i\, (\omega\gamma)_i \exp(-E_i/\kappa T), \qquad (2)$$

where f = electron screening factor, h = Planck's constant, J = C-N spin, J_p = ½, J_t = target spin, $(\omega\gamma)_i = [(2J+1)(2J_p+1)^{-1}(2J_t+1)^{-1}\Gamma_p\Gamma_x\Gamma^{-1}]_i$, Γ_p = proton width, Γ_x = width for decay by radiation x (γ or α), and Γ = total width. The subscript "i" refers to an individual resonance and the sum extends over all known resonances below a selected upper cutoff energy E_{max}. With f = 1, T_9 in GK, E_i in MeV, μ in amu, and $(\omega\gamma)_i$ in eV, Eq. (2) leads to the expression

$$R(T_9) \approx (1.54\text{x}10^5)(\mu T_9)^{-3/2}\, \Sigma_i\, (\omega\gamma)_i \exp(-11.605E_i/T_9) \qquad (3)$$

in $cm^3s^{-1}mol^{-1}$. Note that Avogadro's constant $N_A = 6.022137 \times 10^{23}$ atoms/mol (cgs) has been introduced so that $R(T_9) = N_A<\sigma v>$. Eq. (3) has been the basis for our analysis of stellar RRs to date. Adjustments to the RR to account for direct proton capture, broad resonances, bound states of the C-N, and other effects that may be significant, will be investigated in the future.

Objective estimates of uncertainties $\Delta R(T_9)$ in the reaction rate $R(T_9)$, can be obtained by propagating errors in the resonance parameters E_i and $(\omega\gamma)_i$ according to a well-known formalism [8]. This methodology utilizes the matrix expression

$$\mathbf{V_R} = \mathbf{S}^+\, \mathbf{V_p}\, \mathbf{S}, \qquad (4)$$

where $\mathbf{V_p}$ = diagonal covariance matrix of resonance parameter absolute uncertainties (parameter errors are treated as uncorrelated), **S** = sensitivity matrix whose elements are partial derivatives of RR values for various T_9 w.r.t. the resonance parameters, $\mathbf{S}^+$ is the transpose of **S**, and $\mathbf{V_R}$ = reaction-rate covariance matrix. Matrix **S** provides a weighting based on sensitivity of the RR to changes in resonance energies and strengths. RR uncertainties are then given by the formula

$$(\Delta R)_k = [(\mathbf{V_R})_{kk}]^{1/2}, \qquad (5)$$

where index "k" denotes a specific value of T_9. Errors in the RR values for various T_9 tend to be strongly correlated due to the common set of resonance parameters.

4. Information sources

The starting point for literature searches is always Nuclear Science References (NSR), a low- and intermediate-energy nuclear physics bibliography obtainable from National Nuclear Data Center (NNDC), Brookhaven National Laboratory (Telnet: bnlnd2.dne.bnl.gov; WWW: http://www.nndc.bnl.gov) [9]. A typical NSR citation is shown in Fig. 1.

Figure 1: Example - Typical NSR citation for the $^{31}P(p,\alpha)^{28}Si$ reaction

```
67Ve05

Nucl.Phys. A102, 449 (1967), J.Vernotte, M.Langevin, F.Takeutchi,
Niveaux de 32S Observes dans les Reactions 31P(p,alpha)28Si et
28Si(alpha,gamma)32S
<KEYWORDS> NUCLEAR REACTIONS 31P(p,alpha),E = 1.4-1.9 MeV;
28Si(alpha,gamma),E = 3.7-4.3 MeV; measured sigma(E;theta),sigma(E;E
gamma,theta),gamma-gamma(theta). 32S deduced resonances,J,pi,level-
width,strengths. Enriched 28Si target.
```

Other references are found through citations in the original NSR references. Most of these references can be located through the resources of the Argonne National Laboratory library system. Each reference is identified by using a code symbol based on the author(s) and date, *e.g.*, MS97 (Miller and Smith, 1997) [10].

5. Reference summaries

Each reference is summarized in a standard way which generally includes the title, reference, abstract, reaction(s), facility(ies), experiment, measurement procedures, type of data acquired, data analysis method, results, and related discussions. For references with little content, only the title, reference, and abstract appear in the summary. A typical summary is shown in Fig. 2.

Figure 2: Example - summary corresponding to reference KH73a dealing with p + ^{31}P reactions

TITLE: Isospin Dependence of the Nuclear Level Width
REFERENCE: M. Kildir and J.R. Huizenga, Physical Review C8, No. 5, 1965 (1973).
ABSTRACT: Statistical fluctuation analyses of ^{31}P(p,α) and ^{31}P(p,p') excitation functions are used to deduce level widths for the $T_<$ and $T_>$ isospin states in ^{32}S at 17.8 MeV of 38.7 ± 2.7 and 26.2 ± 3.5 keV, respectively. These two widths in ^{55}Mn at 17.6 MeV are reported also. Relative level densities of the two isospins are calculated for each nucleus.
REACTIONS: ^{31}P(p,α) and ^{31}P(p,p')
FACILITY: Nuclear Structure Research Laboratory and Department of Chemistry and Physics, University of Rochester, Rochester, New York. Measurements were made in the proton-energy interval 8.51 to 10.01 MeV. No mention is made in the article [KH73a] of the type of accelerator used. Presumably it was a Tandem Van de Graaff accelerator.
EXPERIMENT: The objective of this experiment was to determine widths for levels corresponding to each of the two isospins, $T_<$ and $T_>$, based on an analysis of fluctuations in the excitation functions for the reactions ^{31}P(p,p_0), ^{31}P(p,p_2), ^{31}P(p,α_0), and ^{31}P(p,α_1).
MEASUREMENT PROCEDURES: The description of experimental procedures is very sketchy. Excitation functions were measured simultaneously for the (p,p') and (p,α) reactions in the proton energy range of 8.51 to 10.01 MeV in 10-keV steps. The target was placed at 30° to the incident beam in a 51-cm scattering chamber. This target consisted of 40 μg/cm^2 of ^{31}P which was vacuum-evaporatied onto a 20 μg/cm^2 carbon foil. Alpha particles and protons were detected with surface-barrier solid state detectors placed at several angles between 85° and 165° (laboratory angles). The detectors for the protons, except the one at 90°, were covered with sufficient thickness of aluminum to just stop the α-particles.
DATA ACQUIRED: The data acquired consisted of proton and α-particle yield excitation functions measured at various angles in 10-keV energy steps over the range 8.51 to 10.01 MeV.
DATA ANALYSIS: Each of the experimental excitation functions exhibited, on the average, a small decrease in cross section with increasing energy. This energy dependence was removed from these excitation functions before proceeding with the fluctuation analysis. Two different methods were used to estimate this energy dependence. One was based on Hauser-Feshbach calculations. The second involved a simple straight-line fit to the experimental data. Level widths were deduced from auto-correlation functions based on the experimental data. The widths deduced in this manner appeared to be insensitive to the method used to remove the energy dependence of the excitation functions.Widths for both of the levels in two isospins in the compound nucleus ^{32}S determined from the excitation function for ^{31}P(p,p_0), ^{31}P(p,p_2), ^{31}P(p,α_0) and ^{31}P(p,α_1) reactions. Each of these was done at three different angles. Relative level densities from T=0 and T=1 states of ^{32}S were also obtained.
RESULTS AND DISCUSSION: The results are reported in the text and tables of this paper [KH73a]. The average level widths in ^{32}S determined from the ^{31}P(p,p') and ^{31}P(p,α) reactions are 30.0 ± 1.4 keV and 38.7 ± 2.7 keV, respectively. These values are similar to those determined for ^{32}S from several reactions discussed elsewhere in the literature. The most probable explanation for the experimental level width from the (p,α) reaction channels being different from that of the (p,p') reaction channels is the partial or complete conservation of isospin in the intermediate composite nucleus. If isospin is a good quantum number, the (p,α_0) and (p,α_1) reactions proceed through only $T_<$ isospin states in the composite nucleus. Hence, the level width extracted from the excitation functions for these reactions is the width of the $T_<$ isospin states. However, the ^{31}P(p,p') reactions can involve both $T_<$ and $T_>$ isospin states. From the measured excitation functions it was determined that the level widths for the $T_<$ = 0 and $T_>$ = 1 isospin states in the composite nucleus ^{32}S are 38.7 ± 2.7 keV and 26.2 ± 3.5 keV, respectively. It was also found that the ratio of level densities for $T_<$ to $T_>$ states at an excitation of 17.8 MeV in ^{32}S is about 1. This result is in a large part accounted for by nuclear pairing. The T = 0 states originate from an even-even nucleus with a large pairing energy while the T = 1 states of ^{32}S are analog states of ^{32}P which is an odd-odd nucleus.

6. Computer data files

Descriptive and numerical information are extracted from these references primarily - but not exclusively - for the following topics: cross sections; resonance parameters (energies, widths, *etc.*); reduced widths and spectroscopic factors; C-N decay branching ratios (*e.g.*, γ_1, γ_2, γ_3, ... or α_1, α_2, α_3, ...); γ-ray multipolarities and mixing ratios; angular distributions of C-N decay radiation (*i.e.*, γ-rays or α-particles); C-N level energies; C-N level decay lifetimes; C-N level spins, parities, and isospins; reaction-product nuclear-level energies, spins, parities and isospins; thick-target γ-ray yields for applications in the analysis of material-surface elemental composition by the method of proton-induced gamma-ray emission (PIGE).

When we started this project, there appeared to be no guidelines concerning a standard format to use for compiling astrophysical nuclear data. Therefore, a computer-platform-independent format that utilizes only ASCII characters to represent alpha-numeric information (descriptions of experiments and numerical results) has been adopted for the present project. This format is referred to as EXFOR, and it is widely used for the compilation and exchange (between various data centers around the world) of neutron-reaction data [11]. It is relatively simple to read EXFOR files and to convert them to other formats as needed using codes developed at the NNDC. A typical EXFOR file generated in this work appears in Fig. 3.

Figure 3: Example - EXFOR file corresponding to reference D+94 for the $^{31}P(p,\alpha)^{28}Si$ reaction

```
ENTRY              D+94          0                                  D+94 0     1
SUBENT          D+94  1          0                                  D+94 1     1
BIB                   9         20                                  D+94 1     2
INSTITUTES (USANCS)                                                 D+94 1     3
           (USADKE)                                                 D+94 1     4
           (USATTU)                                                 D+94 1     5
REFERENCE  (J,PR/C,49,1,411,1994)                                   D+94 1     6
AUTHORS    (J.M.DRAKE,E.G.BILPUCH,G.E.MITCHELL,J.F.SHRINER,JR.)     D+94 1     7
TITLE      DETAILED-BALANCE TESTS OF TIME-REVERSAL INVARIANCE WITH  D+94 1     8
           INTERFERING CHARGED-PARTICLE RESONANCES                  D+94 1     9
FACILITY   WORK CARRIED OUT AT TRIANGLE UNIVERSITIES NUCLEAR        D+94 1    10
           LABORATORY (TUNL). EXPERIMENTS PERFORMED EARLIER.        D+94 1    11
TARGETS    31P AS WELL AS 23NA, 27AL, 35CL AND 39K.                 D+94 1    12
METHOD     NOT DISCUSSED. PAPER REPORTS ON A THEORETICAL ANALYSIS   D+94 1    13
           OF DATA OBTAINED IN EARLIER EXPERIMENTS AT TUNL.         D+94 1    14
STATUS     RESULTS PUBLISHED IN PHYSICAL REVIEW.                    D+94 1    15
COMMENTS   PAPER GIVES NO INFORMATION ABOUT TARGET FABRICATION,     D+94 1    16
           EXPERIMENTAL SETUP, DETECTORS, CORRECTIONS OR ERROR      D+94 1    17
           ANALYSIS. RESONANCE PARAMETERS OBTAINED EARLIER ARE      D+94 1    18
           USED FOR A STUDY OF DETAILED BALANCE AND TIME-REVERSAL   D+94 1    19
           INVARIANCE (TRI) IN INVERSE REACTIONS. TRI VIOLATION     D+94 1    20
           SOUGHT BY LOOKING FOR EQUIVALENT VIOLATIONS OF DETAILED  D+94 1    21
           BALANCE.                                                 D+94 1    22
ENDBIB              20                                              D+94 1    23
ENDSUBENT            1                                              D+94 199999
SUBENT          D+94  2          0                                  D+94 2     1
BIB                   2         12                                  D+94 2     2
REACTION   31P(P,ALPHA0)28SI                                        D+94 2     3
COMMENTS   VALUES OBTAINED FROM TABLE I OF THE ARTICLE. ALL         D+94 2     4
           RESULTS CORRESPOND TO COMPOUND NUCLEUS 32S. PAIR-IDENT   D+94 2     5
           = INDEX WHICH IDENTIFIES RESONANCE PAIR, AS INDICATED    D+94 2     6
           IN THE TABLE. EA = C.M. ENERGY FOR MEMBER OF RESONANCE   D+94 2     7
           PAIR IDENTIFIED BY "A". GAMMA-A = TOTAL WIDTH OF         D+94 2     8
           RESONANCE "A" OF THE PAIR. EB = C.M. ENERGY FOR MEMBER   D+94 2     9
           OF RESONANCE PAIR IDENTIFIED BY "B". GAMMA-B = TOTAL     D+94 2    10
           WIDTH OF RESONANCE "B" OF THE PAIR. NO ERRORS ARE GIVEN. D+94 2    11
           J-PI = SPIN AND PARITY OF THE RESONANCES. NOTE THAT BOTH D+94 2    12
           "A" AND "B" BY CHOICE HAVE THE SAME SPIN AND PARITY      D+94 2    13
           (SEE DISCUSSION IN THE PAPER).                           D+94 2    14
ENDBIB              12                                              D+94 2    15
```

```
DATA                    6          10                                          D+94 2    16
PAIR-IDENT EA           GAMMA-A    EB          GAMMA-B     J-PI               D+94 2    17
NO-DIM     MEV          KEV        MEV         KEV         NO-DIM             D+94 2    18
          8 2.1864      4.17       2.2191      0.085       2.0                D+94 2    19
          9 2.7231      0.16       2.7398      0.5         2.0                D+94 2    20
         10 2.7645      26.8       2.7716      1.9        -1.0                D+94 2    21
         11 2.8148      2.62       2.8567      2.75        2.0                D+94 2    22
         12 3.0151      3.6        3.0369      2.35       -3.0                D+94 2    23
         13 3.1356      1.97       3.1490      9.0         2.0                D+94 2    24
         14 3.1490      9.0        3.1570      2.6         2.0                D+94 2    25
         15 3.3200      10.5       3.3306      5.5        -1.0                D+94 2    26
         16 3.5174      0.70       3.5245      1.8         2.0                D+94 2    27
         17 3.7261      2.0        3.7315      0.4         2.0                D+94 2    28
ENDDATA                12                                                     D+94 2    29
ENDSUBENT               2                                                     D+94 299999
SUBENT          D+94    3          0                                          D+94 3     1
BIB                     2          9                                          D+94 3     2
REACTION    31P(P,ALPHA0)28SI                                                 D+94 3     3
COMMENTS    VALUES OBTAINED FROM TABLE II OF THE ARTICLE. ALL                 D+94 3     4
            RESULTS CORRESPOND TO COMPOUND NUCLEUS 32S. PAIR-IDENT            D+94 3     5
            = INDEX WHICH IDENTIFIES RESONANCE PAIR, AS INDICATED             D+94 3     6
            IN THE TABLE. E-CM = C.M. ENERGY OF THE PARTICULAR                D+94 3     7
            MEMBER OF THE RESONANCE PAIR FOR WHICH CROSS-SECTION              D+94 3     8
            INFORMATION IS PROVIDED. THETA-CM = C.M. ANGLE FOR                D+94 3     9
            ALPHA-PARTICLE EMISSION. DSIG-DOMEG = DIFFERENTIAL                D+94 3    10
            CROSS SECTION FOR ALPHA-PARTICLE EMISSION.                        D+94 3    11
ENDBIB                  9                                                     D+94 3    12
DATA                    4          9                                          D+94 3    13
PAIR-IDENT E-CM         THETA-CM   DSIG-DOMEG                                 D+94 3    14
NO-DIM     MEV          DEG        MB/SR                                      D+94 3    15
          8 2.2190      180.       0.011                                      D+94 3    16
          9 2.7231      132.       0.0011                                     D+94 3    17
         10 2.7716      180.       5.6                                        D+94 3    18
         11 2.8566      126.       0.023                                      D+94 3    19
         12 3.0152      180.       0.0019                                     D+94 3    20
         13 3.1350      180.       2.0                                        D+94 3    21
         14 3.1565      180.       2.3                                        D+94 3    22
         15 3.3280      180.       0.49                                       D+94 3    23
         16 3.5174      180.       0.20                                       D+94 3    24
ENDDATA                11                                                     D+94 3    25
ENDSUBENT               3                                                     D+94 399999
ENDENTRY                3                                                     D+949999999
```

7. Calculated reaction rates and the fitting procedure

The determination of RRs and estimation of errors can be understood best in terms of examples. First, consider the $^{31}P(p,\gamma)^{32}S$ reaction. A literature survey identified 46 resonances for $E < 2$ MeV ($E_x < 10.864$ MeV). Resonance contributions therefore dominate the cross section σ and Eq. (3) can be applied to find the RR vs T_9. Results from this analysis appear in Table 2. RR values calculated by Herndl *et al.* [12] using the Hauser-Feshbach formalism (H-F) are also shown in this table. Since the level density is relatively high for $E_x \geq 8.9$ MeV in ^{32}S (see Table 1 and Section 3), it is not surprising that there is qualitative agreement between the results from these two approaches to determining RRs. Uncertainties in $R(T_9)$ that are estimated using Eqs. (4) and (5) are correlated for the reasons mentioned in Section 3. This fact is demonstrated by considering the RRs for an abbreviated subset of six stellar temperatures from Table 2. The error correlation pattern for this collection of RRs is shown in Table 3. The correlations are obviously strongest (close to unity) between two RRs for "neighboring" T_9, and they approach a negligible level (near zero) for pairs of RRs corresponding to widely separated values of T_9.

The 7-parameter empirical scheme based on the work of Thielemann *et al.* (*Adv. Nucl. Astro.*, 525, 1987) [13] can be used to fit these calculated RR values. The formula is

$$R_{fit}(T_9) = \exp[a_1 + a_2T_9^{-1} + a_3T_9^{-1/3} + a_4T_9^{1/3} + a_5T_9 + a_6T_9^{5/3} + a_7 \ln(T_9)]. \quad (6)$$

An example of such a fit for the $^{32}S(p,\gamma)^{33}Cl$ reaction is shown in Fig. 4.

Table 2: Example - RRs of $^{31}P(p,\gamma)^{32}S$ in $cm^3s^{-1}mol^{-1}$ for selected stellar temperatures T_9 in GK

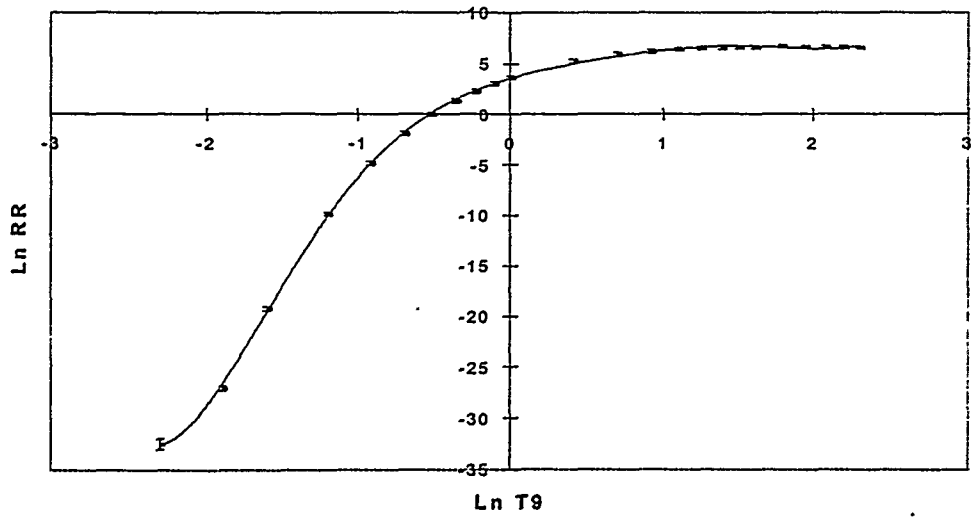
T_9	$[R(T_9)]_{Res}$	$[\Delta R(T_9)]_{Res}$	$[R(T_9)]_{H\text{-}F}$	T_9	$[R(T_9)]_{Res}$	$[\Delta R(T_9)]_{Res}$	$[R(T_9)]_{H\text{-}F}$
0.01	1.63×10^{-83}	(---)	---	0.30	9.15×10^{-3}	(13.0%)	2.34×10^{-3}
0.02	6.76×10^{-44}	(≈100%)	---	0.40	2.17×10^{-1}	(10.9%)	5.51×10^{-2}
0.03	8.73×10^{-31}	(92.2%)	---	0.60	6.06	(9.2%)	2.20
0.04	6.03×10^{-24}	(63.7%)	---	0.90	6.20×10^{1}	(9.2%)	3.77×10^{1}
0.05	2.10×10^{-19}	(70.6%)	---	1.00	9.97×10^{1}	(9.2%)	6.98×10^{1}
0.06	2.71×10^{-16}	(65.3%)	---	1.50	4.40×10^{2}	(8.8%)	5.03×10^{2}
0.07	4.50×10^{-14}	(59.3%)	---	2.00	1.02×10^{3}	(7.8%)	1.48×10^{3}
0.09	3.89×10^{-11}	(50.9%)	---	2.50	1.84×10^{3}	(6.9%)	2.93×10^{3}
0.10	4.05×10^{-10}	(48.1%)	2.24×10^{-10}	3.00	2.83×10^{3}	(6.3%)	4.72×10^{3}
0.15	4.33×10^{-7}	(37.6%)	1.96×10^{-7}	4.00	5.03×10^{3}	(5.8%)	8.72×10^{3}
0.20	2.82×10^{-5}	(17.7%)	1.30×10^{-5}	6.00	8.71×10^{3}	(5.9%)	1.60×10^{4}
0.25	7.99×10^{-4}	(13.8%)	---	9.00	1.11×10^{4}	(6.2%)	2.16×10^{4}

Table 3: Example - Error correlations for RRs corresponding to a limited set of T_9 from Table 2 [a]

Index	T_9	$[R(T_9)]_{Res}$	$[\Delta R(T_9)]_{Res}$	1	2	3	4	5	6
1	0.02	6.76×10^{-44}	≈100%	100					
2	0.07	4.50×10^{-14}	59.3%	0.89	100				
3	0.25	7.99×10^{-4}	13.8%	0.004	21	100			
4	1.00	9.97×10^{1}	9.2%	0	0.0188	28	100		
5	3.00	2.83×10^{3}	6.3%	0	0	5	59	100	
6	9.00	1.11×10^{4}	6.2%	0	0	0.67	13	66	100

[a] Lower half of symmetric correlation matrix is shown; values are given in units of (Correlation x 100).

Figure 4: Example - Calculated RRs and errors for $^{32}S(p,\gamma)^{33}Cl$ and a fit of Eq. (6) to these values



The RR errors for small T_9 are large due mainly to the very high sensitivity of the resonance RR to the resonance energies at relatively low stellar temperature. In Tables 2 and 3 it is seen that $R(T_9)$ decreases rapidly with T_9. This reflects the important influence of the Coulomb barrier on the cross section σ. The quality of fit of Eq. (6) to RR values from Eq. (3) can be judged relative to the errors $\Delta R(T_9)$ from Eq. (5) by using the following criterion:

$$-1 < [R_{fit}(T_9)-R(T_9)]/\Delta R(T_9) < 1. \qquad (7)$$

Eq. (7) implies that the fitted curve should deviate from all the points by less then their errors.

Acknowledgments

The authors gratefully acknowledge the help and advise received from M. Wiescher, J. Daly, R. Miller, and D. Pedaci during the course of this investigation. This work was supported by the U.S. Dept. of Energy, Energy Research Programs, Contract W-31-109-Eng-38. One of the authors (LVW) received support from Research Corporation under Grant No. CC3997.

References

[1] Clayton D D 1983 *Principles of Stellar Evolution and Nucleosynthesis* (Chicago, IL: U. of Chicago Press)

[2] Rolfs C and Rodney W 1988 *Cauldrons in the Cosmos* (Chicago, IL: U. of Chicago Press)

[3] Arnett D *1996 Supernovae and Nucleosynthesis* (Princeton, NJ: Princeton University Press)

[4] Tuli J K *1995 Nuclear Wallet Cards -5th Edition* (Upton, NY: Brookhaven National Laboratory)

[5] Firestone R B and Shirley V S 1996 *Table of Isotopes - 8th Edition* (New York: Wiley)

[6] Caughlan G R and Fowler W A 1988 *Atomic Data and Nuclear Data Tables* **40** 283

[7] Angulo C *et al.* 1996 *Status Report on the European Union Compilation of Nuclear Reaction Rates* 4th Int. Conf. on Nuclei in the Cosmos (U.of Notre Dame, South Bend, IN, 20-27 June)

[8] Smith D L 1991 *Probability, Statistics and Data Uncertainties in Nuclear Science and Technology* (La Grange Park, IL: American Nuclear Society)

[9] National Nuclear Data Center 1997 *Nuclear Science References* (Upton, NY: Brookhaven National Laboratory)

[10] Miller R E and Smith D L 1997 *A Compilation of Information on the $^{32}S(p,\gamma)^{33}Cl$ Reaction and Properties of Excited Levels in ^{33}Cl* Report ANL/NDM-143 (Argonne, IL: Argonne National Laboratory)

[11] CINDA (1935-1997) 1997 *The Index to Literature and Computer Files on Microscopic Neutron Data* (Vienna, Austria: International Atomic Energy Agency)

[12] Herndl H, Goerres J, Wiescher M, Brown B A and Van Wormer L A 1995 *Phys. Rev.* **C52** 1078

[13] Thielemann F *et al.* 1991- from the WWW (http://isotopes.lbl.gov/isotopes/astro/friedel.html)