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U.S. NUCLEAR REACTION DATA PROGRAM IN SUPPORT OF BASIC RESEARCH

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1. Introduction

Information about the U.S. Nuclear Reaction Data Network (USNRDN) such as its members, work in progress, summaries of meetings, and organizational details may be found in its WWW Homepage [1]. This paper is an overview of the data support provided by the network for basic research in nuclear astrophysics, radioactive ion beams, high energy heavy-ion and electron interactions and related activities involving all aspects of data stewardship.

2. Nuclear Astrophysics

Complete, precise, well-documented, and up-to-date evaluated nuclear data are required to model exciting astrophysical phenomena ranging from the Big Bang to the explosion of stars. There are data needs to ensure progress in nuclear astrophysics (NAP) in all areas of nuclear data activities: measurements, compilations, modeling, evaluations, calculations (of reaction rates from cross sections), and (electronic) disseminations. The data needs include nuclear reaction information such as cross sections, S-factors, and reaction rates for numerous reaction types (e.g., capture, transfer) involving many isotopes over a variety of energy ranges (usually with energies less than a few MeV/amu). There are also substantial needs for nuclear structure information, including masses, lifetimes, Q-values, separation energies, level densities and partition functions, for a wide variety of isotopes from the proton- to the neutron-drip line.

The Astrophysics (AP) Task Force of the USNRDN coordinates these activities and works with the Nuclear Astrophysics Data Evaluation Steering Committee. The Task Force activities are described in its Homepage [2] and additional organizational information may be found in the ORNL Nuclear Data for NAP Homepage [3].

2.1 Measurements and Data Compilation

At the Colorado School of Mines, angular distributions for the d(d,p)t, $^{9}Be(d,p_0)^{10}Be$ and $^{9}Be(d,t_0)^{8}Be$ have been measured between 0 and 150 degrees at bombarding energies of 100-150

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keV. These reactions are important in the synthesis of isotopes in the early universe. At the IRMM van de Graaff at Geel, measurements of over 33 neutron reactions leading to short-lived radioactive products have been made at neutron energies from 13-20 MeV by the group at Argonne National Laboratory. Though these energies are significantly above those needed for astrophysics, precise measurements like these should help in model development that can directly address (the inverse of) some reactions important for astrophysics studies. At ORNL, measurements of the reactions $^{134,136}Ba(n,\gamma)$ [4], $^{142,144}Nd(n,\gamma)$, and $^{116,120}Sn(n,\gamma)$ have recently been completed. These measurements are important for the synthesis of heavy elements through the slow neutron capture process in stars. The $^{7}Li(n,\gamma_0)$ reaction, important for inhomogeneous big bang nucleosynthesis and for the solar neutrino problem, has also been recently measured [5].

Compilation of charged-particle reaction data with many reactions of importance to astrophysics is being done at the National Nuclear Data Center (NNDC). These data are available from the Cross Section Information Storage and Retrieval System (CSISRS) through the NNDC online data retrieval system. There are currently 15,040 data sets containing 285,700 data points in the CSISRS (EXFOR) charged particle library. The NNDC is now compiling all new data from the U.S. and Canada, and is working on obtaining data published between 1990 and 1995.

2.2 Data Evaluations and Calculations

Multichannel R-matrix calculations are being used at LANL to extrapolate cross sections of the $^{12}C(\alpha,\gamma)^{16}O$ and $^{13}C(\alpha,n)^{16}O$ reactions from energies measured in the laboratory down to energies relevant for astrophysical studies. Data from all possible reaction channels are included, and the effects of important sub-threshold levels on these low-energy extrapolations are being investigated. Evaluations of (p,γ) and (p,α) reactions on targets in the mass range $A = 30$-50 are being made by an ANL-Notre Dame-Hiram College collaboration and used to calculate stellar reaction rates. These rates are calculated from cross sections derived from both resonance parameters and modeling based on the Hauser-Feshbach formalism. Uncertainties in the computed reaction rates are estimated from errors in the underlying nuclear parameters. Work on the $^{31}P(p,\gamma)^{32}S$ reaction is nearly completed, and a number of other reactions are in progress. The $^{14}O(\alpha,p)^{17}F$ and $^{17}F(p,\gamma)^{18}Ne$ reactions are being evaluated at ORNL. These reactions are both important for nucleosynthesis occurring in stellar explosions. The calculation of neutron capture reaction rates directly from neutron capture cross sections stored in the Evaluated Nuclear Data File (ENDF) is also in progress at ORNL. These reaction rates are needed for studies of heavy element nucleosynthesis, and have not previously been calculated from ENDF evaluated cross sections.

2.3 Data Dissemination

Nuclear data of interest to astrophysics may be obtained by accessing the NAP Homepage [6] of the LANL T2 Nuclear Information Service, the NAP Data Homepage [7] of the Isotopes Project (IP) and the Institute for Nuclear and Particle Astrophysics (INPA) at LBNL, or the ORNL Nuclear Astrophysics Data pages [3]. The NNDC Homepage [8] also provides access to both the nuclear structure and reaction data needed for astrophysics.

3. Radioactive Ion Beams

Over the last few years, an intense worldwide interest has grown in the use of radioactive ion beams (RIB) to study the properties of nuclei far from stability. The relatively recent technological developments that have enabled the production of high-quality radioactive beams promise to lead to a renaissance in nuclear structure and nuclear reaction physics, as well as nuclear astrophysics. Some of the principal issues that will be addressed with RIB research are: (1) The nature of residual interactions, particularly among valence nucleons, in orbitals not accessible near stability; (2) New nuclear shapes and collectivities; (3) Neutron halos for extreme N/Z ratios; (4) Properties of N=Z nuclei far from stability; (5) Nuclear reaction mechanisms sensitive to new nuclear structure properties in RIB nuclei; and (6) Study of astrophysical nuclear reactions, for the first time, involving unstable nuclei in the rp-, r-, p-processes in nucleosynthesis.

The USNRDN Radioactive Ion Beam Task Force has been formed to address RIB nuclear data needs [9]. The current focus is on nuclear data needed to guide the choice of targets for the production of various radioactive product species using the isotope-separation online (ISOL) method; future work will include the study of RIB nuclear reaction and structure physics. Laboratories that are undertaking RIB studies with the ISOL method in the U.S. are Oak Ridge National Laboratory and Argonne National Laboratory, and the RIB Task Force interacts with researchers at these laboratories to respond to their data needs.

To produce proton-rich RIBs, (p,xn) reactions are used on targets that are typically the most proton-rich stable isotope of a given element. When selecting targets candidates in a RIB facility, it is important to have reliable estimates of the production cross sections of various radionuclides produced in proton-induced reactions, for incident energies up to 200 MeV. Since measured cross section data exist in only a few cases, nuclear model calculations can be used to estimate these cross sections once they have been benchmarked against existing data to validate their accuracy. Below we outline some of the nuclear model developments that have been incorporated into reaction theory codes to optimize their ability to predict (p,xn) cross sections.

Neutron-rich RIBs will be produced using proton (or neutron) induced reactions on a U target - many of the fission fragments are neutron-rich. A high-priority data need is an accurate characterization of the fission fragment distribution (in Z and A) so that the production cross sections of neutron-rich products far from stability can be predicted. Existing theories have only a limited predictive capability, and the experimental information is fragmentary. A related data needed is the calculation of the activation induced in and around a uranium target for radiation protection purposes. This can be determined using the CINDER code in conjunction with the LAHET-MCNP code, though improvements in the LAHET fission model are desirable.

3.1 Nuclear Reaction Code Developments

Members of the RIB Task Force have developed and improved nuclear model codes for calculating (p,xn) reactions. Such codes calculate cross sections using compound-nucleus, preequilibrium, and direct reaction mechanisms. Developments include formulating models for various nuclear reaction mechanisms, as well as the use of more accurate nuclear level densities, optical potentials, masses, and other parameters that are inputs into the calculations. Cross sections for radionuclide production via (p,xn) reactions are particularly sensitive to preequilibrium processes. This is because, for relatively high proton incident energies (above 50 MeV, say), a (p,xn) reaction (where x =1,2) primarily occurs when one or more of the neutron ejectiles are of high energy so that subsequent particle decay is energetically forbidden.

Highlights of recent code improvements are listed below:

PRECO-E (C. Kalbach Walker (TUNL)): Shell structure, pairing, isospin conservation, and finite well depth effects have been included in a two-component version of the exciton model. The code has been benchmarked against a large amount of measured data for reactions at 14 to 25 MeV and at 90 MeV on targets with A=24 to 209.

GNASH (P.G. Young (LANL) and M.B. Chadwick (LANL)): Multiple preequilibrium emission has been incorporated within both the exciton-model version and the Feshbach-Kerman-Koonin (FKK) version of GNASH. Multiple preequilibrium processes have been studied through comparison with predictions by the Quantum Molecular Dynamics theory.

HMS-ALICE (M. Blann (LLNL)): A new precompound model that follows successive 1p to 2p1h excitations using a Monte Carlo method has been developed. This model has the advantage of allowing multiple preequilibrium beyond the emission of two fast particles. Initial studies indicate that it has a good predictive capability for determining radionuclide yields.

MINGUS (A.J. Koning (ECN-Petten)): A two-component FKK theory that explicitly follows neutron and proton particle-hole excitations in the preequilibrium reaction, as well as making use of shell-model states for the single-particle excitations, has been developed in collaboration with M.B. Chadwick. Such studies are important for correctly determining the relative partitioning of reaction flux into secondary neutron and proton ejectiles, and are therefore important for predicting (p,xn) cross sections.

3.2 Results and Data Dissemination

To date, nuclear model calculations of (p,xn) cross sections using the GNASH code have been completed for RIB-producing targets of ^{28}Si, ^{40}Ca, ^{58}Ni, ^{64}Zn, and ^{70}Ge. The evaluation methodology consist of first obtaining existing experimental compiled cross sections from the NNDC CSISRS database and from the literature, performing model calculations and comparing the results against these data (to validate the calculations), and using the model calculations to predict unmeasured cross sections of interest to the RIB community. These results have been supplied to Jerry Garrett of ORNL. Calculations of (p,xn) reactions on Au (for the release of Hg isotopes), Pb, Ta, and other targets are currently underway, at the request of Jerry Nolen of ANL.

RIB studies related data may be obtained from the LANL T2 Nuclear Information Service [10] or the NNDC data access [8]. There are plans to make these data evaluations, when completed, part of the ENDF system.

4. High Energy Heavy-ion And Electron Data

A pilot project to compile relativistic heavy-ion data (RHID) measured at the AGS at Brookhaven has been started by the NNDC [11]. A Taskforce appointed by the research community is expected to come up soon with a report on all aspects of such data compilation and dissemination. Discussions are underway with the electron interaction data experimentalists about compiling their data.

5. Other USNRDN Activities

In addition to the above activities of the USNRDN which are closely associated with specific areas of basic research, there are a number of related projects done by network members which contribute to the mission of the network. The Nuclear Data Verification and Standardization Project at NIST has completed an update of the 1991 NEANDC/INDC Nuclear Standards File in collaboration with an IAEA Consultants Group. Measurements of the $^{10}B(n,\alpha)$ and hydrogen scattering cross sections in the MeV region are also in progress. The University of Massachusetts at Lowell group has measured elastic and inelastic scattering cross sections of ^{197}Au, ^{239}Pu, ^{235}U and the total cross section of ^{235}U as part of an educational and training program. The group at Ohio University is interested in resolved structure of low energy cross sections, level density measurements and calculations, and shell model/R-matrix calculation of $A < 20$ reactions. As part of this program, they are studying heavy ion reactions on ^{10}Be targets, p(n,n)p scattering at 10 and 14 MeV, optical model analysis of deuteron reactions on ^{27}Al, and ^{56}Fe, and measurement of cross sections of neutron induced reactions on C, N, O, ^{17}O, S, and ^{56}Fe targets at WNR, LANL in collaboration with the L-3 group. This is a brief summary of recent work completed by members of the network. Future plans of these groups and complete details of their research program may be obtained by contacting the individual groups through the USNRDN Homepage [1].

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