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Nuclear Astrophysics Data at ORNL

MICHAEL S. SMITH[1], DANIEL W. BARDAYAN[1,2] JEFF C. BLACKMON[1], ZHANWEN MA[1,3,4]

[1] *Physics Division, Oak Ridge National Laboratory, MS-6354, Bldg. 6010, P.O. Box 2008, Oak Ridge, TN 37831-6371, USA*

[2] *A.W. Wright Nuclear Structure Laboratory, Yale University, 272 Whitney Ave., P.O. Box 6666, New Haven, CT 06511, USA*

[3] *Chinese Institute for Atomic Energy, P.O. Box 275(46), Beijing, 102413, P.R. China*

[4] *Joint Institute for Heavy Ion Research, P.O. Box 2008, Oak Ridge, TN, 37831, USA*

Abstract. There is a new program of evaluation and dissemination of nuclear data of critical importance for nuclear astrophysics within the Physics Division of Oak Ridge National Laboratory. Recent activities include determining the rates of the important $^{14}O(\alpha,p)^{17}F$ and $^{17}F(p,\gamma)^{18}Ne$ reactions, disseminating the Caughlan and Fowler reaction rate compilation on the World Wide Web, and evaluating the $^{17}O(p,\alpha)^{14}N$ reaction rate. These projects, which are closely coupled to current ORNL nuclear astrophysics research, are briefly discussed along with our future plans.

1 Introduction

Nuclear astrophysics involves study of the synthesis of elements and the evolution of cosmic sites where this synthesis occurs. Systems as diverse as the early universe, the interstellar medium, red giant stars, and supernova explosions are currently the focus of international observational, experimental, and computational studies. These studies address some of the most interesting questions in nature - such as determining the origin of the elements that make up our bodies and our world, and determining the fate of the constitutents of the cosmos.

Nuclear data is the physical basis for many sophisticated theoretical models used to address these questions. These models require large quantities of nuclear data as input - such as the rates of and energy released in nuclear reactions occurring in astrophysical environments, as well as information on the properties (e.g., masses, excited-state energies and widths) of relevant nuclei. Progress on many fundamental problems in nuclear astrophysics can be significantly aided by more effective utilization of nuclear data. There are numerous cases of the significant impact that new, more precise nuclear data evaluations have made on astrophysical studies. For example, the limit on the baryon density of the universe depends critically on the rate of the $^{3}H(\alpha,\gamma)^{7}Li$ reaction [1]. There is a very strong dependence of the abundances produced in supernova explosions on the value of the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate [2]. The lifetime of the isotope ^{44}Ti [3, 4, 5] places constraints on the nucleosynthesis, explosion mechanisms, and light curves of supernova explosions such as Cas A [6, 7] and SN 1987A [8]. The rates of reactions that produce and destroy ^{26}Al have a significant impact [9] on the interpretation of observations of ^{26}Al in the interstellar medium [10] and in meteorites [11]. Explanation of isotopic anomalies of barium isotopes in meteorites depend very sensitively on neutron capture cross sections [12].

In light of the importance of nuclear data on astrophysical studies, the Physics

Division of Oak Ridge National Laboratory has begun a new program of evaluation and dissemination of data for nuclear astrophysics. This program is closely coupled to current nuclear astrophysics research projects at ORNL. The following sections describe recent projects and future plans in nuclear astrophysics data at ORNL.

2 The $^{14}O(\alpha,p)^{17}F$ and $^{17}F(p,\gamma)^{18}Ne$ Reaction Rates

Hydrogen is expected to burn explosively in extremely hot, dense astrophysical environments such as novae, supernovae, X-ray bursts, and supermassive stars. The hot-CNO (HCNO) cycle is a primary reaction chain through which such burning occurs: $^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(e^{+}\nu_e)$ $^{14}N(p,\gamma)^{15}O(e^{+}\nu_e)$ $^{15}N(p,\alpha)^{12}C$. The energy generation rate of this sequence is limited by the beta decay lifetimes of ^{14}O and ^{15}O at moderately high temperatures. When the stellar temperatures are high enough (approximately 300 million degrees or higher), the beta decay of ^{14}O can be bypassed by the $^{14}O(\alpha,p)^{17}F$ reaction, and the reaction sequence $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(e^{+}\nu_e)$ $^{18}F(p,\alpha)^{15}O$ can increase the energy generation rate and alter the abundances of the CNO nuclides. The reaction sequence $^{16}O(p,\gamma)^{17}F(p,\gamma)$ $^{18}Ne(e^{+}\nu_e)^{18}F(p,\alpha)^{15}O$ can alter the CNO nuclide abundances as well, while the sequence $^{14}O(\alpha,p)^{17}F(p,\gamma)$ $^{18}Ne(e^{+}\nu_e)^{18}F(p,\gamma)^{19}Ne(p,\gamma)^{20}Na$ can provide a path from the HCNO cycle into the rapid proton (rp) capture process. The energy generation rate in the rp-process can be two orders of magnitude larger than the HCNO cycle [13], and at temperatures over one billion degrees, elements more massive than Fe can possibly be formed via this process (see, e.g., [14] and references therein).

An accurate prediction of the thermonuclear energy generation is required to model these complex astrophysical events. Expressions for the relevant reaction rates as analytic functions of the stellar temperature are crucial input for these models. These reaction rates are also required to predict the detailed isotopic composition of nuclei synthesized in such astrophysical events. Since many of these reactions involve short-lived unstable nuclei, direct measurements requires radioactive beams - which are (except in a very few cases) currently unavailable. An indirect approach, based on experimental measurements of the relevant parameters of the resonances that dominate the reactions, is generally used for isotopes with mass less than 40; reactions on heavier isotopes are usually calculated with a statistical model code. Although indirect rate determinations are often the only approach possible, they are intrinsically difficult and are often incomplete. Such rate determinations can be incorrect by orders of magnitude because of unknown resonances, missing spectroscopic information on crucial resonances, or incorrect information from isobaric analog states (see, e.g. ref. [15]).

As part of a new program to improve the rates of reactions important for explosive hydrogen burning studies, we have examined recent indirect experimental measurements [16, 17] of the important $^{14}O(\alpha,p)^{17}F$ and $^{17}F(p,\gamma)^{18}Ne$ reactions and generated analytical expressions [18] for the reaction rates as a function of temperature. These are also both reactions that we plan to measure with radioactive beams at ORNL's Holifield Radioactive Ion Beam Facility [19]. Our evaluation work [18] represents the only complete rate expressions for these two reactions over the range of temperatures for nova explosions which incorporates all recent indirect information. We also corrected an error (as large as 13% at high temperatures) in the previously reported determination of the $^{17}F(p,\gamma)$ rate. We determined analytic expressions for the new rates in two popular formats (that of Caughlan and Fowler [20] and of Thielemann et al. [21]), and have posted these with tabular values and plots on the WWW [22]. The astrophysical influence of these new reaction rates is currently being investigated [23].

3 Caughlan and Fowler Reaction Rate Compilation on the World Wide Web

There are a number of existing collections of thermonuclear reaction rates important for astrophysical models. Some of the most widely utilized are a series by Willy Fowler and collaborators; the last in this series is by G.R. Caughlan and W.A. Fowler, published in 1988 [20]. We have put the 160 reaction rates and their inverses in this compilation *online* [22] for the first time in the format as they appeared in print. Our WWW posting includes a text file of reaction rates as analytic functions of temperature, and tables of rates values versus temperature for each reaction. Additionally, we have extended the utility of this compilation by offering GIF and Postscript plots of each rate, a downloadable fortran subroutine of all the reaction rate formulae, and a graphical search function based on the chart of the nuclides. The inclusion of a fortran subroutine makes these rates especially easy to insert into an astrophysical model. We also derived analytic expressions for temperature derivatives of all the rates and their inverses, useful for computer models which couple nucleosynthesis to stellar hydrodynamics. We have posted these formulae on the WWW, along with a downloadable fortran subroutine of the reaction rate derivatives.

4 The ^{17}O(p,α)^{14}N reaction rate

The ^{17}O(p,α)^{14}N reaction is important for determining the relative abundance of oxygen isotopes, which act as tracers of convection processes in the envelopes of red giant stars [24]. This reaction is also important for interpreting oxygen isotope anomalies observed in meteorites [25]. A number of experimental investigations of this reaction have been made [26, 27, 28] since the last evaluation in the Caughlan and Fowler compilation [20]. We are currently making a new determination of the ^{17}O(p,α)^{14}N rate which incorporates these recent measurements and is closely coupled to ongoing experimental investigations of this reaction.

5 Other Efforts and Future Plans

We have recently compiled a nuclear astrophysics bibliography consisting of over 1000 references that is a useful resource for producing evaluations of nuclear reaction and structure information important for astrophysics. This bibliography is posted on the WWW [22]. We have also recently documented the capabilities that the U.S. nuclear data community can offer to the evaluation of nuclear data of importance to nuclear astrophysics [29]. Our future plans include evaluating reactions important for explosive hydrogen burning studies, such as ^{18}F(p,γ)^{19}Ne and ^{18}F(p,α)^{15}O, and collaborating with Argonne National Laboratory on evaluations of explosive hydrogen burning reactions on isotopes with mass between 30 - 50.

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