International Atomic Energy Agency

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PART I

REPORT OF THE PANEL ON NUCLEAR STANDARDS NEEDED FOR NEUTRON CROSS SECTION MEASUREMENTS

Brussels, 8-12 May 1967

I. INTRODUCTION

The International Nuclear Data Committee (INDC), in September of 1965, recommended to the International Atomic Energy Agency that a panel be convened to examine the nuclear standards* needed for neutron cross section measurements. The accuracy requirements for cross sections of structural and fuel materials needed for the design of nuclear reactors and for precision neutron dosimetry have fostered an interest in the selection and investigation of standard cross sections and in the neutron flux measuring techniques. A Panel met in Brussels during the second week of May 1967 to review the problems and progress associated with these standards activities, and to make specific recommendations concerning these matters to the IAEA. This Panel consisted of 23 scientists representing 11 countries, European Atomic Energy Community (EURATOM), the IAEA, and Bureau International des Poids & Mesures (BIPM). Below follows the report of the Panel.

The field of neutron cross section standards is not one in which rapid progress can be expected. Very rarely is there a "breakthrough" to initiate a spectacular advance; on the contrary it is necessary to depend upon persistent application of effort to effect gradual improvements in accuracies or the clearing up of aggravating discrepancies. Despite this, however, the progress of recent years has been very encouraging. There are no doubt many reasons for this, but three are worthy of mention here. First the Symposium on Neutron Flux Standards in the 1-100 keV Region held at Oxford, United Kingdom, 1963, suggested and strongly supported by the European American Nuclear Data Committee (EANDC), certainly stimulated much activity in the field. Second, the EANDC itself has kept a watchful eye on the subsequent activity and has made sure that the interest has been sustained. Third, the recognized Standards laboratories in several countries have become more aware of the problems and are rapidly becoming major contributors to the field. The Panel of which the present report is the product was suggested by the INDC because it recognized the need to stimulate in every possible way, continued effort toward progress in this important area.

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*The term "nuclear standard" should be understood to mean reactions basic to absolute flux determination and reactions suitable as secondary standards.

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We now turn to some general comments on the technical advances. First it must be stressed that, as far as fast flux measurements are concerned, it appears that as a general rule we are still bedevilled by the same problem as we were several years ago, i.e. that where cross sections are well known, e.g. the H(n,n), the techniques are lagging and yet, where the techniques are reasonably good, the cross section standards are lagging, e.g. the fission reactions. However, there has recently been considerable renewed activity in methods of flux determination which are absolute in themselves and do not depend, at least to first order, on cross section data. With these techniques, absolute and accurate cross section data are being obtained at a few spot energies. The methods that have received this recent special attention are (a) the associated activity method which has been applied with considerable success to the $^{7}Li(p,n)^{7}Be$ reaction and (b) the use of photoneutron sources which have been accurately calibrated using traditional techniques. As far as one can tell from data obtained by the methods, they appear to be yielding consistent results and, happily, they are all capable of further development. Presently these methods give accuracies of between 1 and 2% on flux and it might be possible to improve the accuracies to around 0.5%. One other point regarding flux measurements. Because of the realization that systematic errors are probably more dominant than random ones, individual experimenters are increasingly using several methods of flux measurement in one experiment and this is adding much more confidence to the data obtained. The problem of compounding errors is still a very real one and because of the different methods in use we can be misled on some "so-called" discrepancies.

As far as improving the precision of cross section data is concerned, very considerable progress has been made in capture and fission reactions. Whereas a few years ago the Au(n,γ) cross section values varied over a factor of 2 in the keV range, we can now be reasonably sure of the data to a few percent. Similar remarks apply to the U-235 and Pu-239 fission cross sections in the region below 1 MeV. The most striking progress has been in the important region below 100 keV where our overall accuracy might now be as good as 3%.

Drafts of the technical summaries of the status of the field and of recommendations to the IAEA which are presented in this report were prepared by three independent working groups which were selected at the start of the panel meeting; these drafts were finally discussed by the full panel and were accepted after slight modifications.

Summaries of all of the technical recommendations have been extracted; these are given in Appendix A. Each technical recommendation has been classified as either Priority I or II to indicate the Panel's assessment of the most urgent requirements from the point of view of standards.

II. NEUTRON FLUX DETERMINATION

1. Neutron Flux Measurement

The problems of neutron flux measurement and standard neutron cross sections are closely related. Often one is needed to measure the other. Nevertheless, each can be measured sometimes independently of the other. For example, a total neutron cross section can be measured by transmission without knowledge of the neutron flux. And a flux can be determined by associated particle counting without knowledge of a cross section.

We now consider the first problem, that of neutron flux measurement. At thermal neutron energies we usually determine flux by measuring the reaction rate of a thin sample of a detector material whose cross section is 1/v in the energy region of the Maxwellian distribution. The quantity actually measured is the neutron density, n, in neutrons/cm^3. Since the thermal neutron cross section for ^{3}He(n,p) is known to about 0.2%, that for ^{10}B(n, α) to 0.2%, and that for ^{197}Au(n, γ) to 0.3%, the accuracy of flux determination in the thermal neutron range can be very good, depending upon the ability to perform the absolute counting and to correct for epithermal neutrons in the case of ^{197}Au which has a resonance in the epithermal region.

Above thermal neutron energies and below about 100 keV, flux measurements based on standard neutron cross sections rely chiefly on the ^{10}B(n, α) cross section which is probably 1/v to at least 100 keV, or on ^{3}He(n,p) up to 11 eV where it has been carefully measured. The uncertainty in the ^{10}B(n, α) cross section is about 5%, and there is a small additional uncertainty in this energy region due to the branching ratio (n,α_0)/(n,$\alpha\gamma$) if gamma rays are being detected. With monoenergetic neutrons, a BF$_3$ counter with a well-defined sensitive volume may be used, whereas with white spectrum neutrons which require precise time measurement for energy identification, a "boron plug" - a thin sample of ^{10}B observed by several sodium iodide γ-ray detectors - is superior. In this energy region it is sometimes advantageous to use the $^{6}Li(n,\alpha)$ cross section for flux measurement because of its high Q-value.

Above 100 keV, the hydrogen elastic scattering cross section, H(n,n), has usually served as the standard. Although the total cross section is known to about 1.0%, technical problems limit flux accuracies to the order of 2-2.5% below 2.5 MeV and 2-5% up to 15 MeV. Uncertainties in the anisotropy in the H(n,n) cross section enter above 10 MeV, and would enter at lower energies if the technical problems associated particularly with proton-recoil counter telescopes were better in hand. Absolute flux detectors using the H(n,n) reaction are highly sophisticated and require complicated electronics or detailed analysis of response to use.

The alternative approach to neutron flux measurement is the use of methods which are independent of, or nearly independent of, cross sections. These methods are in principle very direct and capable of high accuracy. The first of these, the associated particle method, is usually used with positive ion accelerators. The charged particle produced at the same time as the neutron in reactions such as $T(d,n)^{4}He$, $D(d,n)^{3}He$, and $T(p,n)^{3}He$ is identified and counted in a defined solid angle, thus determining the neutron flux in a defined solid angle according to the reaction kinematics. With the $T(d,n)^{4}He$ reaction, which produces neutrons of energies near 14 MeV, uncertainties as low as 1-2% have been reported. The $D(d,n)^{3}He$ reaction produces neutrons in the few MeV range and the flux has been measured by associated particle counting to typically 2-5%. It is often advantageous to use coincidence techniques between the associated particle and the neutron detector to define the desired events. The $T(p,n)^{3}He$ reaction is suitable for associated particle counting in the interesting energy range from about 100 keV to an energy which overlaps the $D(d,n)^{3}He$ energies. The need for higher flux accuracies and more precise flux standards between 100 keV and 5 MeV makes further development of the associated particle method in the particular case of $T(p,n)^{3}He$ seem desirable despite its difficulty.

The associated activity method of flux determination is a type of associated particle method in which the activity of the residual nucleus produced with the emission of a neutron is counted instead of the recoiling nucleus itself. Reactions such as $^{51}V(p,n)^{51}Cr$, $^{65}Cu(p,n)^{65}Zn$ become sources of known numbers of neutrons in this way as well as the reaction $^{7}Li(p,n)^{7}Be$ which is of special interest for 30 keV neutrons (the average energy at threshold). The accuracy obtainable with associated activity counting is typically 2%.

Another method of flux determination which does not depend extensively upon cross sections is the use of a flat response (vs. energy) detector. These, in general, rely on moderating the initial neutron energy down to thermal; examples are the "long counter", the boron pile, the graphite sphere detector, the oil bath and the manganese sulfate bath. The long counter is usually not considered as suitable for precise work as the other moderation methods (usually used with a collimator) because the latter are more flat in their response. Accuracies of 0.5% have been obtained with these latter methods - but the detectors tend to be large and inconvenient.

A final method for precise neutron flux determination, or more precisely, a convenient source of neutrons of known energy and flux is the photoneutron source; this employs a radioactive supply of γ-rays of suitable known energy and is precisely calibrated by means of a manganese sulfate bath. A precision of 0.5% in source strength can be attained but the energy of the neutrons is not well known at present.

2. Technical Recommendations

Neutron flux measurements based on the H(n,n) reaction are attractive because the cross section can be obtained accurately from total cross section measurements. At the present time the experimental methods used are capable of determining the flux to accuracies of about 2½% below 10 MeV and these errors are not limited by uncertainties in the cross section measurements. It is probably quite difficult to do better than the present accuracies. Above 10 MeV the uncertainties in the angular distribution of the reaction in the center-of-mass system predominate. It is therefore recommended that improved techniques should be developed so that the H(n,n) cross section can be used to obtain the neutron flux to the following accuracy:

Energy range 100 keV - 2 MeV ± 0.5-1.0% (Priority I)
" " 2 MeV - 5 MeV ± 1.0% (Priority II)
" " 5 MeV - 15 MeV ± 2.0% (Priority II)

Knowledge of the differential cross section for hydrogen should be improved in step with the improved techniques and the ratio $\sigma nn(180^{\circ})/(\sigma nn/4\pi)$ should be obtained at all energies > 5 MeV to ± 1%. (Priority II)

Most nuclear physicists, who measure cross sections, would save time and effort if they could rely on a series of "simple" devices whose response as a function of energy is smooth and is accurately predicted. Some detectors which may be suitable for monoenergetic sources of neutrons such as Van de Graaff machines are: (1) the ^{239}Pu fission detector, (2) a flat response detector to replace the long counter, and (3) a neutron reaction detector (e.g. semiconductor). For white spectrum sources (e.g. linac), below 100-200 keV one may use a "Boron Plug" detector with a thin $(n\sigma_{n\alpha}<0.15)$ ^{10}B sample. From 0.1-1.7 MeV, a similar detector but with a thick boron layer containing some moderator may be used, and above 1 MeV a plastic scintillator may be suitable.

The technique of measuring the ^{7}Be produced in the ^{7}Li(p,n) reaction provides an accurate determination of flux at 30 keV. The accuracy of the method is at present limited by uncertainties of ± 1.5% in the branching ratio of the ^{7}Be decay. It is recommended that the branching ratio of ^{7}Be should be determined to ± 0.5% or better so that flux measurements accurate to better than ± 1% can be made. (Priority I)

The total neutron emission rate from a radioactive photoneutron source can be calibrated more accurately than the neutron flux from an induced nuclear reaction at the target of an accelerator. Therefore, the cross sections measured using calibrated sources are probably the most accurate that can be obtained at present. However, the neutron energy spectra obtained from these sources are not well known. It is recommended that the spectra of radioactive photoneutron sources be investigated by both experiment and calculation. (Priority I)

The accuracy of ± 0.5% for the emission rate of radioactive photoneutron sources includes a contribution of ± 0.2% due to errors in the ratio of the thermal neutron capture cross sections of hydrogen and manganese. New measurements to an accuracy of ± .2% of the ratio (σ_{Mn}/σ_{H}) at thermal neutron energy should be undertaken. (Priority II)

The associated particle technique based on the $T(p,n)^3He$ reaction is limited in accuracy by the Coulomb scattering of the ^3He particles in the target. It is recommended that targets should be developed in which the tritium is absorbed in thin layers of material, for instance about 100 $\mu g/cm^2$ of Ti or preferably 30 $\mu g/cm^2$ of ^6Li. (Priority I) Further development of the associated particle counting technique is encouraged (Priority II) and in particular there is need for improvement in the knowledge of

i) the distribution of tritium and deuterium in targets,

ii) the stopping power in target materials for low energy d, α, ^3He particles,

iii) Coulomb scattering in target materials.

The flux is frequently measured on white spectrum sources such as linear accelerators by detectors in which the multiple scattering corrections are not negligible. It is recommended that the multiple scattering corrections for B plug detectors and ^6Li and ^{10}B loaded glass scintillators should be more carefully investigated by Monte Carlo techniques or other methods. (Priority II)

III. STATUS OF NEUTRON STANDARD CROSS SECTIONS AND TECHNICAL RECOMMENDATIONS

In many neutron physics experiments which involve a knowledge of neutron flux density it is convenient to express the flux density in terms of a known neutron reaction cross section. Some such cross sections which have the appropriate properties have come to be regarded as standard cross sections. The following paragraphs review the present status of these standard cross sections and provide recommendations where improved accuracy in absolute values of cross sections and their variation with energy is required. For fuller details the reader is referred to the reviews reproduced in Part II of this report (to be published). The list of papers presented to the panel meeting is given in Appendix B.

1. $^3He(n,p)$, $^6Li(n,\alpha)$, $^{10}B(n,\alpha)$

The $^3He(n,p)$, $^6Li(n,\alpha)$, $^{10}B(n,\alpha)$ reactions are charged particle producing reactions with cross sections which appear to follow the 1/v law closely in the low energy region.

a. ^{3}He(n,p)

In this reaction the total cross section can be described by the equation $\sigma_t = \alpha \lambda + \beta$ up to 11 eV,

where $\alpha = 2963.1 \pm 0.6$b/Å and $\beta = -0.8 \pm 5.1$b

So the total cross section σ_t is equal to the absorption cross section (known to obey a 1/v-law) within the measured accuracy. Recent results indicate a relation $\frac{\sigma_a}{\lambda} = 2962.6 \pm 5.1$b/Å and a 2200 m/s cross section for ^{3}He $\sigma_a^o = 5327^{+10}_{-9}$ barn.

The accuracy is of the order of 0.2% and no important improvements are possible without large efforts that do not seem to be justified at the present time.

For energies between 11 eV and 4 keV no measurements exist. For neutron energies above 4 keV errors of at least 10% are evident. In the range above 1 keV the cross section does not follow the 1/v law.

It would be desirable to verify the ^{3}He(n,p) cross section inferred from ^{3}H(p,n) by careful direct measurements at a few discrete energies. (Priority II)

A counter has been developed at the Danish AEC's Research Establishment Risø for measurements at energies in the range from 10 keV to 1 MeV and this will become available on loan.

b. ^{10}B(n,α) and ^{6}Li(n,α)

The region of primary concern for the boron cross section is below 100 keV. At thermal neutron energies, both the ^{10}B(n,α) cross section and the cross section ratio (n,α_0)/(n,$\alpha\gamma$) are very precisely known to an accuracy of 0.1 to 0.2 percent. Recent accurate measurements of the branching ratio at thermal neutron energy are in good agreement.

Up to 100 keV the ^{10}B(n,α) cross section is known to ± 5 percent, but the uncertainties in the (n,α_0)/(n,$\alpha\gamma$) ratio are of the order of 10 percent. The best fit to existing σ(n,α) cross section in the 1/v region, which seems well established up to 70 keV is

$$\sigma(n,\alpha) = \left(\frac{610}{\sqrt{E_n}}\right) \text{barns, where } E_n \text{ is in eV.}$$

A recent measurement of the total cross section gave for $E_n < 10$ keV

$$\sigma_t = \left\{(610.3 \pm 3.1)/\sqrt{E_n} + 1.95 \pm 0.10\right\} \text{ barns}$$

More work is needed for a better understanding of the constant term.

In the energy region up to 100 keV more measurements of the absorption and elastic cross sections and the angular distributions are needed to bring the $^{10}B(n, \alpha)$ cross section to an accuracy of 1%. (Priority I)

Above 100 keV, the $^{10}B(n, \alpha)$ cross section is subject to serious discrepancies. However, here this reaction is somewhat less important as a standard because of the availability of hydrogen elastic scattering. On the other hand, the $^{10}B(n, \alpha\gamma)$ continues to be useful with the time-of-flight instruments which find it convenient to detect the γ-ray.

From 100 keV to 1 MeV the cross section uncertainty is of the order of 10 percent, and uncertainty in the $n\alpha_0/n\alpha\gamma$ cross section ratio is about 20 percent. More measurements are required of the cross section, the branching ratio, and the angular distribution to achieve 5 percent accuracy in flux measurement by γ-ray detection. (Priority II)

Measurements of the inverse reaction $^{7}Li(\alpha,n)$ are recommended as a possible check of the $^{10}B(n,\alpha)$ cross section. (Priority II)

The $^{6}Li(n, \alpha)$ cross section in the energy region below 1 keV follows the 1/v law. The thermal value is only known to an accuracy of ± 3% due to the poor knowledge of the isotopic composition of natural Li. In order to improve this accuracy the following recommendations can be made:

1) measurements of the ratio $^{6}Li\ \sigma(n,\alpha)/^{10}B\ \sigma(n,\alpha)$ in the thermal and epithermal region; (Priority I)

2) accurate transmission measurements on lithium samples of different enrichments should be performed in the same energy region and also further work on the isotopic and chemical composition of samples is required. (Priority I)

The uncertainty in $^{6}Li(n,\alpha)$ cross section in the energy region 1-100 keV varies between ± 4% at 1 keV to ± 6% at 100 keV. However, there are still some discrepancies in the cross section at about 10 keV.

Between 100 and 600 keV the cross section is mainly due to the p-wave resonance at ~ 250 keV. The discrepancies between existing measurements are large. The accuracy is probably ± 10% and ± 20% respectively below and above 340 keV.

The following recommendations and conclusions can be made.

1) Below 100 keV 1% accuracy is required in the measurements of the ^{6}Li(n,α) cross section. Possibly this can best be done by measuring the total and scattering cross sections. (Priority I)

2) Measurements of ratio ^{6}Li σ(n,α)/^{10}B σ(n,α) should be extended to higher energies. (Priority I)

3) Further measurements of ^{6}Li(n,α) cross section to 5% accuracy should be made using either the ^{235}U fission cross section or H(n,n) as a standard particularly in the energy region above 100 keV. (Priority I)

2. ^{1}H(n,n)

This reaction is basic to the recoil proton detector which is commonly used experimentally in one of the following forms:

a) hydrogen or methane filled proportional counter
b) polyethylene radiator semiconductor counter
c) telescope counter
d) plastic or liquid scintillation counter

^{1}H(n,n) whose total cross section is known to about 1% can be used at present as a standard cross section for neutron flux determination only above ~ 50 keV.

The accuracy of neutron flux determination above 10 MeV with a proton recoil telescope counter is limited by insufficiently known differential cross sections. Therefore some new relative differential measurements between 5 and 20 MeV with ± 1% relative error are required. (Priority II)

In addition it would be useful to perform new phase shift analysis calculations which are consistent with the newer total cross section data which have a claimed accuracy of ± 0.2% between 100 keV and 5 MeV. (Priority II)

3. C(n,n)

This reaction could be a useful standard for scattering measurements particularly for energies below about 1.5 MeV due to the absence of competing reactions apart from the small $^{12}C(n,\gamma)$ cross section.

Within 5 percent accuracy no anisotropy has been observed below 1 MeV. Above this energy slight anisotropy is possible and the evidence appears definite at 1.45 MeV. Present data on C(n,n) are not good enough for use as a standard and further work perhaps along the lines suggested in the paper "The C(n,n) Reaction as a Cross-Section Standard", presented to the Panel by R. Batchelor, is recommended. (Priority II)

4. Pb(n,n)

Lead is required as a standard as an alternative to carbon because the lower neutron energy loss on collision is of advantage when using detectors with energy dependent efficiency such as Li glass.

The value of the (n,n) cross section for natural lead is known to about 0.5% accuracy in the energy range below 1 keV.

Natural lead can be used as a standard below 1.68 keV, the limit being set by the first excited state of ^{204}Pb.

With samples of separated ^{208}Pb, the range can be extended to 78 keV. Cross section data up to 2 keV are at present considered satisfactory.

5. $^{197}Au(n,\gamma)$

The $^{197}Au(n,\gamma)$ reaction is still considered to be the best capture reaction for use as a standard. The capture cross section is accurately known (0.3%) at thermal energy, and to about 5% from 150 keV up to at least 1 MeV. Recently, substantial improvements in the accuracy of the measurements in the energy range 20-200 keV have been obtained. Absolute determinations of the cross section at about 25 keV and 30 keV indicate that the apparent discrepancy between activation measurements and direct (n,γ) measurements appears to have been resolved.

Accurate relative measurements of the energy dependence from 20 keV to 200 keV have been carried out, which fit well with the existing higher energy data. However, there is considerable uncertainty in the cross section in the energy range below about 20 keV.

It is recommended that the earlier activation measurements be disregarded in future evaluations, and that further measurements be performed to resolve completely the question of discrepancies; (Priority I) evidence for structure in the gold (n,γ) cross section makes it worthwhile to re-examine this reaction in the energy region from 1 to 100 keV. (Priority II)

6. $^{235}U(n,f)$ and $^{239}Pu(n,f)$

The $^{235}U(n,f)$ and $^{239}Pu(n,f)$ fission cross sections, if determined with sufficient accuracy, could become the primary standards above about 10 keV, where resonance fluctuations no longer appear. The principal reason for selecting these reactions as standards is the ease with which the fission fragments can be detected. At present, the ^{235}U cross section is the better known, but that of ^{239}Pu may be less energy dependent.

In the case of ^{235}U, the cross section is known to 5% between 100 keV and 1 MeV. The precision is not as good from 10 keV to 100 keV and above 1 MeV because the data agree less well. Further measurements are required over the whole energy range to obtain 1% accuracy. (Priority I)

With regard to ^{239}Pu, there are a few very recent values for the $^{235}U/^{239}Pu$ fission cross section ratio at isolated energy points.

It is recommended that a few accurate spot points of the $^{239}Pu(n,f)$ cross section be made together with accurate measurements of the shape of the cross section over the whole energy range. (Priority I)

To achieve 1% accuracy in fission cross section measurement it is essential to make improvements in the preparation and assay of fission foils and in fission fragment counting. (Priority I)

Some improvement in these areas has been achieved during the last years.

7. Threshold reactions

Threshold reaction cross sections are important as standards for the estimation of slowing down spectra and in-pile dosimetry.

a. $^{27}Al(n,\alpha)^{24}Na$

The $^{27}Al(n,\alpha)^{24}Na$ cross section has been measured several times in the 5 MeV - 20 MeV energy region by reference to the cross sections

H(n,n), ^{235}U(n,f), ^{6}Li(n,α) and ^{32}S(n,p). Below 8 MeV the accuracy is about 5%. Between 8 MeV and 13 MeV it is about 7%. The decay scheme and half life of the resulting ^{24}Na are well known.

Since only one set of measurements has been made in the 8-13 MeV energy region, further work is desirable. (Priority II)

b. S(n,p)

The cross section for the ^{32}S(n,p) reaction has been measured by several groups, but discrepancies of up to 50 percent occur over the whole energy range of interest.

New measurements are desirable from threshold to 15 MeV with a 5% accuracy. (Priority II)

Since ^{32}P is a pure β-emitter absolute counting is difficult and an alternative reaction should be sought (Priority II), for example ^{115}In(n,n'), ^{58}Ni(n,p)^{58}Co, or a fission threshold reaction such as ^{232}Th(n,f), ^{238}U(n,f) or ^{237}Np(n,f).

8. General Technical Conclusions

a) Important standard cross section measurements should be repeated at more than one laboratory since in general the discrepancies exceed the quoted errors.

b) Over the whole range from thermal energy up to 100 keV the ^{10}B(n,α) cross section is the best known cross section and there is no significant evidence that it deviates from the 1/v law below that energy.

c) The relatively high Q-value of the ^{6}Li(n,α) reaction makes it attractive; it will become more attractive when more accurate information is available on the isotopic and chemical composition of the foils and on the reaction cross section both at thermal and fast neutron energies.

d) The H(n,n) cross section is at present the best known standard above 100 keV energy.

e) Above 10 keV the ^{235}U(n,f) or perhaps ^{239}Pu(n,f) may become a suitable standard cross section.

f) At the present time, the accuracy of the 2200 m/sec value of the $^{10}B(n,\alpha_0)/^{10}B(n,\alpha\gamma)$ ratio and the thermal cross sections of the $^{10}B(n,\alpha)$, $^{3}He(n,p)$ and $^{197}Au(n,\gamma)$ seem to have the required accuracy.

g) The fact that discrepancies frequently exceed the quoted errors indicates that the latter are too small. This may be due to a large extent to the improper treatment of random and systematic errors.

Some thought should be given to the establishment of a uniform treatment of errors on an international basis.

IV. STATUS OF OTHER STANDARD NUCLEAR DATA

1. $\bar{\nu}$ ^{252}Cf

Absolute values of $\bar{\nu}$, the average number of neutrons emitted per fission have been requested at high accuracy by reactor designers for ^{233}U, ^{235}U and ^{239}Pu.

$\bar{\nu}$ for the spontaneous fission of ^{252}Cf is an ideal standard in this field, because the short half life permits the preparation of virtually mass-less samples, and because the alpha/fission ratio is low.

Three methods are reported for the measurement of $\bar{\nu}$ with accuracy better than 1 percent, namely those of delayed coincidence counting, of independent measurements of the fission yield and the neutron yield, and of calculation in terms of α and η for ^{235}U together with a knowledge of the $^{235}U/^{252}Cf$ $\bar{\nu}$ ratio.

The present status of these measurements is that there is an apparent discrepancy of the order of 2 percent between measurements quoted with 0.5 percent accuracy.* A suggested best value of 3.766 ± 0.011 is reported. Some new measurements are planned by several laboratories in order to meet the 0.25 percent accuracy asked for in the request lists. To this end further measurements are desirable on ^{252}Cf fission neutron spectrum and delayed neutron and γ contributions. (Priority I)

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*See Condé paper

V. STANDARD MATERIAL AND FOILS FOR NEUTRON MEASUREMENTS

1. Fission Foils

Samples are prepared and assayed by several specialized laboratories and improved accuracy is now being obtained. At the Bureau Central de Mesures Nucléaires (BCMN) of EURATOM, intercomparison of fission foils by alpha and fission counting have given agreement to 0.2%. Further measurements and developments are planned e.g., half life measurements on uranium isotopes are to be measured to ± 0.1%. The overall accuracies of ~ ± 0.2% for the definition of boron, uranium and plutonium layers are feasible.

2. Standard Materials Stocks

A boron stock of 100 kg natural boric acid (^{10}B = 19.824 ± 0.020 atom %) is available at BCMN for distribution. A second stock of 200 kg natural boric acid with the same nominal isotopic composition is available at the National Bureau of Standards, Washington. A stock of natural lithium is now being defined at BCMN.

3. Recommendations

The panel meeting encourages standards laboratories to maintain stocks, prepare and distribute accurately defined samples of standard neutron cross section materials (from a single source for all laboratories where appropriate). (Priority II)

VI. GENERAL RECOMMENDATIONS TO THE I.A.E.A.

1. A number of laboratories and especially the centers for nuclear standards have special materials and services which they can make available for standards activities. The IAEA should effectively publicize this fact and its related information and if called on, assist with necessary arrangements for obtaining these.

2. In certain circumstances, it may prove desirable to exchange personnel or equipment or provide some appropriate common facility to resolve a persistent discrepancy. The IAEA should consider in such circumstances, if desired, to locate and contract for use of the required facility and make necessary arrangements for the equipment and/or personnel exchange.

3. The IAEA should consider organizing a future panel similar to the present one, in about four years' time.

4. The IAEA should conduct a complete survey of neutron cross section standards activities.

5. In view of the apparent shortage of evaluated data for standards purposes, it is recommended that the IAEA continues or extends support for such activity. This topic, however, was not examined in detail by the Panel.

6. The IAEA should, perhaps through the INDC, seek to monitor the progress in implementing the technical recommendations set forth in this report.

7. The IAEA should seek, perhaps through the INDC to encourage duplication of important measurements.

APPENDIX A

SUMMARY OF TECHNICAL RECOMMENDATIONS

1. Neutron Flux Determination

a) Improved techniques should be developed so that the H(n,n) cross section can be used to obtain the neutron flux to the following accuracy

Energy range	100 keV - 2 MeV	± 0.5-1.0%	Priority I
" "	2 MeV - 5 MeV	± 1.0%	Priority II
" "	5 MeV - 15 MeV	± 2.0%	Priority II

- See Page 5

b) Knowledge of the differential cross section for hydrogen should be improved in step with the improved techniques and the ratio $\sigma nn(180^\circ)/(\sigma nn/4\pi)$ should be obtained at all energies > 5 MeV to ± 1%. Priority II

- See Page 6

c) The branching ratio of ^{7}Be should be determined to ± 0.5% or better so that flux measurements accurate to better than ± 1% can be made. Priority I

- See Page 6

d) The spectra of radioactive photoneutron sources should be investigated by both experiment and calculation. Priority I

- See Page 6

e) New measurements to an accuracy of ± .2% of the ratio (σ_{Mn}/σ_H) at thermal neutron energy should be undertaken. Priority II

- See Page 6

f) In order to reduce effect of Coulomb scattering, targets should be developed in which the tritium is absorbed in thin layers of material, for instance about 100 $\mu g/cm^2$ of Ti or preferably 30 $\mu g/cm^2$ of ^6Li. Priority I

- See Page 7

g) Further development of the associated particle counting technique is encouraged and in particular there is need for improvement in the knowledge of Priority II

   i) the distribution of tritium and deuterium in targets
   ii) the stopping power in target materials for low energy d, α, ^3He particles
   iii) Coulomb scattering in target materials

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h) It is recommended that the multiple scattering corrections for B plug detectors and ^6Li and ^{10}B loaded glass scintillators should be more carefully investigated by Monte Carlo techniques or other methods. Priority II

- See Page 7

2. <u>Standard Material and Foils for Neutron Measurement</u>

a) The panel meeting encourages standards laboratories to maintain stocks, prepare and distribute accurately defined samples of standard neutron cross section materials (from a single source for all laboratories where appropriate). Priority II

- See Page 15

b) To achieve 1% accuracy in fission cross section measurements it is essential to make improvements in the preparation and assay of fission foils. Priority I

- See Page 12

3. Neutron Standard Cross Sections

$^{3}He(n,p)$

a) To verify the $^{3}He(n,p)$ cross section inferred from $^{3}H(p,n)$ by direct measurements at a few discrete energies. Priority II

- See Page 8

$^{10}B(n,\alpha)$ and $^{6}Li(n,\alpha)$

a) Up to 100 keV more measurements of the absorption and elastic cross sections and the angular distributions are needed to bring the $^{10}B(n,\alpha)$ cross section to an accuracy of 1%. Priority I

- See Page 9

b) Measurements of the cross section $^{10}B(n,\alpha)$, the branching ratio $(n,\alpha_0)/(n,\alpha\gamma)$, and the angular distribution in the energy region from 100 keV to 1 MeV are required to achieve 5 percent accuracy in flux measurement by γ ray detection. Priority II

- See Page 9

c) Measurements of the inverse reaction $^{7}Li(\alpha,n)$ are recommended as a possible check of the $^{10}B(n,\alpha)$ cross section. Priority II

- See Page 9

d) Between thermal and 100 keV, a 1% accuracy on the $^{6}Li(n,\alpha)$ cross section is desirable. It is suggested that new measurements of the total and elastic scattering cross sections be made and also measurements of the $^{6}Li(n,\alpha)/^{10}B(n,\alpha)$ ratio. Priority I

- See Pages 9, 10

e) Further measurements of ^{6}Li(n,α) cross section to 5% accuracy should be made using either the ^{235}U fission cross section or H(n,n) as a standard particularly in the energy region above 100 keV. Priority I

- See Page 10

^{1}H(n,n)

a) New relative differential measurements between 5 and 20 MeV with ± 1% relative error are required. Priority II

- See Page 10

b) New phase shift analysis calculations which are consistent with the newer total cross section data with ± 0.2% accuracy between 100 keV and 5 MeV are required. Priority II

- See Page 10

C(n,n)

a) Present data on C(n,n) are not good enough for use as a standard and further work is recommended. Priority II

- See Page 11

^{197}Au(n,γ)

a) The earlier activation measurements should be disregarded in future evaluations, and further measurements are required to resolve discrepancies in the intermediate energy range. Priority I

- See Page 12

b) The present status of the gold (n,γ) cross section indicates that it may be well worthwhile to look for structure in the energy region from 1 to 100 keV. Priority II

- See Page 12

$^{235}U(n,f)$ and $^{239}Pu(n,f)$

Above 10 keV further fission cross section measurements of ^{235}U and ^{239}Pu are required over the whole energy range to obtain 1% accuracy. A few spot measurements are required together with accurate measurements of the shape of the cross section curves. Priority I

- See Page 12

Threshold Reactions

a) $^{27}Al(n,\alpha)^{24}Na$

Since only one set of measurements has been made in the 8-13 MeV energy region, further work is desirable. Priority II

- See Page 13

b) $^{32}S(n,p)$

New measurements are desirable from threshold to 15 MeV with a 5% accuracy. Priority II

- See Page 13

4. $\bar{\nu}\ ^{252}Cf$

Further measurements on ^{252}Cf fission neutron spectrum and delayed neutron and γ contributions are desirable in order to meet the 0.25% accuracy asked for in the request lists. Priority I

- See Page 14

APPENDIX B

PAPERS PRESENTED DURING THE STANDARDS PANEL

AUTHOR	TITLE OF REPORT
1. J. Als-Nielsen	Summary reports based on:
	"Slow Neutron Cross Sections for ^{3}He, B, And Au" (J. Als-Nielsen & O. Dietrich, The Physical Review, Vol. 133, No. 4B, B925-B929, 24 February 1964).
	"Precision Measurement of Thermal Neutron Beam Densities Using a ^{3}He Proportional Counter" (J. Als-Nielsen, A. Bahnsen & W.K. Brown, Nuclear Instruments and Methods 50 (1967) 181-190).
	"Corrections in the Gold Foil Activation Method for Determination of Neutron Beam Density" (J. Als-Nielsen, Nuclear Instruments and Methods 50 (1967) 191-196).
2. E.J. Axton	"The Calibration of Monoenergetic Neutron Sources and their Application to Activation Cross Section Measurement"
3. R. Batchelor	"The Fission Cross-Sections of U^{235} and Pu^{239}"
	"C(n,n) Reaction as a Cross-Section Standard"
	"Neutron Flux Measurements for Monoenergetic Neutrons Based on Standard Cross-Sections"
4. G. Ben-David	"The Use of Threshold Reactions for Fast Neutron Spectroscopy"
5. Randall S. Caswell	"The Status of the ^{3}He(n,p) and the ^{10}B(n,α) Standard Neutron Cross Sections"
6. H. Condé	" $\bar{\nu}$ of ^{252}Cf"
7. John C. Hopkins	"The ^{1}H(n,n) Cross Section as a Nuclear Standard"
8. J.L. Leroy	"Survey of the Different Neutron Flux Measuring Methods by the Associated Particle Technique"
9. V. Naggiar	"Aspects of the Programme of the Bureau International des Poids et Mesures in the Field of Neutron Measurements"

10.	W.P. Pönitz	"Capture and Fission Cross Sections as Standards for Neutron Cross Section Measurements"
		"Integral Methods for Neutron Flux Measurements & the Neutron Slowing Down Spectrometer"
		"The Associated Activity Method for Neutron Flux Measurements"
11.	R. Popić et al.	"Some Uses of Semi-conductor Detectors in Cross Section Work with d-T Neutrons"
12.	M.G. Sowerby	"Some Notes on the ^{6}Li(n,α) Cross-Section from Thermal Energies up to the (n,n'α)d Threshold (1.718 MeV)"
13.	J. Spaepen, Presented by:	
	G.H. Debus	"Boron Stocks"
	A.J. Deruytter	"Fission Foils"
	H. Liskien	"^{27}Al(n,α)^{24}Na- and ^{32}S(n,p)^{32}P-cross-sections as Standards"

APPENDIX C

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