Compilation and Evaluation of Alpha-Induced Nuclear Reaction Cross Sections for Astrophysics

ABSTRACT: Nucleosynthesis and energy production in stellar environments depend critically on nuclear reaction cross sections. Reactions induced by alpha particles are important in the helium burning stage of stars, novae, and supernovae events. They involve light to medium weight nuclei up to about Z=32, and center-of-mass energies up to about 20 MeV. The proposed project involves three components. A complete set of all available experimental data for the alpha-induced reactions for nuclei in the range of interest will be compiled and will be available online to the community. Optical Model (OM) parameters will be adjusted to match elastic scattering and total reaction data. These parameters will also be made available to the community and may be used to calculate data for other isotopes. Finally, a set of cross section evaluations for these reactions will be made and may be used by the astrophysics community to calculate reactions rates. The astrophysical implications of the data and the conversion into reactions rates will be explored.

PROJECT NARRATIVE

A. Participants

Oak Ridge National Laboratory Experimental Nuclear Astrophysics Group (ORNL): The Experimental Nuclear Astrophysics Group is a part of the Oak Ridge National Laboratory Astrophysics Program. In addition to experiments, the group hosts a Nuclear Data for Nuclear Astrophysics Web site, and has recently been involved in the calculation of astrophysical reaction rates for relevant reactions. These rates are derived from laboratory measurements of cross sections convoluted with a thermal (Maxwell-Boltzmann) relative velocity distribution.

National Nuclear Data Center (NNDC): The National Nuclear Data Center is funded by the U.S. Department of Energy to provide services in the field of low and medium energy nuclear physics to users in the United States and Canada. The NNDC databases are available online, both using the telnet protocol and on the Web. All data are provided free of charge.

Since 1962, the National Neutron Cross Section Center (then known as the Sigma Center) has provided information on neutron-induced nuclear reactions. In 1980, the evaluations of nuclear structure and radioactive decay data became part of its responsibility and its name was changed to the National Nuclear Data Center. In 1996, the reaction compilation effort was expanded to include charged-particle induced reaction data with an initial concentration on proton-induced reactions.

In addition to its long history of expertise in compilation, the recent addition of new staff members has again provided the NNDC with expertise in the evaluation of nuclear reaction data.

Nuclear Physics Data Center (NPDC): The Russian Federal Nuclear Center, VNIIEF, originated a project in 1973 to compile data on the interaction of charged particles with light nuclei to support the calculation of thermonuclear reaction rates; this library now contains over 1500 references. As a result of this work, the NPDC was established in 1997. The NPDC staff has achieved an expertise in the compilation and evaluation of these data, including making experimental measurements and developing techniques for the extrapolation of these cross sections to very low energies.

During the last six years specialists of the Center took an active part in the ISTC Projects "Development of the library of evaluated nuclear data on charged particles for International Thermonuclear Reactor (ITER) and other applications of thermonuclear fusion" and "Benchmarks data on γ-ray production for fusion application", which were involved the compilation and evaluation of nuclear data for the International Thermonuclear Energy Reactor (ITER). These projects have been successfully completed.

SaBa, an electronic version of the evaluated and experimental data on charged particles, has been developed by NPDC for thermonuclear applications. It contains an optimal set of data processing procedures and friendly interface, which can be used for various applications in the astrophysical data program.

B. Astrophysical Data Needs

Nucleosynthesis and energy production in stellar environments depend critically on nuclear reaction cross sections. The recent observation of highly energetic star explosions, the so-called hypernovae[1], gamma-ray bursts[2], and the use of type IA supernovae[3] as standard candles to determine the Universe expansion rate are clear examples of new developments in this field.

Due to the success of space missions like Hubble, CGRO, and Chandra, as well as terrestrial observatories such as KEK and ESO among others, scientific activities in Astrophysics have been considerably boosted in recent years. Since new facilities will become operational in the near future and many others are under serious consideration, these activities are only likely to continue growing. A keystone in the field will be the launch, scheduled for 2002, of the gamma-ray observatory Integral. New and exciting results are expected in Nuclear Astrophysics.

Reactions induced by alpha particles are important in the helium burning stage of stars, novae, and supernovae events[4]. They involve light to medium weight nuclei up to about z=32, and center-of-mass energies up to about 20 mev. The most widely used a-potential (McFadden-Satchler)[5] was determined about 35 years ago and is an "average potential", that is, it is applicable for all nuclei, and as a consequence, not suitable for accurate calculations. The availability of a compiled body of cross section data is of prime need for our understanding of stellar physics and the refinement of theoretical models. Such data have been measured, but most have not yet been made available to the community in an easily accessible electronic form.

C. Approach and Objectives

The NNDC, NPDC, and ORNL propose to cooperate on a program to produce nuclear data of use in calculating astrophysical reaction rates. The final product of this project will be evaluations of alpha-induced cross sections for nuclei with 8=Z=32 and $E_{c.m.}$ =20 MeV. The initial phase of this work, which is covered by this project, will focus on the nuclei, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, and ^{40}Ca.

The project will involve the following three main components.

1. Data compilation

A search will be made of the available literature for experimental measurements of these quantities. The references will be coded by the NPDC compiler in the nuclear reaction bibliographic data format, CINDA2001[6].

All data will be compiled at both the NNDC and the NPDC into the EXFOR format[7]. If we are unable to acquire the actual data, the NPDC will scan the data from the figures given in the literature using a code developed at NPDC to scan and write the data in EXFOR format[8]. All scanned data points will be read at least twice; more if there is a serious discrepancy in the readings. The data will be transmitted by NPDC to the NNDC for entry into the EXFOR data library.

A two-month visit to the NNDC by the NPDC data compiler for training in CINDA and EXFOR compilation is planned. The FSU co-investigator will also visit BNL during this time to set up procedures for producing the bibliographic references and the data compilations.

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[1] Q.D. Wang, Astrophys. Journal **517**, L27 (1998).
[2] L. Amati *et al.*, Science **290**, 953 (2000).
[3] S. Perlmutter *et al.*, Nature **391**, 51 (1998).
[4] See *Opportunities in Nuclear Astrophysics: Origin of the Elements*, http://www.nd.edu/~nsl/kn/whitep.pdf, especially, pp. 20-21, p. 25, and Section XII.
[5] L. McFadden and G. R. Satchler, Nucl. Phys. **84**, 177 (1966).
[6] CINDA2001 database is under development and will be available in the spring of 2002.
[7] V. McLane, *EXFOR Systems Manual*, Brookhaven National Laboratory informal report BNL-NCS-63330-00/04-Rev. (April 2000)
[8] S.A.Dunaeva, A.V.Kuryakin. The software on input, processing and writing data in EXFOR format, Preprint 43-96, RFNC-VNIIEF, Sarov, 1996.

2. Optical Model Fitting

A set of Optical Model (OM) parameters will be produced by matching OM calculations to alpha-induced elastic scattering angular distribution data and total reaction cross sections using the well-established codes SCAT2[9] and ECIS[10] (including its search and fitting version ECISVIEW[11]). These parameters may be used to calculate data for other isotopes.

This work will be done as a joint collaboration between the NNDC and NPDC. During the first year, a visit to the NPDC by a U.S. researcher to the NPDC is planned to initiate contact and set up a work schedule.

3. Cross Section Evaluation

The experimental data for (a,n), (a,p), and (a,?) reactions will be evaluated using the statistical reaction model codes EMPIRE-2[12] and MOST[13], and the above OM parameter set. The code EMIRE-2 currently resides at the NNDC and P. Oblozinsky has extensive experience in its use. NNDC will be acquiring the MOST code in the near future. We plan to make comparisons with results produced using the code NON-SMOKER[14], which is a code heavily used by the astrophysics community. A recommended set of cross sections will be produced for each nucleus.

During the first year, a visit by an NPDC evaluator to NNDC for a period of three months is foreseen to work with the NNDC evaluators and acquire hands-on experience with the codes to be used. The EMPIRE-2 code will be installed at the NPDC. Evaluation work will begin in the second year of the project with evaluations for the nuclei, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, and ^{40}Ca.

The completed evaluations will be stored in the Evaluated Nuclear Data File (ENDF) format[15] and made available to the community. A retrieval code will be developed to produce data in formats convenient for use by the astrophysics community to calculate thermonuclear reactions rates. A visit of an NPDC programmer to the NNDC for a period of six weeks is foreseen for this purpose. Michael Smith, the ORNL researcher, will plan to visit NNDC during this time.

The astrophysical implications of the data and the conversion into reactions rates will be explored by ORNL in collaboration with the other participants.

D. Milestones and Measurements of Success

First Year of Project

The literature search and bibliography for all nuclei in the range of interest will be completed. All references will be transmitted to the NNDC in the CINDA2001 format. These references will then be made available to the community on the NNDC Web site.

Compilation of the data will be completed for all alpha nuclei (*i.e.*, even Z, A divisible by 4) in the range of interest.

An Optical Model parameter library will be produced for all alpha nuclei in the range of interest. This set of OM parameters will be transmitted to the Nuclear Data Section at the International Atomic Energy Agency in Vienna, Austria for entry into the Reference Input Parameter Library (RIPL)[16], which is available free of charge to the community.

A paper on the project will be submitted to NIC7. Comments from the astrophysics community will be solicited.

Second Year of Project

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[9] O. Bersillon, SCAT2: *Un programme de modele optique spherique*, CEA Saclay report CEA-N-2227 (1981); revision 1991.

[10] J. Raynal, *Notes on ECIS94*, CEA Saclay report CEA-N-2772 (1994); revision 1997.

[11] A.J. Koning, J. van Wijk and J.P. Delaroche, *ECISVIEW: An interactive toolbox for optical model development*, unpublished (2000).

[12] M. Herman, *EMPIRE-2: Statistical model code for nuclear reaction calculations*, unpublished (2000).

[13] S. Goriely, *MOST: An updated HF model of nuclear reactions*, Nuclei in the Cosmos, N. Prantzos et al., Eds. (Editions Frontières, Paris, 1998) p.314.

[14] T. Rauscher, F.K. Thielemann, *Code NON-SMOKER*, At.Data and Nuclear Data Tables **75** (2000) 1-351.

[15] V. McLane, editor, *ENDF-102 Data Formats and Procedures for the Evaluated Data File ENDF-6*, Brookhaven National Laboratory Informal Report BNL-NCS-44945, Rev. 2/97 (1997).

[16] *Handbook for calculations of nuclear reaction data: Reference input parameter library*, International Atomic Energy Agency report IAEA-TECDOC-1034 (Vienna, 1998).

By the end of the second year, data compilation will be completed for all nuclei in the range of interest. All data will be entered into the CSISRS database which is available online and free of charge[17].

Evaluations for the nuclei, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, and ^{40}Ca will be completed. The data will be made available in the ENDF format on the NNDC Web site.

Participation of FSU personnel	
Dunaeva Svetlana Aleksandrovna	Manager
Kamskaya Elena Vladimirovna	Compilation, evaluation
Pozdysheva Diana Nikolaevna	Compilation, software
Taova Sophia Mihajlovna	Software, database upgrading
Zvenigorodsky Anatoly Grigorievich	Evaluation
Participation of US personnel	
Charles L. Dunford	Manager
Victoria McLane	Compilation, training, coordination.
Pavel Oblozinsky	Evaluation, model code training.
Alejandro Sonzogni	Evaluation, astrophysical theory.
Michael Smith	Astrophysical theory, reaction rates.

[17] All data will be available on the NNDC Web site: ***www.nndc.bnl.gov***.