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COLLEGE ON MEDICAL PHYSICS
AND
WORKSHOP ON
NUCLEAR DATA FOR SCIENCE AND TECHNOLOGY:
MEDICAL APPLICATIONS
(20 SEPTEMBER - 15 OCTOBER 1999)

"Medium Energy Neutron and Proton Data"

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Medium Energy Neutron and Proton Data

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Workshop on Nuclear Data for Science and Technology: Medical Applications

ICTP Trieste, Italy

4-15 October, 1999

LANSCE
Los Alamos Neutron Science Center

Outline: Medium energy neutron and proton data

- What data are needed?
  - Neutrons -- cross sections, kerma coefficients, etc.
  - Protons -- stopping powers, reactions
- What data have been measured?
  - CINDA for neutrons
  - New compilations for protons
- How well have the data been measured?
  - Uncertainties
  - Discrepancies (kerma, cross sections, …)
- Neutron standard cross sections
- Present techniques- and plans for the future

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Some Sources of Neutron Data on the Web

- http://iaeand.iaea.or.at/
  - CINDA
  - EXFOR
  - ENDF, BROND, JENDL, FENDL, etc.
- http://t2.lanl.gov/.
  - http://t2.lanl.gov/data/ndviewer.html.
- http://said.phys.vt.edu/said_branch.html
- http://nn-online.sci.kun.nl /NN/help/index.html)
- Ftp -anonymous@pap.univie.ac.at

Cross Section Standards above 20 MeV

- N-P elastic scattering
- ^{235}U and ^{238}U fission cross sections

-- for both, more work needs to be done

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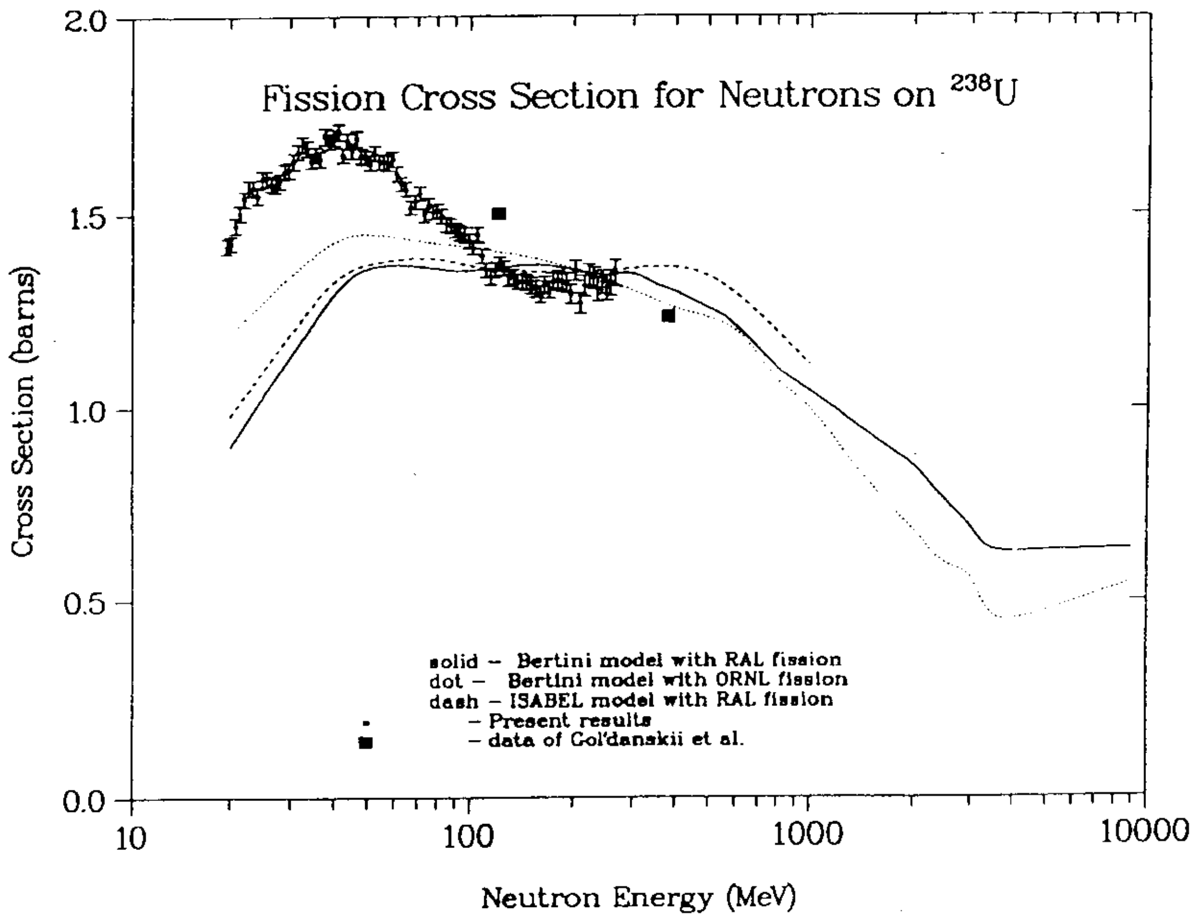
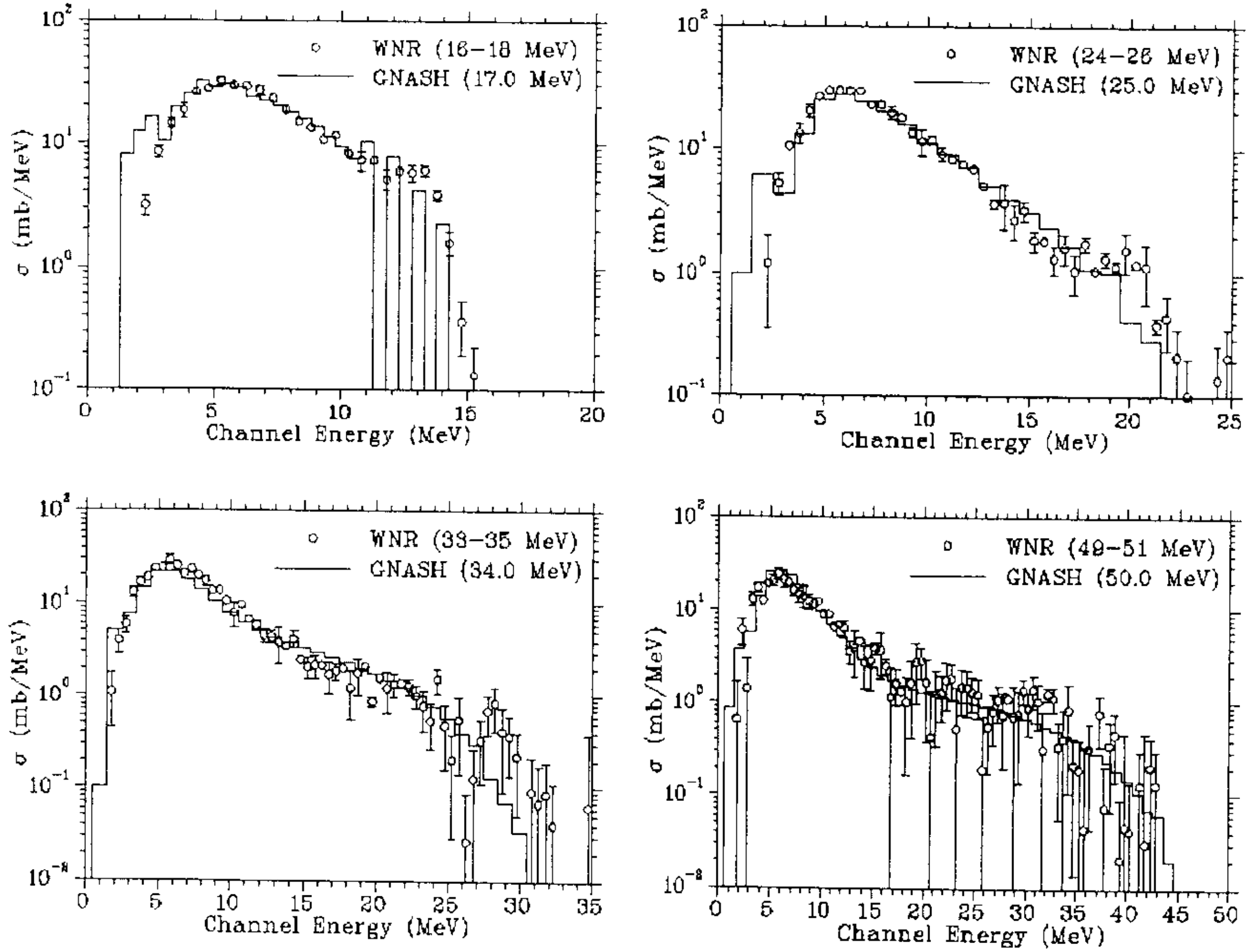


Fig. 5. A comparison of fission cross sections calculated with intranuclear cascade models, the present results for ^{238}U, and other data for neutron induced fission.

Examples of experimental neutron data

- Basic nuclear data
  - Total cross sections
    - spallation neutron source
  - (n,charged particle) reactions on carbon
    - monoenergetic source
  - (n,charged particle) reactions on silicon
    - spallation neutron source
- Kerma factors
- Depth-dose experiments

Si(n,xα) Angle-Integrated Cross Sections



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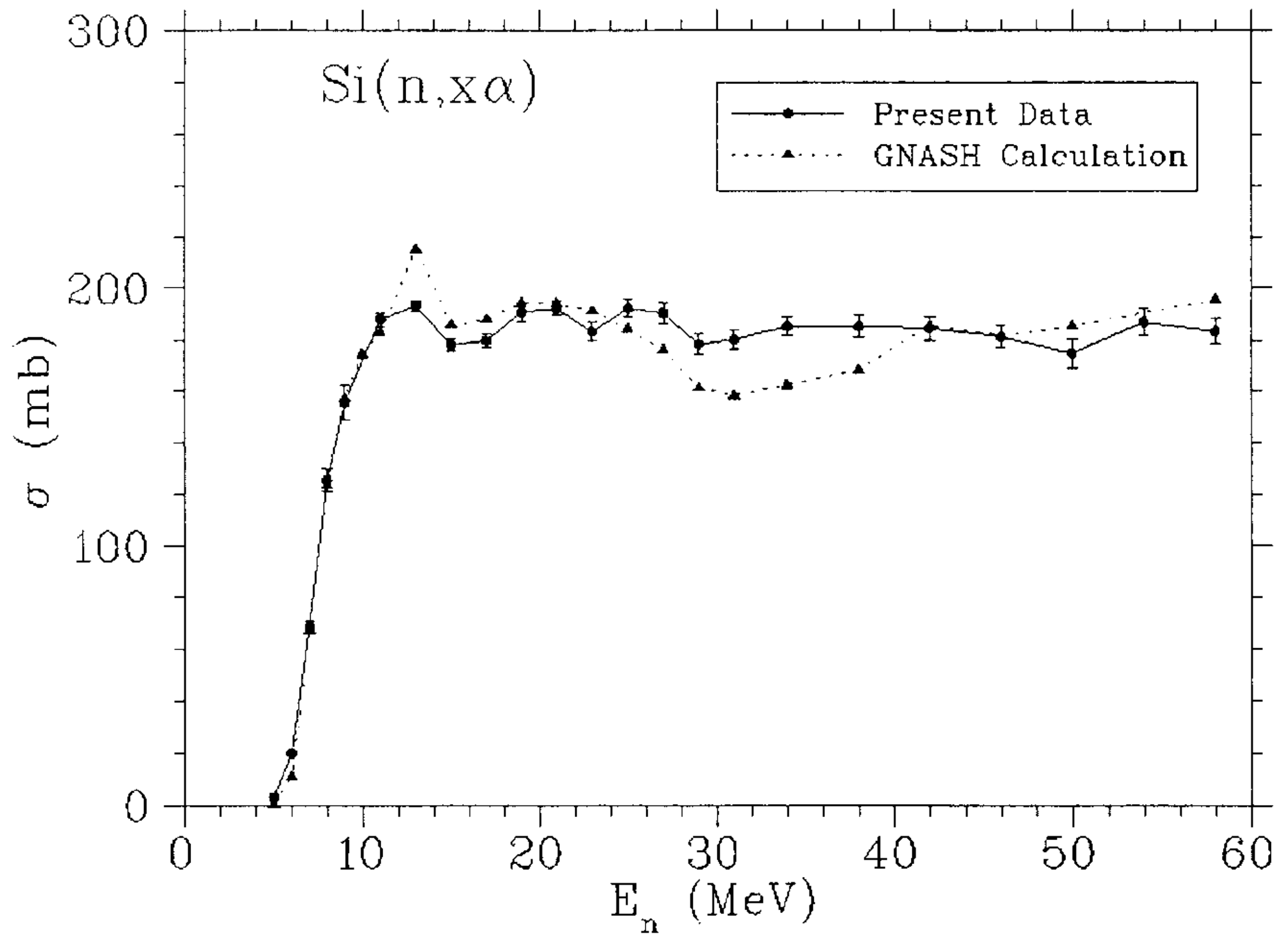

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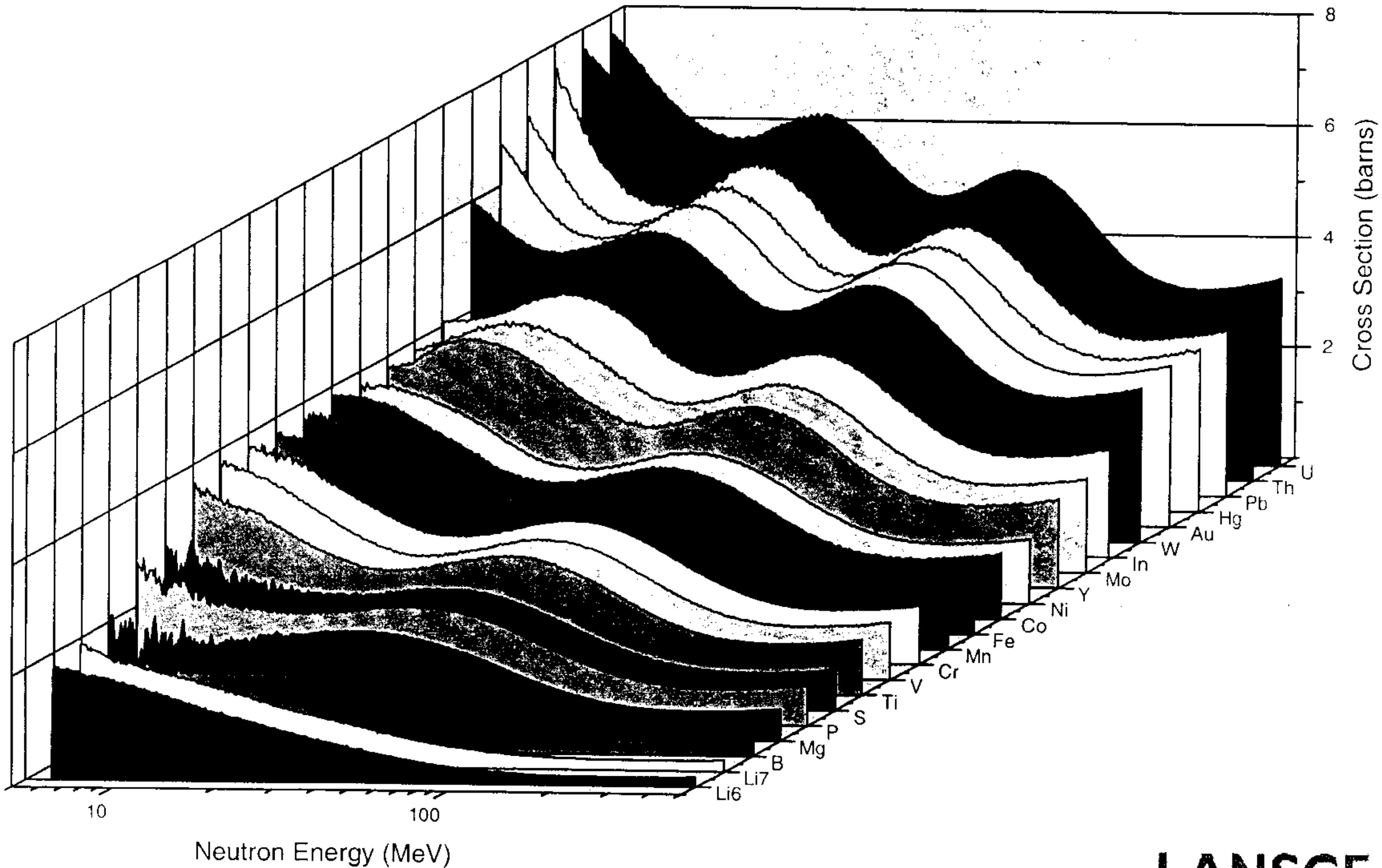
Neutron Total Cross Sections - Results for 22 of the 36 samples measured



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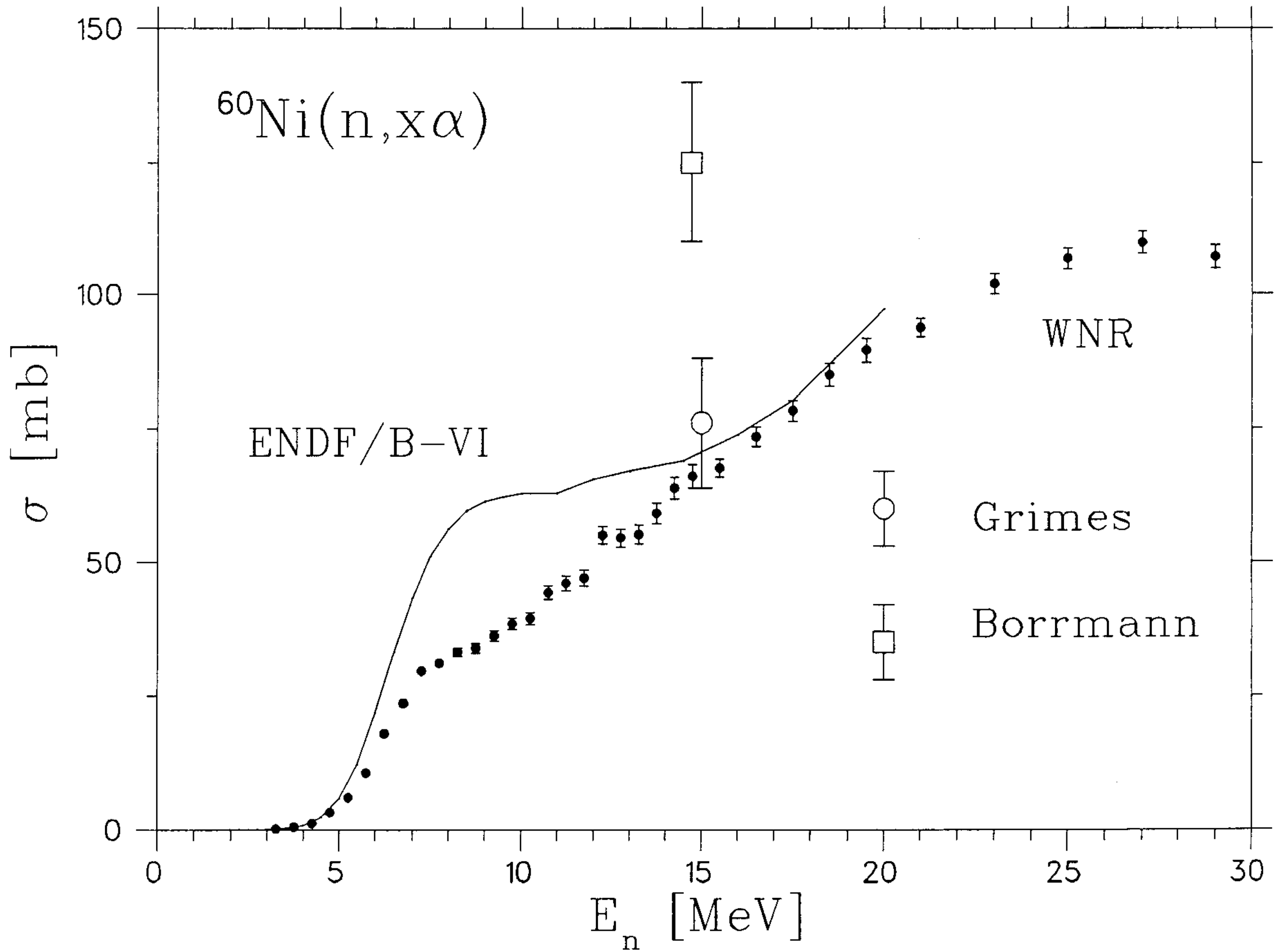

$^{60}Ni(n,x\alpha)$
ENDF/B–VI
WNR
Grimes
Borrmann
σ [mb]
E_n [MeV]
150
100
50
0
0
5
10
15
20
25
30

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Kerma values deduced from neutron-induced charged-particle spectra of carbon from 40 to 75 MeV

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Abstract. The double-differential cross-sections for the $^{12}C(n, px)$, $^{12}C(n, dx)$, $^{12}C(n, tx)$ and $^{12}C(n, \alpha x)$ reactions have been measured at three incident neutron energies, 42.5, 62.7 and 72.8 MeV, at laboratory angles between 20° and 160°. From these measurements, the energy-differential cross-sections have been determined and consequently the partial and total kerma values. Results of the experimental double-differential and energy-differential cross-sections at the three incident neutron energies are presented. The deduced kerma values are compared with previous measurements and theoretical predictions.

1. Introduction

An important number of therapy facilities use neutron beams up to 70 MeV energy, therefore it is essential to focus attention on kerma (kinetic energy released in matter per mass unit) and kerma factors (kerma per unit fluence) measurements (White *et al* 1992). The neutron dose measured in a 'tissue-equivalent' ionization chamber has to be related to the dose delivered to human tissue. However, the main composition of human tissue (hydrogen, 10%; carbon, 18%; nitrogen, 3%; oxygen, 65%; others, 4%) differs from that of the tissue substitute, mainly in the carbon and oxygen composition. For example, the corresponding percentages for A-150 plastic are 10.1%, 77.6%, 3.5%, 5.3% and 3.5%. Thus, the kerma values for carbon and oxygen are essential to determine accurately the neutron absorbed dose. Moreover, the predictions of various calculations, based on different models, differ considerably in the case of carbon (Schuhmacher *et al* 1992).

Due to important experimental difficulties, measured cross-section data are scarce at incident neutron energies above 20 MeV (Subramanian *et al* 1983).

We report here partial and total kerma values for carbon, calculated from our measured double-differential cross-sections for the $^{12}C(n, px)$, $^{12}C(n, dx)$, $^{12}C(n, tx)$ and $^{12}C(n, \alpha x)$ reactions, at three incident neutron energies: 42.5, 62.7 and 72.8 MeV. In section 2, the experimental set-up used for the data acquisition is briefly described. Experimental results are presented in section 3. Discussions and comparison with previous measurements and theoretical predictions are covered in section 4.

2. Experimental set-up

Kerma Factors near 14 MeV

Target	Partial Kerma Factors* Protons fGy m**2	Deuterons fGy m**2	Alphas fGy m**2	Sum p+d+a fGy m**2	Recoils Elastic fGy m**2	Non-elastic fGy m**2	Total fGy m**2	Fraction c.p. **
natC	0	0	1.050	1.050	0.540	0.250	1.840	0.571
***	0	0	1.230	1.230	0.540	0.240	2.010	0.612
27Al	0.495	0.024	0.286	0.805	0.073	0.185	1.063	0.757
46Ti	0.545	0.009	0.151	0.705	0.025	0.066	0.796	0.886
48Ti	0.094	0.006	0.044	0.144	0.024	0.060	0.228	0.632
51V	0.060	0.007	0.026	0.093	0.024	0.054	0.171	0.544
natFe	0.200	0.007	0.065	0.272	0.022	0.045	0.339	0.802
54Fe	0.767	0.010	0.127	0.904	0.024	0.048	0.976	0.926
56Fe	0.150	0.007	0.062	0.219	0.022	0.045	0.286	0.766
natNi	0.653	0.013	0.148	0.814	0.018	0.042	0.874	0.931
58Ni	0.850	0.015	0.166	1.031	0.018	0.042	1.091	0.945
60Ni	0.259	0.011	0.109	0.379	0.017	0.039	0.435	0.871
93Nb	0.039	0.007	0.018	0.064	0.004	0.016	0.084	0.762

Conclusions

- Data are available as never before (www)
- Theoretical modeling is essential to obtain a complete data set
- Experiments are continually improving

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Title: MEDIUM NEUTRON AND PROTON NUCLEAR DATA FOR THERAPY

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Los Alamos
NATIONAL LABORATORY

Medium Energy Neutron and Proton Nuclear Data for Therapy

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Abstract

The availability of nuclear data on the interaction of neutrons and protons with biomedical materials is discussed. Evaluated data, experimental data compilations of experimental and theoretical results, and new measurements comprise the microscopic data. Experimental data, while usually available only in partial ranges of interest, are essential for validating and normalizing nuclear models used to produce comprehensive evaluated data libraries. Integral measurements of radiation transport such as depth-dose curves and of KERMA coefficients test the data and the transport calculations.

Keywords: neutrons, protons, nuclear data, cross sections, standards, techniques, detectors, facilities, dosimetry, benchmarks

Introduction

Data on the interaction of neutrons and protons with biomedical materials are needed for a better understanding of the fundamental processes in radiation therapy with these particles. Although one would like comprehensive and accurate experimental data at all relevant energies for all interactions of importance, it is not reasonable (or even intelligent) to ask for such a data set. Instead, computer files of evaluated data are available to the user. These files are based on available experimental data and on nuclear model calculations. Traditionally these files have concentrated on neutron interactions in the energy range of fission and fusion reactors, that is, for neutron energies less than 20 MeV. Recently, the development of accelerator-based transmutation schemes for the destruction of radioactive waste or the production of tritium has fostered the extension of these data bases to 150 MeV and for the interactions of both protons and neutrons with biomedical and other elements. This summary, written as part of the tutorial Workshop on Nuclear Data for Medical Applications, discusses the availability of data (evaluated, compiled and indexed), standard cross sections, and a few examples of how the data are being obtained and benchmarked.

Availability of data

Nearly all data of importance are now available on the World-Wide Web. The user is referred especially to the International Atomic Energy Agency Nuclear Data Section web site at http://iaeand.iaea.or.at/. Here, one can access evaluated data files for neutron data less than 20 MeV including ENDF, BROND, JENDL, JEF, and FENDL. The FENDL data file (Fusion Evaluated Nuclear Data Library) was constructed by an international effort that combined features of the national and regional data files. In principle, it contains the best of these data sets. In addition there is the EXFOR compilation of experimental neutron nuclear data and the CINDA file of references to experimental, theoretical and evaluated neutron nuclear data. Compilations of charged particle data are underway in Japan, the United States, and Europe.

To extend the range of neutron energies to 150 MeV and to include also proton data up to that energy, the Los Alamos Nuclear Data Group has prepared data files for most of the materials of interest. These have been described[1] and are available at the Web site, http://t2.lanl.gov/. In addition at this site, experimental and evaluated data are easily inspected by the Nuclear Data Viewer at http://t2.lanl.gov/data/ndviewer.html.

Other data services at the Nuclear Energy Agency, the Russian Nuclear Data Center at Obninsk, the Japan Nuclear Data Center at JAERI, the Chinese Nuclear Data Center and other regional and national centers may be preferred by individual users.

Standard cross sections

For neutrons, standard cross sections are given in the Standards File, which is described in a joint NEANDC/INDC report.[2] The region above 20 MeV is described more specifically in another report.[3] The primary standard is the neutron-proton differential cross section which is determined by the n-p total cross section and the measured relative angular distribution. Phase-shift analyses[4,5] (http://said.phys.vt.edu/said_branch.html and http://nn-online.sci.kun.nl/NN/help/index.html) put the measured data on a comparable basis. There are uncertainties at the level of a few percent in the angular distribution of n-p scattering at 14 MeV[6] and these uncertainties grow at higher energies. The total n-p cross section seems to be well understood up to about 100 MeV, but at higher energies there are discrepancies of several per cent in this basic quantity.

In practice, measurements in the 20-100 MeV range often use fission chambers for flux normalization. Thus it is crucial to have accurate fission cross sections for the fissionable materials, such as ^{235}U and ^{238}U. Although the accuracy of these cross sections is improving,[7] more work needs to be done to improve their accuracy relative to the n-p cross section.

For protons, to the knowledge of this author, there is not a standard set of reference cross sections in the energy range up to 100 MeV. Measurements of beam current, target thickness, detector solid angle and efficiency serve to normalize the data to accurate cross sections. As the energy increases, the efficiency of detectors needs to be treated carefully because of the probability of reactions in the detector and the possibility of losing events due to these reactions. For precision measurements (sub 1%) even at 14 MeV, this is a consideration.

Experimental techniques

A complete discussion of experimental techniques to obtain nuclear data in the 20-100 MeV range is well beyond the scope of this paper. Three examples will be selected to illustrate (1) a case where the data can be measured in their entirety; (2) the use of monoenergetic neutrons to determine the cross section for producing charged particles by neutrons; and (3) the use of a "white" neutron spectrum from a spallation neutron source to obtain similar information.

Although most measurements are limited to specific neutron energies or specific angles or outgoing energies, neutron total cross sections can in fact be obtained over the entire 20-100 MeV energy range (and in fact to much lower and much higher energies) with a "white" neutron source, that is, one which produces a continuum of neutron energies throughout this range. An efficient way of making such a spectrum is by directing a pulsed proton beam onto a heavy metal target. Time-of-flight techniques differentiate the specific neutron energies. At the Los Alamos Neutron Science Center, the beam is 800 MeV protons and the target is tungsten. Biomedical and other elements were studied previously[8] at this facility and more recent studies have extended the measurements to hydrogen isotopes and other materials.[9,10] The earlier measurement results are shown in Ref. 11. Of importance is that the absolute accuracy of these measurements is less than 1% in this energy range for samples that are uniform and well characterized. The data then serve as tight constraints on nuclear model calculations for the sum of the elastic and all the partial reaction cross sections.

A second example is the study of charged particles produced by neutrons on biomedical elements carried out with a monoenergetic neutron source produced by the ^{7}Li(p,n) reaction.[12,13] Neutron energies of 42.5, 62.7 and 72.8 MeV were studied and charged particles (protons, deuterons, alpha particles) from reactions on carbon were detected at 14 or more angles from 20 to 160 degrees. These data are of good statistical accuracy so that double differential cross sections (in angle and in emitted particle energy) could be measured over the range. The data obtained are essential in normalizing nuclear model calculations, which might have difficulties for these rather light nuclides. From these microscopic data, KERMA factors were deduced.[14]

A third example is the use again of a "white" neutron source to measure charged-particle production. The production cross section for alpha particles from silicon was studied up to 50 MeV.[15] These measurements take much longer than those with the monoenergetic source (example 2 above), but they provide data over the full energy range. These data, like all other experimental results, are essential in tuning the nuclear model calculation, and they have, for example, provided indications that isospin should be included in the calculations for nuclides near zero isospin (T=0). The angle-integrated emission spectra and the excitation function for the production of alpha particles from natural silicon are shown in Figures 1 and 2.

Integral quantities and benchmarks

Intergral quantities such as KERMA coefficients and LET distributions are generally not compiled in the data. Rather reports from the International Commission on Radiation Units and other committees summarize the field. These quantities are measured at monoenergetic and "white" neutron sources by low-pressure proportional counters and other techniques. Where time-of-flight techniques are used, the timing properties of the detectors are important and further improvements are a challenging area of research.

Depth-dose curves can be investigated by measurements in water phantoms. An example is a recent experiment at LANSCE shown in Figure 3.[16] Although the dosimeter did not have good timing characteristics and was in fact used in an integral mode, other detectors could be used to give the dose versus depth for each neutron energy. In this particular experiment, the integral test was over the LANSCE fast neutron spectra as modified by a series of polyethylene absorbers and the results are being compared with calculations.

Conclusions

A marked improvement in medium energy nuclear data has occurred in the past few years driven by accelerator-based transmutation programs and by the development of new experimental techniques (and, treated elsewhere in this Workshop, theoretical developments in pre-equilibrium reaction models). Many sources of nuclear data are available to users on the Web. Nuclear data standards are improving. And neutron sources, both monoenergetic and "white" are being further improved and utilized for measurements. Further developments and greater accuracy are expected in the future. For applications to medical therapy, the relative importance of these developments needs to be judged according to the future success and needs of the radiation therapists and the cell biologists.

Acknowledgment:

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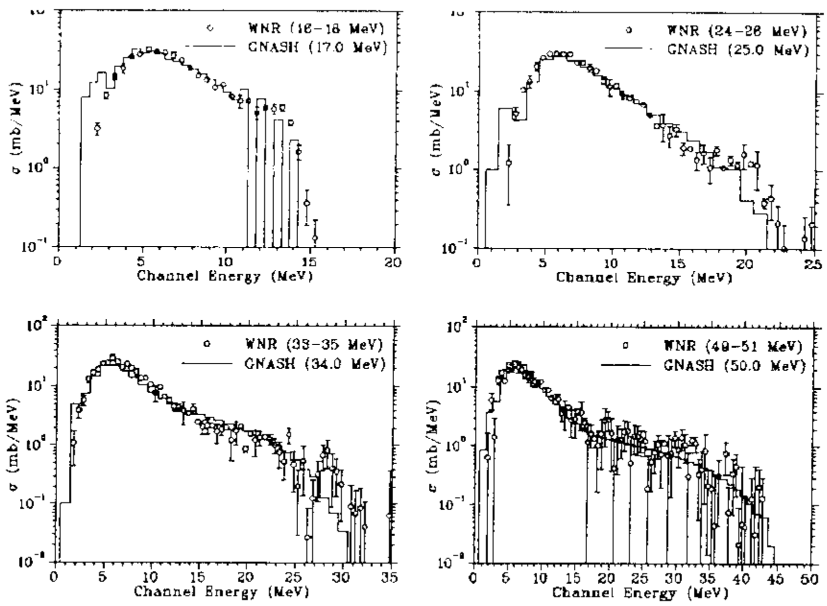
Figure Captions:

Figure 1 - Angle-integrated alpha-particle spectra from neutron bombardment of silicon.

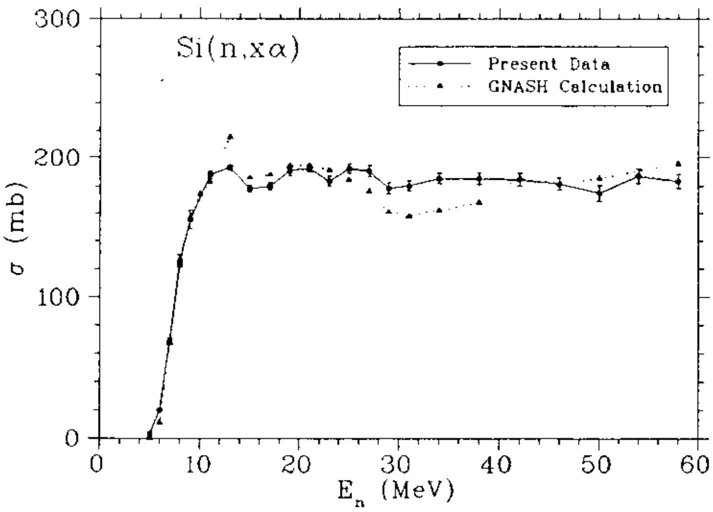
Figure 2 - Excitation function of alpha-particle production from neutron bombardment of silicon.

Figure 3 - Setup for dosimetry measurements with a spallation neutron source. The beam travels from left to right. At the left, the beam passes through a fission chamber for flux normalization; then it passes into a water phantom in which a dosimeter is placed.



WNR (16-18 MeV)
GNASH (17.0 MeV)
WNR (24-26 MeV)
GNASH (25.0 MeV)
WNR (33-35 MeV)
GNASH (34.0 MeV)
WNR (49-51 MeV)
GNASH (50.0 MeV)
σ (mb/MeV)
Channel Energy (MeV)

Figure 1



Si(n,xα)
Present Data
GNASH Calculation
σ (mb)
E_n (MeV)
300
200
100
0
0
10
20
30
40
50
60

Figure 2

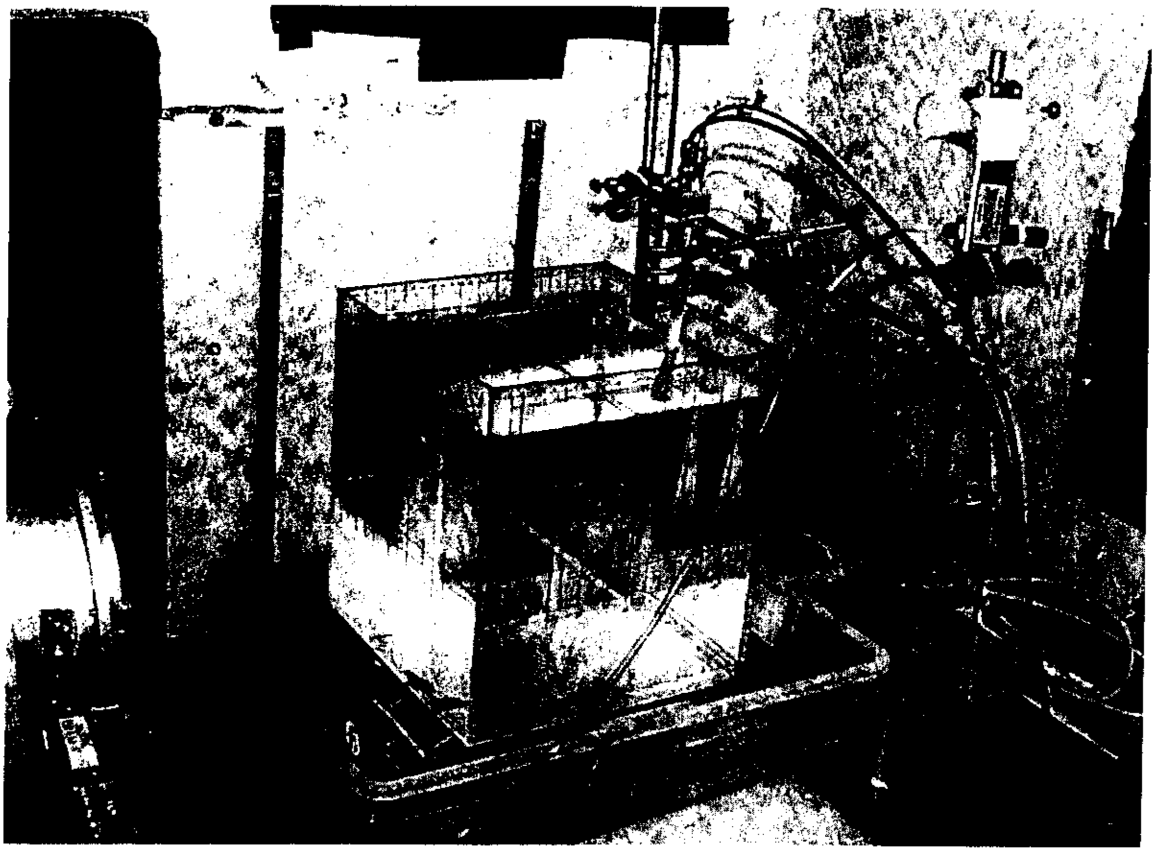


Figure 3