CONF-9010199--2

BNL-45308

BNL--45308

DE91 004005

Abstract

Data Requirements for Intermediate Energy Nuclear Applications*

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Several applications that include spallation neutron sources, space radiation effects, biomedical isotope production, accelerator shielding and radiation therapy make use of intermediate energy nuclear data extending to several GeV. The overlapping data needs of these applications are discussed in terms of what projectiles, targets and reactions are of interest. Included is a discussion of what is generally known about these data and what is needed to facilitate their use in intermediate energy applications.

Received by OSTI
NOV 23 1990

Submitted to IAEA Advisory Group Meeting on Intermediate Energy Nuclear Data for Applications in Vienna, Austria, October 9-12, 1990.

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I. Introduction

Several applications that include spallation neutron sources, space radiation effects, biomedical isotope production, accelerator shielding and radiation therapy make use of intermediate energy nuclear data extending to several GeV. The applications make use of both man made and natural intermediate energy sources. Because it can be difficult, expensive and time consuming to answer all questions experimentally, analytical methods are sought that will produce accurate predictions. The accuracy of the methods are assessed by comparing calculations with benchmark measurements, i.e. measurements in which the experimental conditions are well defined and measured parameters uniquely interpreted. Establishing validated analysis methods requires the use of an extensive measurement-data base, nuclear model codes incorporating applicable theories, and evaluation techniques to distill the information into a file of recommended data for applications. For maximum cost effectiveness the recommended data should be computerized and interfaced to radiation transport codes.

Two methods are used to interface nuclear data to radiation transport codes. One method includes a Monte Carlo method of calculating cross-sections internally interfaced to a Monte Carlo radiation transport code under the general class High Energy Transport Code (HETC). This method has the advantage that all cross-sections needed are provided by calculation but are not separately available for fine tuning or for sensitivity studies, i.e. examining the changes in calculated results due to changes in input data. The other method is evaluated nuclear data stored in computerized libraries, e.g. ENDF/B, JENDL, JEF etc., obtained by various techniques for use in Monte Carlo or deterministic radiation transport calculations.

II. Overview of Nuclear Data

The total and nonelastic cross-sections play an important role in intermediate energy nuclear data. Above 20 MeV for light targets and above a few MeV for heavy targets these cross-sections are smooth and their magnitude systematically well known. The sum of partial reaction cross-sections, even if not individually well known, cannot exceed the nonelastic cross-section. In the case of incident neutrons, the total cross-section minus the nonelastic cross-section can determine the elastic scattering cross-section. (The total cross-section for incident charged particles is infinite when Rutherford scattering is integrated over all angles).

As examples of the smooth systematic behavior of neutron induced total and nonelastic cross-sections, comparisons between calculation and experiment of the total cross-sections for carbon and lead are shown in Fig. 1 and the nonelastic cross-sections in Fig. 2. The solid curves come from optical model calculations using global parameters [1] and show that the neutron total and nonelastic cross-section envelopes are well predicated by nuclear modeling.

The nonelastic cross-sections above 20 MeV are easily paramaterized. An approximate formula for the nucleon-nucleus nonelastic cross-section [See Table 3 Ref. 19] is

$$\sigma_{ne}=45A^{0.7}f(A)f(E) \text{ mb, where}$$

$$f(A) = 1+0.016 \sin(5.3-2.63 \ln A)$$

$$f(E) = 1-0.62e^{-E/200}\sin(10.9E^{-0.28})$$

$$E=\text{Projectile laboratory energy (MeV)}$$

An approximate formula for the nucleus-nucleus nonelastic cross-section [See Table 3 Ref. 18] is

$$\sigma_{abs} = \pi\, r_o^2 \beta\,(E)\,(A_p^{1/3} + A_t^{1/3} - \delta)^2$$

$$\beta\,(E) = 1 + 5/E$$

$$\delta = 0.2 + 1/A_p + 1/A_t - 0.292E^{-E/792} \cos\,(0.229E^{0.453})$$

$$r_o = 0.126 \times 10^{-12} \text{ cm}$$

$$E = \text{Projectile laboratory energy (MeV per nucleon)}$$

III. Applications

This report was prepared with the help of material received from those on the National Nuclear Data Center (NNDC) distribution list for intermediate nuclear data and through activities of the Medium Energy Nuclear Data Working Group (MENDWG)[2,3,4]. The questions asked were (1) What are your data requirements in terms of projectiles, targets, energy range, data and application; (2) What experiments, cross-section codes, transport codes, combined cross-section/transport codes and nuclear data libraries were found useful, and (3) What improvements were needed in the categories of (2)?

The several applications requiring intermediate energy nuclear data have been divided into 4 main categories, space applications, accelerator applications, medical applications and pure research.

Space applications includes the induced activity and radiation damage in humans and in structural and instrumentation materials (especially semiconductors) due to primary cosmic radiation and secondary radiations that result. Also included is the pursuit of astrophysical questions concerning the analysis of solar flares, the composition of meteorites and simulated cosmic irradiated materials and the remote sensing of planetary surfaces by gamma-ray spectroscopy.

Accelerator applications includes the formation of intermediate energy charged particle beams to bombard materials serving as spallation neutron sources for re-

search, fusion materials testing or the transmutation of nuclear wastes, or to bombard nuclear wastes directly. The application also includes the design of appropriate shields for accelerators.

Medical applications include intermediate energy beam therapy and the production of biomedical isotopes for use as tracers and local radiation sources.

Pure research needs are directed toward improved data for the validation of nuclear theory and model codes.

About half of the respondents were interested in space applications. The next largest number were interested in accelerator applications.

IV. Data Requirements

The foregoing applications have overlapping data requirements.

With regard to input beams, all applications have a high priority need for proton-induced reaction data as seen in Table I. There is also a strong need for neutron-induced data in space, accelerator and research studies. Cosmic ray spectra contains significant amounts of alpha particles and heavier ions leading to the need for these data. Subnucleon data are also of interest. Meson (+,0 and -) beam data are needed to predict the consequences of meson fields associated with cosmic rays and proton accelerators. The K+ meson is an ideal beam to probe aspects of the strong interaction and nuclear structure. The design of muon catalyzed fusion facilities requires muon data. Little information regarding the data requirements for photon and electron beams were received from contributors.

With few exceptions, the range of targets is not very beam dependent. The general classes of target materials for which data are needed are for tissue and bone, structural materials, detector materials, fusion materials, shielding, materials and spallation and actinide burner materials. A list of target materials is given in Table II. The target materials and monitor reactions needed for radioisotope production are covered elsewhere [5,6,7]. Mono-isotopic element or separated isotopic target data are useful to validate nuclear models because the interpretation of data is easier when there are fewer competing reactions.

The data types of interest include the elastic scattering angular distribution of the projectile, production of spallation products and double-differential cross-sections for particle production. The data requirements for the detection of reaction products through β and γ-ray spectroscopy are generally satisfied by the contents of the Evaluated Nuclear Structure Data File. [See Table 3 Ref. 29]

Specific research requests for nuclear data include the following:

1. ^{3}He bombardment of ^{57}Co and ^{59}Co targets in the energy range 50 to 200 MeV to analyze hole analog states.

2. Neutron and proton bombardment on mono-isotopic targets ^{56}Fe and heavier, in the energy range 20 to 200 MeV measuring double differential neutron

and proton emission spectra to an accuracy of 20% in order to select appropriate statistical multi-step models.

3. The K^+ total cross-sections per nucleon on several targets from deuteron up in the energy range 500 to 2000 meV to investigate the "swelling" of nucleons and inelastic scattering cross-sections to investigate meson-nuclear forces. [8,9]

The energy range for space applications is particularly important below 250MeV but the interest extends to the GeV range. For accelerator applications and, in particular, spallation neutron sources and actinide burners the energy range of interest extends from a few hundred MeV to several GeV.

Measurement accuracies of 10 to 20 percent appear sufficient for most data although lower percent accuracies are desired for pure research and astrophysics diagnotistics.

V. Existing Resources

Experimental data are compiled and exchanged in the international exchange format, EXFOR, and are available to requesters from regional centers[10]. Most of the compiled data are neutron-induced cross-sections below 20 MeV in support of fission and fusion physics. EXFOR also contains several thousand compiled charged particle, photon and neutron induced data sets extending above 20 MeV and forms a very substantial base for continuing the compilation of intermediate energy data.

Also available from the regional centers are the indexes to bibliography CINDA, an index to neutron data [See Table 3 Ref. 2] and NSR, Nuclear Structure References [See Table 3 Ref. 3]. The indexing of references for NSR has generally been limited to below 100 MeV and cooperation with the indexing services for particle physics should be explored.

Other useful compilations and articles are listed in Table 3.

The two main methods to calculate intermediate energy data are the intranuclear cascade model and the precompound reaction model. The modeling of the first method is most appropriate at higher energies and that of the second method at lower energies.

Table 4 contains a list of some codes useful in calculating nuclear data and radiation transport.

VI. Suggestions for Future Work

The following steps outline a plan for satisfying the future needs of the intermedidate energy nuclear data community.

1. Expand experimental data base

   A. Prepare draft atlas of compiled data in EXFOR

      1. Total cross sections
      2. Nonelastic cross sections
      3. Isotope production cross sections
      4. Particle and heavy ion production cross sections
         a. Total yields
         b. Single-and double-differential distributions

   B. Update data base

      1. Circulate draft atlas for review
      2. Identify completed experiments that should be included
      3. Existing data centers should cooperate to update EXFOR

   C. Identify deficiencies in existing data base

      1. Issue revised atlas
      2. Include evaluated data or eye guides if available.
      3. Review atlas and identify gaps to be filled in order to validate nuclear models

   D. Cooperative Measurement Program

      1. Compile list of measurements in progress or planned
      2. Identify measurements needed to complete data base that are not yet planned and can be added to a data request list, such as WRENDA [See Table 3 Ref. 28]

2. Validate nuclear model codes

   A. Identify nuclear theories applicable to intermediate nuclear data that collectively cover the entire range of application

   B. Identify nuclear model codes incorporating appropriate nuclear algorithms.

   C. Identify nuclear algorithms needed but still are not part of nuclear model codes

   D. Add code development needs to an appropriate request list

   E. Benchmark nuclear model codes incorporating the same or similar algorithms against each other

   F. Compare nuclear model calculations with benchmark experiments

   G. Develop cadre of useful nuclear model codes for intermediate nuclear data

1. List most desirable features of codes investigated
2. Suggest list of basic codes that should be maintained and distributed
   a. Remove obsolete coding
   b. Revise to standard language, e.g. (FORTRAN 77), if necessary
   c. Include desirable options not yet included
   d. Seek stable arrangement for long term maintenance and distribution of these codes

3. Provide data for intermediate nuclear data applications

   A. Assemble tools for providing nuclear data
      1. Experimental data base
      2. Nuclear models
      3. nuclear systematics
      4. Integral benchmark experiments

   B. Access and select tools most appropriate to completing each part of the nuclear data requirements.

   C. Prepare evaluated data for use
      1. Collect partial and completed evaluated data from various individuals and working groups
      2. Enter into common computerized format, e.g. ENDF-6, for coupling to radiation transport codes

   D. Validate data for applications
      1. Assemble 1st order data library with emphasis on completeness rather than accuracy where necessary.
      2. Perform wide spread comparisons between calculations and benchmark experiments. Include sensitivity coefficients.
      3. Identify major discrepancies between calculation and experiment and probable causes with the help of the sensitivity coefficients.
      4. Report discrepancies to measurers and theorists for discussion of the probable causes.
      5. Reflect any data improvements in the next revision of the data library.

4. Endorse and help implement a continuing mechanism for monitoring and upgrading intermediate energy nuclear data through data centers and working groups.

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9. E. Piasetzky, Il Nuovo Cim. 102A, 281 (1989).

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Table I
Input Beam Data Required

Input Beams	Applications: Space	Accelerator	Medical	Research
γ	Y	Y		
e	Y	Y		
μ		Y		
π	Y	Y		Y
K				Y
p	P1	P1	P1	P1
n	P1	P1	Y	P1
d	Y	Y	Y	
t	Y	Y	Y	
^{3}He	Y	Y	Y	Y
α	P2	Y	Y	
HI	P2	Y		Y

Y - Data needed.
P1 - Data needed, first priority category.
P2 - Data needed, second priority category.

Table II
Target Materials

Tissue and Bone	H, C, N, O, P and Ca
Structural	Mg, Al, Si, Ti, Cr, Mn, Fe, Ni, Cu
	Zr, Nb, Sn and W
Detectors	Si, Ge, Ga and As
Spallation and Burner	W, Pb, $^{206-8}$Pb, Th, U, ^{238}U, ^{237}Np, $^{238-9}$Pu and ^{241,3}Am

Table 3

References to Nuclear Data Indexes Compilations and Reports*

1. INIS ATOMINDEX, Issued semimonthly. Available from Division of Publications, International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria. In the U.S., from UNIPUB, P.O. Box 1222, Ann Arbor, MI 48106.

2. CINDA, the Index to Literature and Computer Files on Microscopic Neutron Data. Availability same as Ref. 1.

3. S. Ramavataram, Nuclear Structure References, Supplements published 4-monthly as Recent References issues of the Nuclear Data Sheets journal published by Academic Press. See also the Reaction Index, same publication.

4. N. E. Holden, S. Ramavataram, and C. L. Dunford, Integral Charged Particle Nuclear Data Bibliography. See BNL-NCS-51771. Information is derived from Ref. 3. Annual supplements.

5. Heavy-Ion Reactions, A Current Awareness Bulletin. Updates to the US-DOE Energy Data Base. Issued semimonthly on heavy-ion (A>4) reactions. Available from National Technical Information Service, Springfield, VA 22161 as PB87-900500.

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8. E. D. Arthur, D. M. McClellan, and D. G. Madland, "Bibliographic Survey of Medium Energy Inclusive Reaction Data." LA-10689-PR (1986).

9. EXFOR, Data compiled and exchanged in the international exchange format, EXFOR, are available to requestors from the following regional centers or national centers within regional centers.

   U.S. and Canada: National Nuclear Data Center, Brookhaven National Laboratory, Building 197D, Upton, NY 11973.

   OECD Countries: Nuclear Energy Agency Data Bank, 91191 Gif-Sur-Yvette, Cedex, France

   USSR: For Charged Particles, CAJaD, Inst. Atomnoi Energii I.V. Kurchatova, 46 Ulitsa Kurchatova, Moscow, D-182, USSR

For Neutrons- CJD, Inst. of Physics & Energetics, Obninsk, Kaluga Region, USSR

Others: IAEA Nuclear Data Section, P.O. Box 200, A-1400 Vienna, Austria.

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26. R. Michel et al. Nucl. Inst. and meth. B42, 76 (1989). (cosmogenic nuclides).

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29. T. Burrows, "The Evaluated Nuclear Structure Data File: Philosophy, Content, and Uses," Nucl. Inst. and Meth. A286,595 (1990). Available from regional centers, See Ref. 9, this Table.

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31. N. Zaitseva et al," Cross Sections for the 100 MeV Proton-Induced Nuclear Reactions and Yields of Some Radionuclides Used in Nuclear Medicine," P6-90-138, JINR, Dubna (1990).

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*This list is not exhaustively complete. The author welcomes any suggestions for inclusion.

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Table 4
Computer Codes and Libraries

Intranuclear Cascade

VEGAS, K. Chen et al. Phys. Rev 166, 949 (1968)

ISABEL, Y. Yariv and Z. Fraenkel, Phys. Rev. C, 20, 2227 (1979).

Intranuclear Cascade-Radiation Transport

HETC, Code package CCC-178, T. Armstrong, K. Chandler, ORNL-4744, (1972) Nucl. Sci. Eng. 49,110 (1972). Radiation Shielding Information Center (RSIC), Oak Ridge National Laboratory.

CASIM, A. Van Gunneken, Nucl. Inst. Meth. A251,21 (1986), RSIC CCC-265.

HERMES, P. Cloth et al., Jul-2203 (1988).

TIERCE, Priv. Comm., Claude Philis, CEA Bruyeres-le Chatel, France (1989).

LAHET, R. Prael and H. Lichtenstein, LA-UR-89-3014 (1987).

HETFIS, J. Barish et al., ORNL/TM-7882 (1981).

NMTC/JAERI, JAERI-M82-198 (1982).

Precompound

ALICE, M. Blann, LLNL Report UCID 20169 (1984), contact author.

GNASH, P. Young and E. Arthur, LANL Report LA-6947 (1977) and E. Arthur et al., Proc. Int. Conf. on Nucl. Data, Mito, Japan, p. 607 (1988).

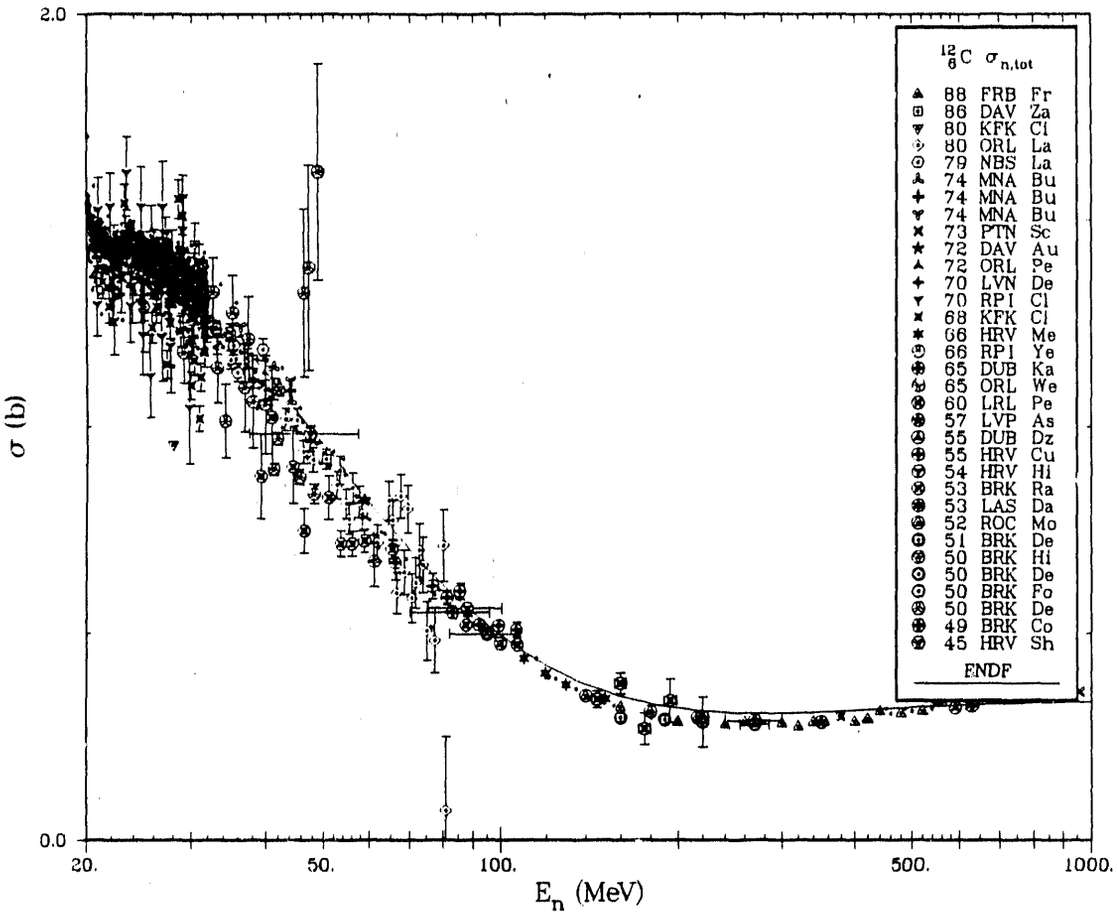
Libraries

HELLO, ORNL/TM-6486, RSIC DLC-58, Neutron-photon group cross sections to 60 MeV.

HILO, ORNL/TM-7818, RSIC DLC-87, Neutron-photon group cross sections to 400 MeV.

ENDF/B-VI, National Nuclear Data Center, BNL (1990). Photon interaction data to 1000 MeV, Neutron-and proton-induced data to 1000 MeV for ^{56}Fe. (Pb and Bi in preparation. See T. Fukahori and S. Pearlstein's contribution to this Advisory Group Meeting).

(a)



(b)

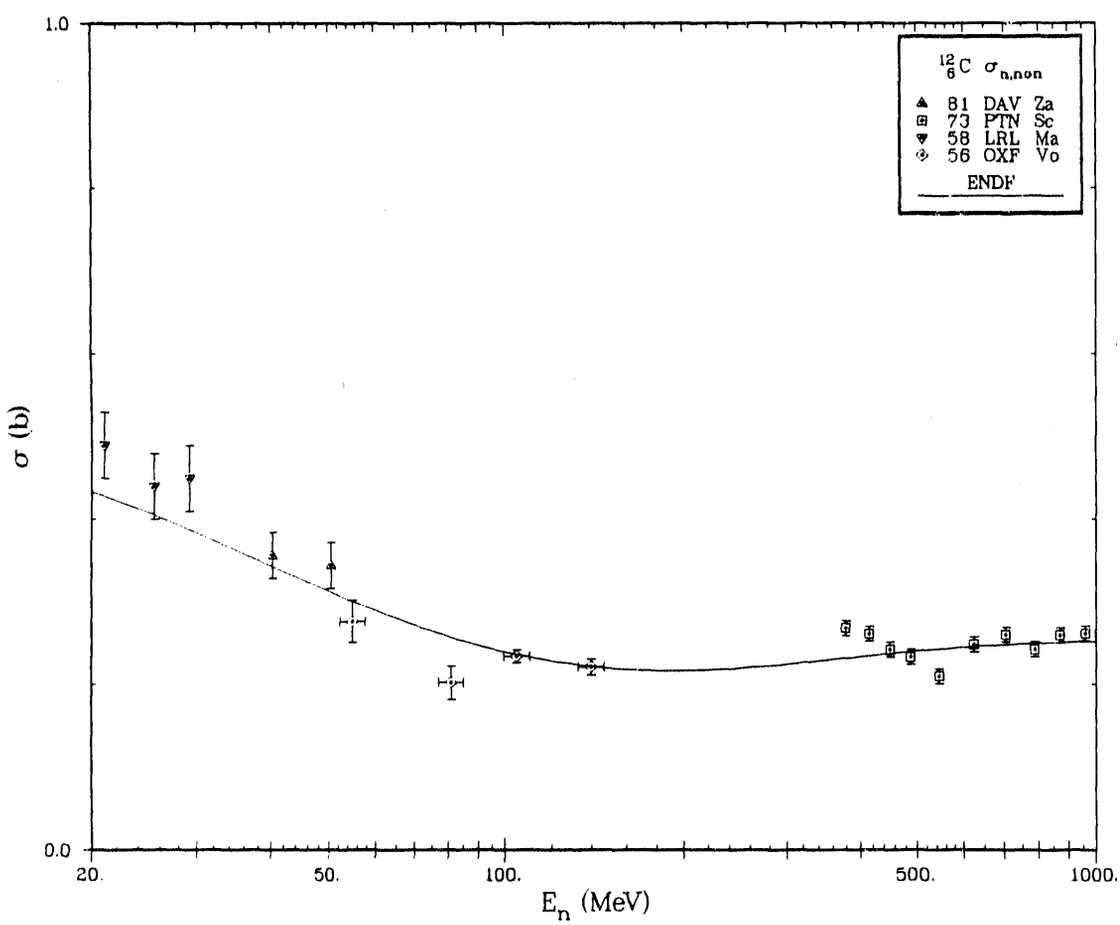
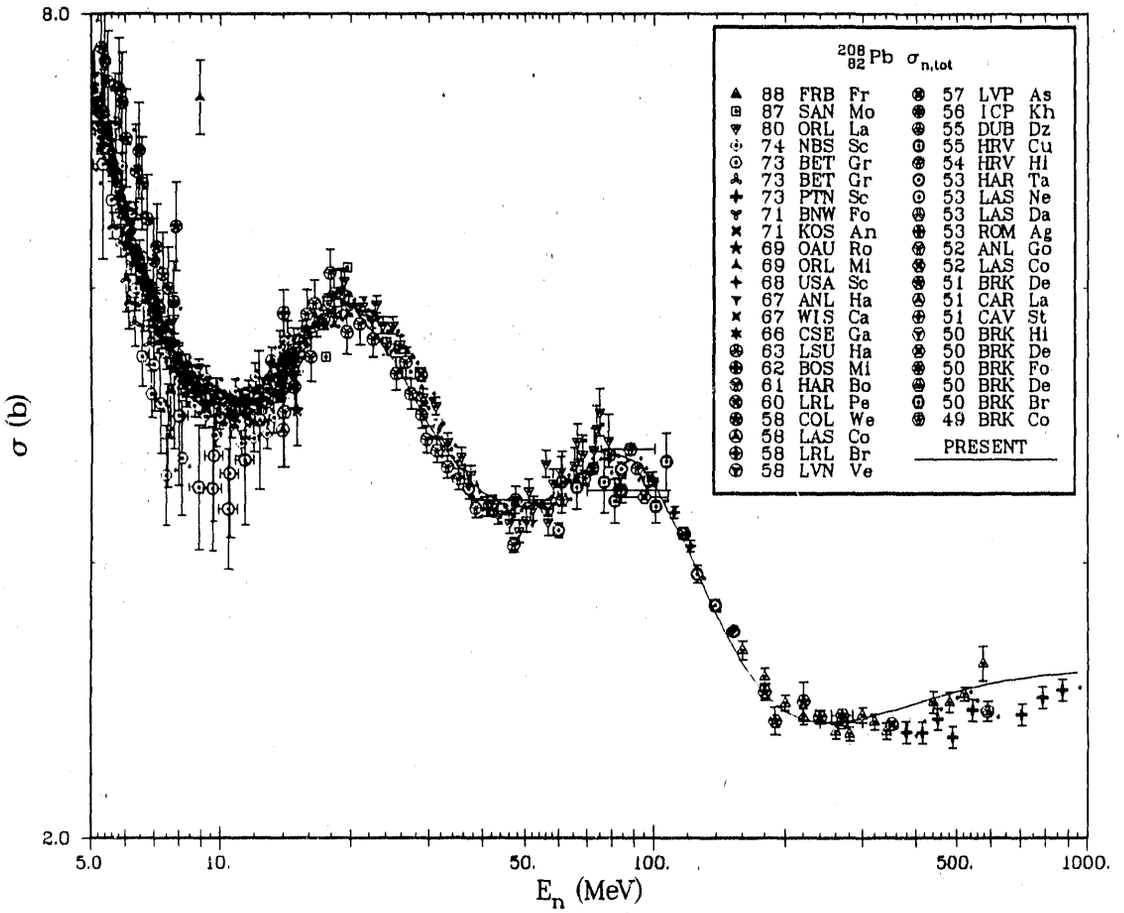


Fig. 1 Carbon total (a) and nonelastic (b) neutron cross-section.

(a)



(b)

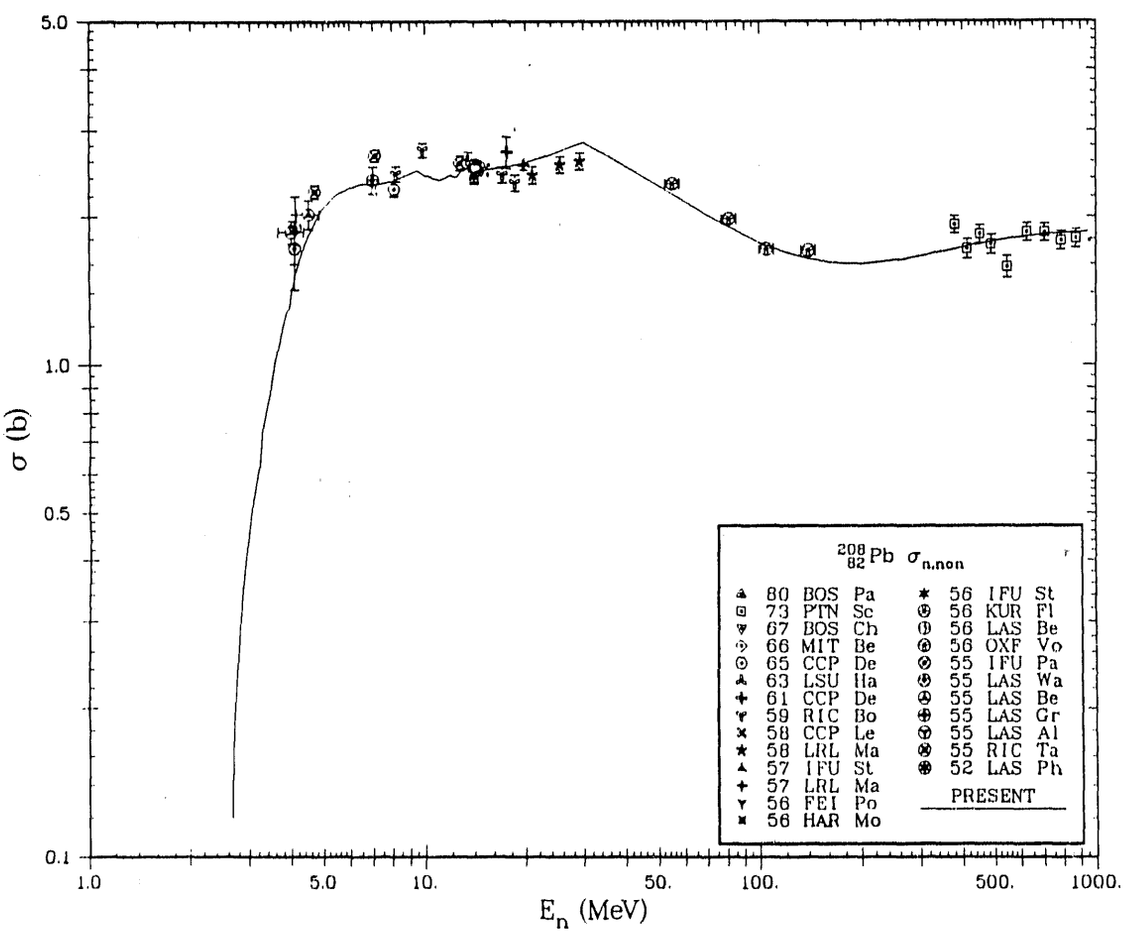


Fig. 2 Lead total (a) and nonelastic (b) neutron cross-section.

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