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NUCLEAR DATA REQUIREMENTS FOR FUSION REACTOR NUCLEONICS*

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Abstract

Nuclear data requirements for fusion reactor nucleonics are reviewed and the present status of data are assessed. The discussion is divided into broad categories dealing with data for Fusion Materials Irradiation Test Facility (FMIT), D-T Fusion Reactors, Alternate Fuel Cycles and the Evaluated Data Files that are available or would be available in the near future.

1. Introduction

There have been a number of articles discussing various aspects of the nuclear data requirements for fusion applications. At the IAEA Advisory Group Meeting on Nuclear Data for Fusion Reactor Technology held in December 1978, Head,[1] summarized the nuclear data requirements of the magnetic fusion power program of USA. Data requirements for studies of fusion reactor design,[2] nuclear heating,[3] transmutation and activation of reactor wall,[4] radiation damage,[5] shielding,[6] and hybrid reactor calculations,[7] were presented and discussed in detail. The status of evaluated data files available was also discussed.[8] More recently, fusion nuclear data needs have been reviewed by Haight,[9] and the FMIT data by Browne and Lisowski.[10] Since it is redundent to repeat this discussion in detail, changes and modifications that have occurred in the data needs will be emphasized here. In addition, the discussion will be confined to mentioning broad categories of data rather than a detailed listing which may be found in the references and in the U.S. Data Request List.[11] The discussion will be divided into first, data needs for the Fusion Materials Irradiation Test (FMIT) Facility which is under construction and the data are needed within one or two years or immediately. Second, the data for the design of a D-T fusion reactor will be discussed. Third, the charged particle cross sections for alternate fuel cycles will be listed. The data needs and the priorities assigned to them are taken from the list of Ng.[12] Finally, the evaluated data libraries that are available now and the expected improvements or additions to these will be mentioned.

2. Fusion Materials Irradiation Test Facility

Nuclear data needs of the FMIT project were discussed at a Symposium,[13] in 1977 and again reviewed and updated at a similar meeting,[14] in 1980. This is a facility designed to produce a high flux (~10^{15}n/cm^2·sec) of 14 MeV neutrons for materials damage studies in test volumes of the order of 10cm.^{3} The device operates by having 0.1 amp beam of 35 MeV deuterons bombarding a flowing lithium target. In addition to the broad peak of ~14 MeV neutrons it is expected that there would be an appreciable tail of neutrons extending up to about 50 MeV. The data requirements are varied and are discussed under the following broad categories.

(i) Source Characteristics

Thick sample yields and spectra of the reaction Li(d,xn) at a deuteron energy of 35 MeV have been measured by the UC Davis Group.[15] Neutron spectra were measured from ~1 MeV to ~50 MeV - the maximum kinematically allowed energy and angles of 0-150°. From these measurements, though it was found that emitted neutrons of energy greater than 30 MeV constituted only about 1% of the spectrum, they have to be considered in the design of the shield because of their high energy. The actual data needed to determine the source characteristics are the spectrum of neutrons produced as a function of the angle for different deuteron energies upto 35 MeV. This has been indirectly obtained from the thick sample data by fitting a simple model of the microscopic differential cross section to this data.[16] However, there is need to measure these thin sample neutron yield spectra.[15]

(ii) Dosimetry Reactions

The use of dosimetry reactions for determining the neutron fluence and spectrum with the FMIT have been reviewed by Greenwood.[17] Multiple-foil

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passive dosimetry technique analyzes the activation products and by unfolding determines the most probable flux and spectrum of the incident neutrons. For FMIT applications, Greenwood,[18] has assembled a cross section file extending to 44 MeV by extrapolating to higher energies by various methods. However, reaction data at selected energies from 1 to 50 MeV are needed for ^{59}Co, ^{197}Au, ^{54}Fe, ^{58}Ni, ^{90}Zr, ^{89}Y, ^{169}Tm, ^{93}Nb, ^{23}Na, ^{107}Ag, ^{238}U and ^{55}Mn. Details of the different (n,particle) reactions and accuracies desired may be found in the forthcoming compilation of Requests for Nuclear Data.[11] Helium accumulation fluence monitors provide neutron fluence data as a further check on the foil technique results. Source characterization by these two techniques and the helium generation cross sections for fast neutrons have been discussed by Kneff et al.[19,20] Total helium production cross sections as a function of energy are needed for Al, Fe, Cu, Ti, Ni, W and Au up to 40 MeV.[11] Solid state track recorders are being developed for neutron dosimetry,[21] and need ^{235,238}U fission cross sections and (n,p), (n,α) reactions for Ag, Br, C, O and N in the 14-40 MeV range.[11]

(iii) Materials Damage Studies

The status of materials damage studies program has been reviewed by Doran and Guinan.[22] The data needed are differential angular cross sections for elastic scattering and for all non-elastic reactions for Fe, Ni, Cr, Al, Cu, W, Sn, Ti and V in the energy range 15-35 MeV.[11] The angular and energy distributions of the emitted particles are necessary so that the recoil energy of the residual nucleus can be calculated. Total helium and hydrogen production cross sections should be available for these materials at a few points from 15-35 MeV to help in the unfolding of total helium production data.

(iv) Shield Design

Nuclear data relevant to the shield design of the FMIT facility have been reviewed by Carter et al.[23] Total differential elastic and non-elastic neutron cross sections are needed for the constituents of the shield for energies up to 50 MeV. Neutron total and non-elastic cross sections for Fe, O, C and Ca were measured by the UC Davis Group,[24] at 35.3, 40.3 and 50.4 MeV and total cross sections were also measured for C, O, Al, Si, Ca, Cr, Fe, Ni, Cu, Au and Pb from 2-80 MeV at ORELA.[25] However, high accuracy (±5%) total and differential elastic data on some of the important shielding materials like Fe, Ni, Cr and Ti would be helpful in order to check these data.[11]

(v) Neutron and Deuteron Activation Data

These data are needed to estimate the problems involved in the maintenance of the FMIT facility including the test cell and monitoring equipment. Activation data needs have been discussed by Johnson et al.[16] Since only about 5 neutrons are emitted for 100 deuterons of 35 MeV energy incident on lithium, it is expected that the amount of activation caused by deuterons is much larger than that originating from neutrons.[16] There are much less data on deuteron induced activation than on neutron activation. Some of the deuteron induced activations have been measured at the UC Davis with 35 MeV deuterons incident on Li, C, Al, Fe, Ni, Cu, Mo, Ta, Au and Pb. Measurements on Na, K, Ca, Cr and Mn and other nuclei have been planned. There are neutron activation cross sections in ENDF/B which have been extended to 40 MeV with nuclear model calculations of various degree of sophistication. These, however, have to be checked against differential data at higher energies or integral measurements. Neutron activation data are needed for Cu, Al, Cr, Mn, Fe, Ni,Ti, Co, Na and K up to 40 MeV.[11]

(vi) Other FMIT Data

In addition to the above, data are needed to determine the effect of prompt neutron, gamma-ray and charged particles originating from deuteron bombardment and also neutron and gamma-ray transport and radiation heating data. The status of these have also been discussed by Johnson et al.[16] The neutron yield and spectrum data for deuterons on lithium were discussed earlier in the section on source characterization. Data on gamma-ray production were also obtained from the same experiments.[15] Proton emission from (d, Li) reaction was calculated on the assumption that proton emission was similar to neutron emission.[16] The data needed for determining neutron and gamma-ray transport and radiation heating are differential elastic scattering, non-elastic scattering neutron, charged particle and gamma-ray emission spectra and KERMA factors. These data are needed up to 50 MeV. ENDF/B-IV evaluations may be used up to 15 MeV supplemented by nuclear model calculations and the Wilson,[26] and Alsmiller - Barish,[27] data libraries for higher energies.

3. D-T Fusion Reactor Design

The data for fusion reactors based on the D-T reaction are many and are needed for energies up to 15 MeV. These will be divided into data for the next generation D-T reactor designs and those for the D-T Fusion Engineering Prototype and Demonstration power plant. The data in the first section are assigned a higher priority, (priority I) than those in the second (priority II).

3.1 Data for Next Generation D-T Reactor Designs

(i) Data for Shielding, Activation and Neutron Transport Calculations

Data on secondary neutron emission spectra as a function of angle and neutron activation cross sections for all significant activities are needed for incident energies from 9 to 15 MeV, for Al, ^7Li, C, Ni, Cu, ^{10}B, Fe, Cr, Pb, Si, W, O, N. The data should have a precision of 10%.[11] Some of the recent measurements on the neutron emission spectra have been listed by Browne and Lisowski.[10]

The need for reliable data on induced-activation is becoming exceedingly important for two reasons. First, the need for recyling most of the materials within ~30 yrs after component replacement or reactor decommissioning is now recognized. Second, the benefits of personnel access into the reactor building within hours after shutdown to perform some "hands-on" maintenance have been indicated, particularly for near-term facilities such as FED/ETF. The result of these new developments is that providing adequate data for induced-activation (cross sections, branching ratios, decay schemes, etc.), of all materials in the reactor,[5] is necessary.

(ii) Data for Materials Damage Studies

These data include helium and hydrogen production data for Li, C, Ni, Si, Cu, O, N, ^{10}B, Fe, Cr, Pb, W and Al between 9 and 15 MeV. There are some data measurements at 15 MeV,[13] and more measurements are needed at lower energies.

(iii) Data for Tritium Breeding

Data are needed for $^7Li(n,n')\alpha t$ reaction for 11 to 14 MeV neutrons with an accuracy of 5% if possible, and at least 10%. For ^6Li, the data for tritium production are needed from 0.5-5.0 MeV with a precision of 10%. These data with the spectrum of secondary neutrons for the reactions mentioned above are important for a calculation of tritium breeding in the fusion reactor blanket. Recent measurements on $^7Li(n,n')\alpha t$ reaction from 4-14 MeV and their implications have been discussed by Swinhoe et al.[29] They find that their results are uniformly lower than the ENDF/B-IV evaluation by 26%; their data uncertainty is estimated to be about 5%. There have been some recent $^7Li(n,n')\alpha t$ measurements at Argonne from 6.9-9.0 MeV and the preliminary results are about 10-18% lower than ENDF/B-IV.[29] A new evaluation of ^7Li is also in progress at LASL.[30]

One of the most important of the recent developments concerns the tritium breeding medium and neutron multipliers. Perceived safety problems with liquid lithium has led to a strong shift in emphasis to solid tritium breeders. The candidate solid breeders are Li_7Pb_2, Li_2O, and the ternary oxides such as $LiAlO_2$, Li_2SiO_3, Li_2TiO_3, and Li_2ZrO_3. The two materials of Li_7Pb_2 and Li_2O have an excellent tritium breeding margin that is comparable to that of natural lithium. Unfortunately, the STARFIRE,[31] study shows that serious problems such as the tritium release characteristics and compatibility problems may eventually rule out the use of Li_2O and Li_7Pb_2. This would leave the tertiary oxides as the only viable solid breeders. Calculations show that the tritium breeding ratio (TBR) with all ternary oxides is less than one. Therefore, the use of a neutron multiplier is necessary. The utilization of beryllium can provide a comfortable margin in the TBR but the resource limitations of beryllium cast serious doubt on its use. Lead and bismuth are good neutron multipliers but their low melting points (327 and 271°C) present engineering difficulties. PbO has a melting point of 888°C but the presence of oxygen, low thermal conductivity, and compatibility problems make it unsuitable. Therefore, the problem of identifying a neutron multiplier with high melting point and large (n,2n) cross section down to the low MeV energy range is emerging as a critical problem. The STARFIRE study identified Zr_5Pb_3 as a potential candidate. However, the presence of zirconium makes the neutron multiplication properties of Zr_5Pb_3 marginal. The achievable breeding ratio with $LiAlO_2$ and Zr_5Pb_3 is ~1.04. Such a low breeding ratio does not assure an adequate margin to account for data and calculation uncertainties. The required net breeding ratio in an operating reactor needs to be ~1.02-1.05.

The tritium breeding capability is thus emerging as a potential feasibility problem for solid breeders (the ternary oxides). This suggests not only a need for a complete base of nuclear data but it indicates the importance of better accuracy. The magnitude of the (n,2n) and parasitic absorption cross sections as well as the energy distribution of secondary neutrons from all neutron-producing reactions need to be known to a high accuracy for all the solid breeders and neutron multipliers defined above. The neutron slowing down and absorption properties in the structural material and coolant are also critical in the solid breeder systems. It appears at present that stainless steel alloys and water are the most likely candidates for reactors in the next two to three decades.

(iv) Cross Section Data For Near Term Fuels.

Data are needed for d-t and t-t reactions at low energies where the existing data are discrepant and contain much larger errors than suspected. The data discrepancies for d-d, d-t and t-t reactions have been recently discussed by Jarmie et al.[32] They have also plans to measure these reactions from 10-100 keV with an expected accuracy of 5%.

(v) Cross Sections for Diagnostics

Cross section data needed for

plasma diagnostics are for $^{64}Zn(n,p)$ and $^{16}O(n,\alpha)$ up to 14 MeV.[illegible] These reactions are used in detectors which measure the 14 MeV *neutrons produced* by confined tritons from the d(d,p)t reaction in the PLT. Ti(γ,n) and Ti(γ,p) cross sections are also needed to $E_\gamma \simeq 20$ MeV. *In addition,* cross sections for the production of electron-positron pairs in D and H by electrons up to 20 MeV in energy are also necessary. *T(e,e'n)* and *T(e,e'p)* electro disintegration data up to 50 MeV are essential to estimate the background neutron noise produced by runaway electrons in *TFTR*.

3.2 Data For D-T Fusion Engineering Prototype and Demonstration Power Plant Designs.

The data mentioned up to now are needed with a high priority (priority I) as opposed to the data in this section which have a lower priority of II.

(i) Data for Shielding, Activation and Neutron Transport.

Data on neutron spectra are needed as a function of the secondary neutron energy and angle for Be, Ti, Nb, Sn, Mo, V, ^{11}B and F for incident neutron energies from 9 to 15 MeV. In addition, activation data for all significant activation cross sections are necessary.

(ii) Data for Materials Damage Studies

Helium and hydrogen production data are needed for Be, Ti, Nb, Sn, Mo, V, ^{11}B and F for neutron energies between 9 and 15 MeV. Other data for materials damage studies are the charged particle energy spectra for (n,α) and (n,p) reactions for 15 MeV neutrons on Al, ^7Li, C, F, Ni, Cu, ^{10}B, ^{11}B, Fe, Cr, Pb, Sn, Si, W, O, Li, N, Be, Ti, V, Nb, and Mo.

(iii) Data for Fusion Hybrid Studies

Data for fusion-fission hybrid reactors have been recently reviewed by Jassby.[33] Some of the data needed for this purpose are the high energy neutron multiplying reactions in Th and ^{238}U such as (n,2n) and (n,3n) from 11-14 MeV with an uncertainty of 10%.[illegible]

(iv) Gamma-ray Production Cross Sections

Gamma-ray production data have been measured for 27 materials of interest to the fusion program at ORELA.[25] They extend from 0.1 MeV-20 MeV for neutron energies and the gamma-ray energies cover the range $0.3<E_\gamma<10.5$ MeV. These data are necessary for heat deposition calculations in the blanket, shield and magnet of the fusion device. Data are needed for the boron isotopes from the inelastic threshold to 15 MeV.

4. Alternate Fusion Fuel Cycles

Alternate fusion fuel cycles and the nuclear data for them have been recently discussed by Shuy and Conn.[34] They discuss reactions important *for the d-d*, d-^3He, d-^6Li, p-^6Li and p-^{11}B fuel cycles. Of these, data are needed with priority I on the fuel cycles p-^6Li and p-^{11}B to evaluate them. *They are:* $^6Li(^3He,p)2\alpha$ from 1.85-5.0 MeV, $^7Be(d,p)2\alpha$ below 2.0 MeV and $^7Be(^3He,2p)2\alpha$ reaction below 3.0 MeV. In addition, branching *ratios for other reactions of* ^3He *on* ^6Li in the energy range from several hundred keV to a few MeV should be measured. Elastic scattering data of ^3He *on* ^4He (50 keV-8 MeV), ^3He *on* ^6Li (100 keV-5 MeV) and ^3H on ^4He (up to 8.0 MeV) are necessary. For the p-^{11}B fuel cycle, reaction cross sections *are needed for* $^{11}B(p,\alpha)^8Be$ and $^{11}B(p,\alpha)2\alpha$ reactions from 0.2-2.0 MeV. These include the spectra of the emitted α particles as a function energy and angle.

5. Evaluated Data

Since the last review,[8] of the evaluated data files available for fusion, ENDF/B-V library has been released. *This contains evaluations up to* 20 MeV for a number of materials with improvements in the quality of evaluation brought about by including *new experimental data, improved nuclear* model code calculations, integral data testing and more stringent checking codes. Secondary neutron energy *distributions include the pre*-equilibrium components, and better gamma-ray production data are used and checks for energy balance applied. *Details of the evaluations may be* found in the summary documentation,[35] or the individual evaluation reports.

For high energy calculations for FMIT, the Wilson,[26] and the Alsmiller-Barish,[27] libraries continue to be used along with *ENDF/B-IV changed* to include new experimental data at higher energies.[23] Arthur et al.,[36,37] have carried out evaluations for $^{54,56}Fe$ up to 40 MeV and for ^{59}Co up to 50 MeV and have plans to extend the energy of evaluations for other materials. The dosimetry library has been extended by Greenwood,[18] to 44 MeV and the HEDL has enlarged the activation library in ENDF/B up to 40 MeV using various nuclear model calculations.[16] Evaluations of charged particle reaction data of interest to fusion by G. Hale (LASL) are available in the ENDF/B format.[38] Compilation of experimental data *on* these reactions from the Howerton (LLL) library (in ECSIL format) and Nuclear Reaction Data Centers' X-4 format and the Hale evaluations may be obtained from the National Nuclear Data Center at Brookhaven.[39]

In carrying out an evaluation, nuclear model codes play a very important part to supplement measured data or supply information for *which* no data are available. Recent developments in this field have been discussed by Young et al.,[40] Gardner,[41] and in other papers at the 10-50 MeV Symposium.[14]

Integral experiments such as those in progress at Oak Ridge National Lab,[42,43] and others described at the Knoxville Conference,[44] are important for checking the data base and providing indication of possible problems with evaluations.

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