Nuclear Data for Astrophysics

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In order to address important astrophysics problems such as the origin of the chemical elements, the inner workings of our Sun, and the evolution of stars, crucial nuclear datasets are needed. Recent evaluation and dissemination efforts have produced a number of such datasets, many of which are online and readily available to the research community. Current international efforts in this field are, unfortunately, insufficient to keep pace with the latest nuclear physics measurements and model calculations. A dedicated effort is required to update and expand existing datasets. I discuss several strategies and new initiatives that would ensure a more effective utilization of nuclear data in astrophysics. These include launching a new web site **www.nucastrodata.org** to aid in locating available nuclear data sets, and an interactive online plotting program with an easy-to-use graphical user interface to over 8000 reaction rates. An enhanced effort in this field could be maintained by formalizing the position of a Nuclear Astrophysics Data Coordinator.

1. Motivation for Nuclear Astrophysics Data Activities

Nuclear astrophysics research addresses some of the most fundamental questions in nature: What are the origins of the elements that make up our bodies and our world? How did the sun, the stars, and the galaxy form, and how do they evolve? There is an intimate connection between nuclear physics and studies of these fascinating astrophysical phenomena. A diverse set of nuclear data is required to model the composition changes and energy release in astrophysical environments ranging from the Big Bang to the inner workings of our own Sun to exploding stars. Measurements and theoretical descriptions of microscopic nuclear physics phenomena provide the foundation for the sophisticated models of macroscopic astrophysical systems. These models are today challenged by incredibly detailed observations from ground-based (e.g., Keck [1], SUBARU [2]) and space-based (e.g., CHANDRA X-ray Observatory [3], Hubble Space Telescope [4]) devices that give us an unparalleled view of the Cosmos. We truly live in a golden age of astrophysical observations.

However, our ability to decipher these observations requires, in many instances, more extensive and precise nuclear data than ever before. This symposium featured many examples of this cosmic sensitivity to nuclear physics [5], including: $^{12}C(\alpha,\gamma)^{16}O$, which impacts the abundances produced in supernova explosions, the ratio of C to O after core He burning, and the subsequent evolution of massive stars; $^{7}Be(p,\gamma)^{8}B$, which helps determine the nature of the neutrino oscillations; $^{18}F(p,\alpha)^{15}O$, which determines the synthesis of ^{18}F nuclei in novae; ^{14}O(α,p)^{17}F, which impacts the hot CNO breakout in stellar explosions; ^{13}C(α,n)^{16}O, which influences the production of neutrons for the s-process in red giant stars; and ^{84}Kr(n,γ)^{85}Kr, to impacts heavy element abundance anomalies in meteorites. Efforts are underway around the world to provide this, and much more, important nuclear physics information which influences astrophysics models.

2. Nuclear Data Needs in Astrophysics

Astrophysical models require an enormous amount of nuclear reaction and nuclear structure information, and the particular data required (e.g., reaction type, relevant energy range, nuclei involved) varies greatly with the astrophysical phenomena studied [6]. What quantities are needed? For reactions, the required information includes cross sections to determine thermonuclear reaction rates and Q-values to determine releases of nuclear energy. Astrophysical S-factors – a processed cross section – are also extremely useful because they vary much more slowly with energy than cross sections, enabling cross sections to be extrapolated to energies below which they have been measured. Further details of data needs involving reactions induced by charged particles [7], by neutrons [8], and by neutrinos [9] have been recently written.

Nuclear structure data is invaluable to determine the rates of unmeasured reactions, stellar energy generation, and nuclear reaction pathways. Some of the relevant information includes: masses, decay lifetimes and branching ratios, parameters of resonances (energies, spins, parities, widths) above particle capture thresholds, separation energies near the driplines, alpha-nucleus potentials, level densities, and optical model parameters. Some specific nuclear structure data needs are addressed elsewhere in these proceedings, and general data needs for astrophysics have been reviewed recently [10].

3. Nuclear Astrophysics Data Activities and Resources

Willy Fowler and collaborators were the first to produce extensive sets of nuclear physics information tailored for input in astrophysics simulations [11]. The work he initiated has grown into an international effort as the variety, sophistication, and detail of astrophysics simulations has increased over the last 35 years. There is now an international recognition of the importance of the nuclear astrophysics data work that he initiated [12], and an impressive array of resources have been produced and, in many cases, put online (Section 3.4). Laboratory nuclear measurements, nuclear modeling, nuclear data compilations and evaluations, and data dissemination are all vital activities for the production of important nuclear astrophysics datasets. Some of these resources and recent progress in each of these areas is described in the subsections to follow.

3.1. Measurements

The availability of beams of radioactive nuclei is one of the most exciting recent developments in nuclear physics. These beams enable the direct measurement of reactions on unstable isotopes that drive stellar explosions [13], as well as mapping out the properties of nuclei that previously could only be estimated by theory or systematics. Measurements at radioactive beam facilities are already changing our understanding of astrophysical processes [14]. Another new vista in experimental nuclear astrophysics involves making measurements at low energies utilizing the tremendous background reductions in underground laboratories [15] or via coincidence techniques [16]. For example, a solar thermonuclear reaction cross section has for the first time been directly measured at the extremely low energies found in the core of our Sun with an underground accelerator facility [15], and more such studies are planned in the future. The current status of nuclear measurements for astrophysics has been recently reviewed [13,17], and this proceedings contains some of the latest work in the field.

3.2. Modeling

Since it is impossible to measure all the nuclear reactions and structure information needed for astrophysics simulations, nuclear models play a crucial role in studies of the cosmos. They not only provide essential unmeasured information, but are used to extrapolate measurements to new energy regimes as well as to provide a framework with which to understand laboratory results. Significant advances have been made in nuclear modeling in recent years, with a new focus on global microscopic models that can deliver predictions with accuracies rivaling those of phenomenological models tuned for a specific mass range [18]. There have been a number of impressive calculations of properties of and reactions involving thousands of nuclei, including references [18–20] and others discussed in this symposium. It is crucial to benchmark these global calculations with experimental measurements wherever possible. Radioactive beam facilities are especially important in this regard, as they are enabling the exploration of uncharted parts of the nuclear landscape.

3.3. Compilations and Evaluations

Compilations and evaluations are the first crucial steps towards incorporating laboratory measurements and theoretical calculations into datasets for astrophysics simulations. Compilations involve collecting all available information on, for example, a particular reaction or nucleus; literature searches play an important role here. Evaluations are one of the most labor-intensive of all nuclear data activities. New evaluations must be initiated to combine the *latest* and *current* results to get a truly *best* result for the quantities of interest. This often involves combining disparate datasets and performing necessary extrapolations. Recent successful nuclear data evaluation projects for astrophysics include: new evaluations of 86 important charged-particle reactions from the NACRE collaboration in Europe [21]; a new large collection of neutron-induced reaction evaluations [22]; a new collection of 56 charged-particle reaction rate evaluations for stable and proton-rich unstable isotopes in the mass 20 - 40 region [23]; and evaluations of a number of crucial charged-particle induced reaction rates and nuclear decays [24]. As will be described below, however, the current manpower devoted to compilations and evaluations for astrophysics cannot keep up with the pace of worldwide measurements and modeling efforts.

3.4. Dissemination

It is not enough to perform state-of-the-art nuclear measurements or theoretical calculations and then to compile and evaluate this information. Nuclear data must also be distributed to the community in formats that astrophysics researchers can directly insert into their models. Without this step, the results of the latest measurements or model calculations will not be utilized to help solve the very astrophysical puzzles that motivated their generation. Dissemination work provides another crucial link between nuclear physics activities and astrophysics modeling.

The modern mechanism for rapid, user-friendly information distribution is electronic dissemination via the World Wide Web (WWW). Significant strides have been made in nuclear astrophysics data dissemination in the past six years: researchers can now search, browse, display, and download data sets specialized for nuclear astrophysics studies (e.g., reaction rates), as well as those for general nuclear physics research, from the WWW. The first website dedicated to disseminating nuclear data relevant for astrophysics [25] was launched in 1996, and now there are sites at numerous institutes around the world – including ORNL [26], LANL [27], ULB [28], LLNL [29], Basel [30], KFK [31], IAS [32], and Cambridge [33]. Many of these sites feature datasets developed at the host institute and links to other datasets of interest.

4. Brewing Crisis

In spite of the impressive collection of online resources cited above, there are a number of reasons why the current effort in nuclear astrophysics data is insufficient to meet the needs of the research community. First, the subcritical manpower in this area simply cannot keep up with the worldwide pace of nuclear measurements and modeling efforts. There are, for example, numerous published reaction rates based on experimental measurements made in the last decade that have never been compiled or evaluated. Second, many of the specialized astrophysical datasets (e.g., [21,22]) are not folded into the existing large reaction rate libraries, and are therefore not widely utilized in astrophysics simulations. This is a terrible waste of resources, and one that is growing worse as more up-to-date information from recent nuclear measurements is not accessible to astrophysicists. Third, many very valuable datasets lack a user-friendly interface or a data format appropriate for astrophysics models, requiring significant effort by researchers to use the data. Fourth, there is little coordination and communication between groups working in this area. Researchers often create their own sets of nuclear data culled from scattered data collections of their choosing, making it extremely difficult to compare results from different groups, or to update popular simulation codes. This confusion is exemplified by REACLIB [34], a widely-used collection of approximately 8000 thermonuclear reaction rates. REACLIB is becoming a standard rate library used by numerous research groups around the world to simulate a wide variety of astrophysical phenomena. The last full update and public release of REACLIB was, however, in 1991, and there are currently numerous versions of this library in use (e.g., [23,33–37]). Because each of these versions is updated from the last public release in a different way, it is very difficult and possibly misleading to compare results from simulations using these libraries. Another serious problem: there is no mechanism whereby mistakes in REACLIB rates can be communicated to REACLIB users. This dataset also lacks a friendly interface, and there are many important rate collections that have not yet been incorporated into this library.

Significant progress was realized in other fields (e.g., reactor physics in the U.S. in the 1970s) when standardized sets of data were widely available to researchers (e.g., the Fusion Evaluated Nuclear Data Library or FENDL [38]), allowing the model codes to be decoupled from the input data. Some astrophysicists will always prefer to use proprietary data sets, and no one dataset can satisfy all astrophysics simulation needs. However, a set of freely available, regularly updated, communal datasets would lead to a standardization that would help advance the field and would encourage the development and improvement of the input datasets themselves in a synergistic way. For example, REACLIB has evolved from a tool developed for use by a few researchers to a tremendous community resource, and its utility for astrophysics research for the future could be ensured by taking some proactive measures now.

5. Future Strategies

Strategies are needed to improve the current situation in nuclear data for astrophysics studies. First and foremost, dedicated manpower in nuclear astrophysics data is needed to keep pace with the international efforts in measurements and nuclear modeling. This recommendation has been recently endorsed in reports from meetings of the International Nuclear Data Committee [39,40], as well as by an Advisory Group for Long Term Nuclear Data Development [7,12], of the International Atomic Energy Agency. Below, some of the top priorities for a new expansion in this field are described.

5.1. Compilations and Evaluations

An expanded, dedicated evaluation effort is required if accurate, up-to-date nuclear datasets are to be produced in a timely fashion for astrophysical studies. While most evaluation efforts to date have been produced by nuclear astrophysics researchers, an expanded effort will most likely require exploiting the significant overlap between the nuclear data and nuclear astrophysics communities [41]. For example, members of the Cross Section Evaluation Working Group (CSEWG) [42] evaluate reactions important for a variety of applications, some of which are also critical for astrophysics. There are many important datasets that are needed for astrophysics research, including charged-particle induced reactions for quiescent and explosive burning stages in stars [7], and neutron-induced reactions for the synthesis of heavy elements [8]. A partial list of evaluation projects includes: reactions on radioactive isotopes with mass less than 40 needed to support new work at radioactive beam facilities; approximately 80 reactions in the Caughlan and Fowler 1988 collection [43] which were not updated by NACRE [21] and are now out of date by 14 years; enhanced compilations of nuclear structure information at the proton- and neutron-driplines; and (α, n) reactions on nuclei from O to Si that generate neutrons for the s-process. It is especially important to focus on evaluation projects that support the frontier areas in experimental nuclear astrophysics discussed in Section 3.1.

5.2. A Nuclear Astrophysics Data Coordinator

Because the manpower for this work is so limited, it is important to coordinate worldwide compilation and evaluation efforts plans in order to share expertise and avoid duplications. Since no one entity can (or should) control the international efforts in this field, coordination should primarily take the form of enhanced communication. This can be greatly facilitated by the establishment of a Nuclear Astrophysics Data Coordinator [40,44] whose core duties would be dissemination and communication, as well as active research participation. The dissemination duties would include: maintaining and updating a central WWW listing of nuclear astrophysics datasets (see Section 5.3); modifying existing datasets for compatibility with astrophysical codes; and improving the user interface of datasets via the creation of indices, search capabilities, graphical interfaces, bibliographies, error checking, plotting tools, and other enhancements. The communication duties would include: publicizing nuclear astrophysics data projects that are recently completed or currently in progress; establish and maintain a nuclear astrophysics email distribution list; publicizing relevant scientific meetings; establishing and maintaining a priority list of important nuclear reactions and properties for further study; helping to build on common interests in the nuclear data and nuclear astrophysics communities; and promoting international data activities such as cooperative research programs, symposia, and exchange of technical expertise and computer codes. It is crucial that the Coordinator be actively involved in astrophysics research, and be sited at a location with an active research group [39]. This will help ensure that the Coordinator is a member of the research community that he will interface with. Also, by being a data user himself, the Coordinator will truly be able to fulfill the needs of the user community.

5.3. Dissemination

The development of web sites and web-based tools such as interactive data viewers is essential to ensure a widespread utilization of the latest nuclear data. Two new dissemination initiatives are discussed below.

5.3.1. New Website for Nuclear Astrophysics Data

Despite the wealth of information posted online [25–33], there has been little synergy between the existing nuclear astrophysics data websites, and there is no site which links *all available nuclear datasets* relevant for astrophysics studies. To rectify this situation, **www.nucastrodata.org** has been launched with support from independent corporate sources. This new site features an extensive set of links to nuclear datasets from around the world (over 60 so far) important for nuclear astrophysics studies. This site helps users navigate through these datasets, as well as to publicize them to the research community. The site is independent of any host institution and does not compete with any existing nuclear astrophysics data site. With community support, this website will grow into a very valuable resource for astrophysics research.

5.3.2. New Interactive Reaction Rate Viewer

Much of the existing information for nuclear astrophysics studies posted on the WWW is posted in the form of tables, which usually require a number of steps by the user (downloading, programming, plotting) to visualize. While some sites feature pre-made plots of reaction rates [26,27], no site has a user-friendly, interactive plotting package that accesses the largest reaction rate databases. To address this need, a new visualization tool [45] has been developed which provides an easy-to-use, interactive, platform-independent, graphical user interface to the rates of over 8000 nuclear reactions in the widely-used REACLIB library [34]. Viewable through a web browser, users can plot multiple rates, access rate parameters, add new rates and plot them, and create "rate vs. temperature" tables all through a point-and-click graphical user interface based on the chart of the nuclides. Such visualization tools will most likely be developed for many nuclear astrophysics data websites in coming years.

6. Summary

Nuclear physics information is crucial for the understanding of many phenomena in astrophysics. There is a wealth of nuclear astrophysics data already online. Dedicated effort is needed, however, to ensure that these datasets are updated to include the latest experimental and theoretical work, and to ensure that the limited manpower in the field works in a coordinated fashion. It is internationally recognized that the current effort in this area must be enhanced. A number of strategies to improve the utilization of nuclear data for astrophysics studies have been identified, and some new initiatives - a web site **www.nucastrodata.org** and a new interactive reaction rate plotting program, are already helping to reach these goals. Community support for these and similar efforts is essential to ensure that Willy Fowler's legacy in nuclear data for astrophysics will continue to flourish in support of frontier research in nuclear astrophysics.

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