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# RECENT DEVELOPMENTS IN CROSS-SECTION MEASUREMENTS FOR FUSION REACTORS

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Abstract: A brief review of some of the recent experimental work on differential data measurements is given. The neutron, $\gamma$-ray and charged particle emission cross sections, measured using various interdisciplinary techniques, are discussed. Special attention is paid to reactions relevant to gas production, tritium breeding and formation of long-lived activation products. Some of the areas needing further experimental work are outlined.

(differential data, cross section, excitation function, neutron emission, $\gamma$-ray emission, charged particle emission, gas production, tritium breeding, activation, transmutation)

## Introduction

Fast neutron induced reaction cross-section data for potential first wall, blanket, structural and shielding materials of a fusion reactor are needed for design calculations. The energy range of interest extends from thermal to about 16 MeV; hence in addition to scattering and radiative capture phenomena a large number of neutron threshold reactions are also involved. The status and needs of cross-section data have been recently reviewed [cf. 1]. Nuclear model calculations can provide some of the unknown data. However, in several cases experimental studies are not only advantageous but also mandatory. This paper briefly reviews some of the recent experimental work on the determination of differential data relevant to fusion reactor technology (FRT).

## Neutron Emission

Neutron scattering cross sections and secondary neutron emission spectral data are needed for transport calculations as well as for estimating displacement damage and nuclear heating effects. The status of data for all the potential constituents of first wall and blanket materials has been recently summarized [cf. 2,3]. In most of the cases relatively extensive experimental information is available at 14 MeV, and new evaluations of those data have been recommended. For a few elements (H, Li, Be, B, C, Al, Ti, Fe and Cu) data exist also between 6 and 14 MeV. However, for many elements, especially O, F, V, Cr, Mn, Ni, Pb and W, the experimental data base between 6 and 14 MeV is weak.

In recent years work on neutron emission spectra has been performed in several laboratories, especially at Osaka, Beijing, Islamabad, Livermore ($E_n$ = 14 MeV), Tokai Mura, Sendai ($E_n$ = 18 MeV), Obninsk, Dresden, Braunschweig, Geel, Bruyères-le-Châtel, Argonne, Ohio, Durham, Los Alamos (broad energy range). Detailed studies on double differential neutron emission cross sections of potential first wall materials V and Fe were carried out at Osaka [cf. 4] using the 14.1 MeV intense neutron source. In comparison to earlier studies measurements were done at 16 angles between 15 and 160°. The data for V differ considerably from the ENDF/B-IV evaluation.

For the two most important blanket constituents, Li and Be (or Pb), high precision data are needed over a broad range of energy. For $^6$Li and $^7$Li some new measurements were done and a comparison of differential data in the energy range of 7 to 14 MeV was carried out [5]. Measurements using pulsed monoenergetic neutron sources require considerable effort. At Geel (in collaboration with Mol) a measurement programme has been initiated [cf. 6] in which a pulsed white neutron source is used and cross sections are obtained for all incident energies simultaneously. Due to the long source-sample distance the background conditions are much better than in the usual monoenergetic source experiment. Measurements were completed recently for $^7$Li with 1.6 to 13.8 MeV neutrons, recording the secondary neutron spectra at six emission angles between 24 and 150°. A typical double-differential neutron emission cross section obtained for a primary neutron energy bin of 8.55 ± 0.20 MeV is shown in Fig. 1. Elastic and inelastic neutron scattering to the first level of $^7$Li (at 0.478 MeV) appear as one single discrete peak ($n, n_0+n_1$). The second discrete peak ($n,n_2$) is due to inelastic scattering from the 4.63 and 6.54 MeV states, superimposed on a continuum due to three-particle breakup

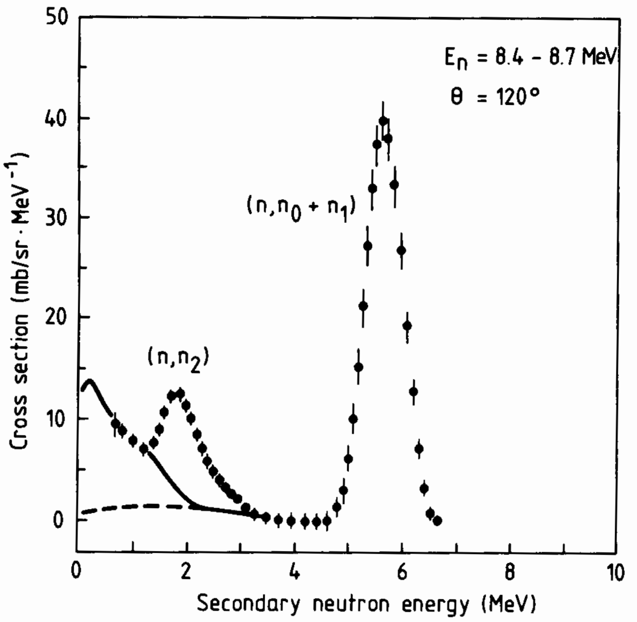

Fig. 1 Double differential neutron emission cross section for the $^7$Li(n,xn) process at an emission angle of 120°; the primary neutron energy was 8.37-8.75 MeV. The dashed line gives the contribution of the three-particle breakup process $^7$Li(n,n′t)$^4$He; the solid curve denotes the sum of the three-particle breakup and the two step reaction $^7$Li(n,t)$^5$He → $\alpha$+n′ [after Ref. 6].

and two step reaction. The angle-integrated data for the "elastic" part agree well with recent evaluations; for the other neutron-emission processes the integrated data appear to be systematically higher than the ENDF/B-V evaluation by 15%. Similar studies are in progress for Be.

## $\gamma$-Ray Emission

The $\gamma$-ray emission cross-section data are needed for $\gamma$-ray heating and shielding calculations. The status of $\gamma$-ray production data was recently reviewed [7] and the production of discrete $\gamma$-rays, especially in structural materials, discussed [8]. In general terms, $\gamma$-ray emission data needed for FRT are available both at 14 MeV and at neutron energies between 0.1 and 20 MeV. There are, however, several discrepancies, calling upon some new measurements and evaluations.

In recent years work on $\gamma$-ray emission has been done in several laboratories (e.g. Tokyo Institute of Technology, Tokai Mura, Beijing Normal University, Bratislava, Bruyères-le-Châtel, Oak Ridge, Los Alamos etc.). Systematic studies having a newer approach have been initiated at Los Alamos [cf. 9] with the following capabilities:

a) perform investigations at high neutron energies through the use of a spallation neutron source (presently up to 100 MeV, soon up to 400 MeV)
b) encompass higher $\gamma$-ray energies (up to 25 MeV) through the use of BGO detectors
c) incorporate angular distributions (multidetector array).

A pulsed white neutron source and five cylindrical BGO scintillators (located at various angles) lead to a detailed and useful information. Some of the results for $E_n$ = 9-10 MeV are given in Fig. 2(a),(b). Fig. 2(a) describes typical $\gamma$-ray spectra for Be and Ta measured at 90°. At 2 MeV $\gamma$-ray energy, the counts in the Be spectrum are ~ 3% of those in Ta, while at 10 MeV the ratio is 15 to 20%. Evidently the $\gamma$-ray yield from a high Z element is much higher than from a low Z element, especially if the emission of low-energy $\gamma$-rays is considered.

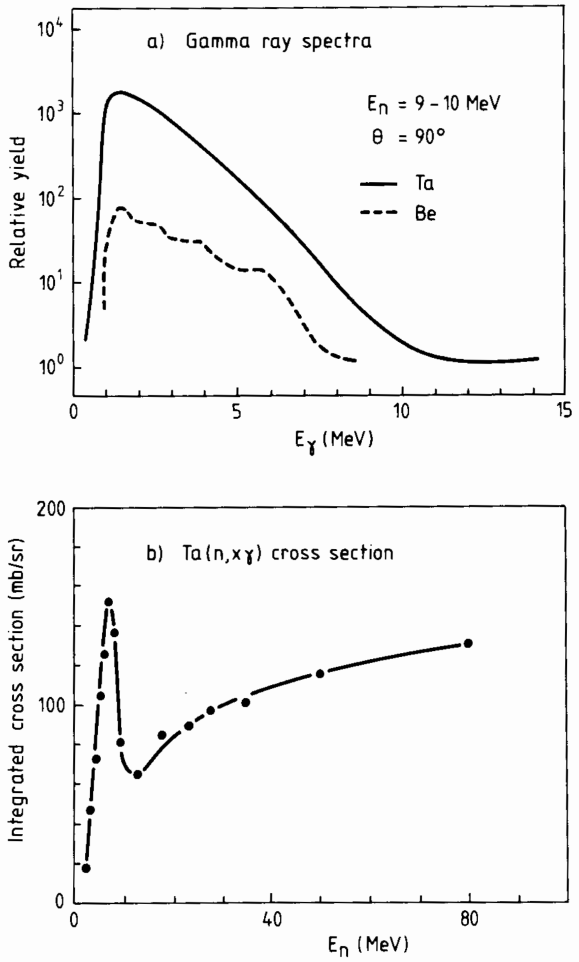

Fig. 2 (a) $\gamma$-ray spectra measured at 90° for a primary neutron energy of 9-10 MeV incident on Ta and Be. (b) Integrated photon production cross section for Ta as a function of average incident neutron energy [after Ref. 9].

The integrated photon ($E_\gamma$ = 2 to 25 MeV) production cross section for the $^{181}$Ta(n,x$\gamma$) reaction is shown in Fig 2(b) as a function of neutron energy. The cross section increases with neutron energy, reaches a maximum at ~ 7.5 MeV and then decreases. Beyond 15 MeV the cross section increases again slowly. A comparison of these data with the earlier Oak Ridge data up to 20 MeV shows similar energy dependence; the absolute magnitudes, however, are 20 to 30% lower. The results beyond 20 MeV describe the first measurement of an (n,x$\gamma$) process on a heavy mass nucleus.

The angular distributions of the photon production cross sections for different neutron energies were found to be isotropic. Since the spectra are dominated by low-energy components, the measured isotropy for the integrated cross section implies that the $\gamma$-rays at low energies are isotropic.

## Charged Particle Emission and Gas Production

The (n,xp) and (n,x$\alpha$) processes lead to transmutation products as well as hydrogen and helium gases. These products would affect the mechanical properties of potential first wall materials. Of particular interest is helium production since it causes the greatest damage.

As far as (n,xp) reactions are concerned, detailed studies were performed recently on $^{93}$Nb at Vienna [cf. 10,11] using 14 MeV neutrons. The energy and angular distributions of emitted protons were investigated by means of a multitelescope system. The total hydrogen production cross section is in fair agreement with the earlier data. A series of investigations is also underway at Ohio [cf. 12-14] using a charged particle TOF spectrometer. So far proton emission cross sections have been measured at 8 MeV for $^{58}$Ni, and at 9 and 11 MeV for SS 316, $^{58}$Ni, $^{60}$Ni, $^{63}$Cu and $^{65}$Cu. Those measurements should provide a very useful data base since spectral data in the incident neutron energy range of 6 to 14 MeV are scanty. On the other hand, at $E_n \leq 10$ MeV the (n,p) cross sections measured via the activation technique lead to almost total proton emission cross sections since the (n,n'p) contribution is negligible. Excitation functions of (n,p) reactions on some isotopes of molybdenum were determined up to 10 MeV radiochemically at Jülich [15].

Most of the available (n,d) reaction cross-section data are for $E_n$ = 15 MeV and were reported from Livermore. Angular distribution studies performed at high energies (e.g. 22 MeV [16], and 27, 40 and 61 MeV [17]) are of mechanistic interest. At energies below 14 MeV this reaction has been rarely investigated. So far only the excitation function of the $^{58}$Ni(n,d)$^{57}$Co reaction was reported from Jülich [18]. At Ohio [13,14] (n,d) cross sections were measured for $^{58}$Ni, $^{60}$Ni and $^{63}$Cu at 11 MeV.

The (n,t) and (n,$^3$He) reactions on medium and heavy mass nuclei are known to have negligibly small cross sections [cf. 19] and studies are only of mechanistic interest. For light mass nuclei the (n,t) cross section is fairly large and studies are of significance from the viewpoint of tritium breeding rather than gas production. Tritium emission data are therefore treated separately (see below).

Because of its relatively high importance the (n,x$\alpha$) process has been extensively studied at 14-15 MeV, using charged particle detection, mass spectrometry and activation technique. The recent total $\alpha$-emission cross-section data for elements of natural isotopic compositions obtained via charged particle detection (mostly from Livermore, a few from Vienna [cf. 20] and mass spectrometry [cf. 21,22] are given in Fig. 3. The trend for the pure (n,$\alpha$) reaction based on activation measurements on individual isotopes of various elements is also shown for comparison [cf. 23]. Obviously for very light nuclei (Z < 10) the pure (n,$\alpha$) contribution is small, the (n,2$\alpha$) and multiparticle breakup processes leading to the emission of several $\alpha$-particles being dominant. For nuclei with Z > 10, however,a greater part of the measured (n,x$\alpha$) cross section is furnished by the (n,$\alpha$) reaction.

For several medium mass target nuclei the (n,n$\alpha$) cross section was determined radiochemically at Jülich [24] using 14.7 MeV neutrons. Its contribution was found to lie between 10 and 15% of the (n,$\alpha$) cross section. The role of the (n,n$\alpha$) process in total helium production is thus not as important as of the (n,n'p) process in total hydrogen generation.

At neutron energies other than 14 MeV, some measurements on helium production have been done in recent years. Angular distribution studies at higher energies (e.g. 18 MeV [cf. 25], and 27, 40 and 61 MeV [17]) show that $\alpha$-emission is mainly forward peaked. For energies below 14 MeV systematic investigations have been done at Ohio [12-14] using the spectrometer mentioned above. So far helium emission cross sections have been measured at 8 MeV for $^{58}$Ni, and at 9 and 11 MeV for SS 316, $^{58}$Ni, $^{60}$Ni, $^{63}$Cu and $^{65}$Cu. Measurements in the energy range of 5 to 10 MeV have also been done on nickel and copper using the multitelescope system at Geel [26]. Since at $E_n \leq 10$ MeV the (n,n$\alpha$) contribution is negligible, the (n,$\alpha$) cross section measured by the activation technique gives the total helium emission cross section. Data for elemental nickel and molybdenum were therefore also obtained from the isotopic activation data and Hauser-Feshbach calculations or systematics [27]. The various results for nickel are shown in Fig. 4. The most recent data (from Geel and Ohio) are systematically lower than the other data. The results of two

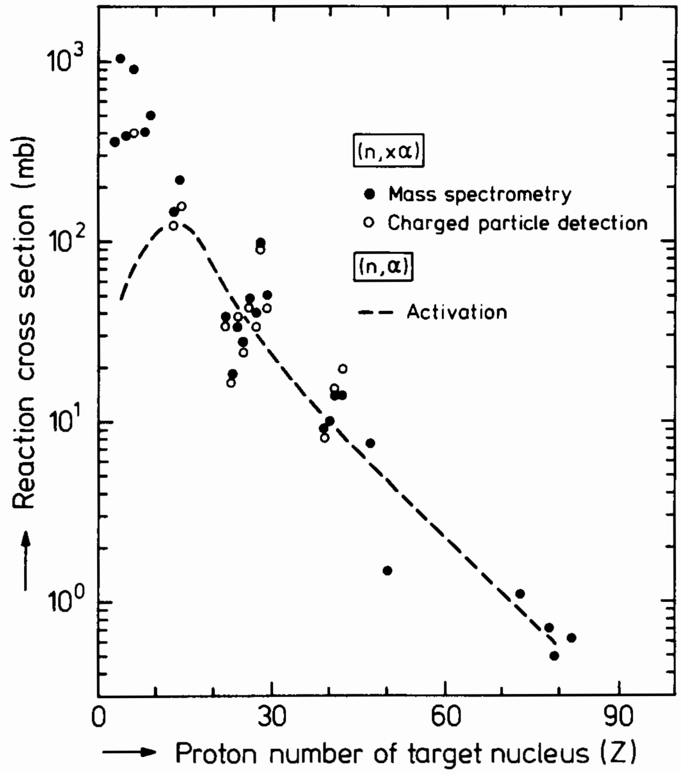

Fig. 3 Helium emission reaction cross sections at 14 MeV [data from Livermore measurements and Refs. 20-22] as a function of Z of the target nucleus. The curve describing the activation data relates to the pure (n,α) contribution [cf. 23].

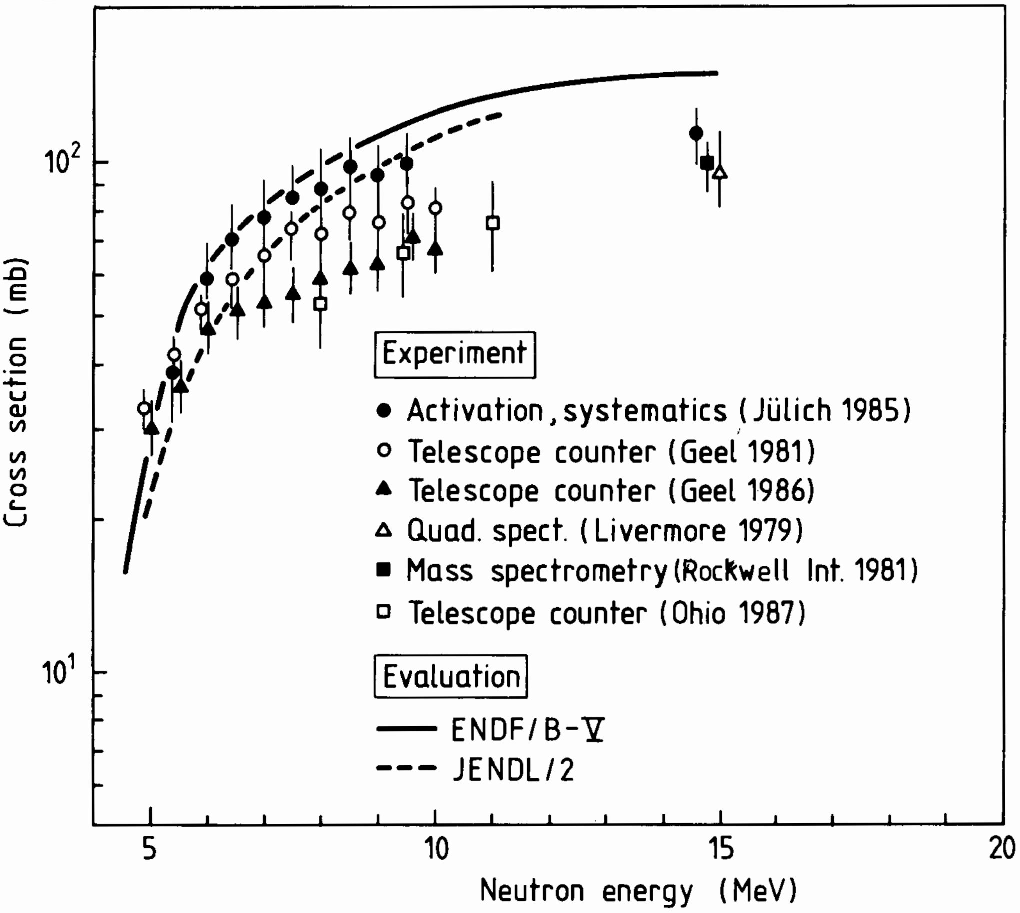

Fig. 4 Helium emission cross sections for elemental nickel.

evaluations (ENDF/B-V and JENDL/2) are also shown. In view of the discrepancy measurements of helium emission cross-section ratios from individual isotopes, namely $^{60}$Ni to $^{58}$Ni, $^{63}$Cu to $^{58}$Ni and $^{65}$Cu to $^{58}$Ni, have also been done at Geel as a function of energy. In the case of $^{60}$Ni to $^{58}$Ni the ratio is larger than that from the evaluation, especially at $E_n$ > 7 MeV. A comparison with model calculations is underway [26].

## Tritium Emission

The (n,t) cross sections of light mass nuclei are relatively high and the data are of significance for estimating tritium build-up in and around a reactor core, as well as in the atmosphere. In FRT the data are needed for tritium fuel breeding calculations.

A systematic study of (n,t) reactions on light mass nuclei was carried out recently at Jülich. Excitation function was measured for the $^9$Be(n,t)$^7$Li reaction (in collaboration with CBNM Geel) from 12.5 to 19.5 MeV [28]. Measurements on the $^{10}$B(n,t)2α process were done from thermal to 10.6 MeV [cf. 29], and on the $^{14}$N(n,t)$^{12}$C reaction from 5.0 to 10.6 MeV [30]. For the $^9$Be(n,t)$^7$Li reaction the cross section was also measured at Zagreb [31] at 14.6 MeV using the charged particle detection technique.

The cross section of the $^9$Be(n,t)$^7$Li reaction at the maximum of the excitation function is about 30 mb and that of the $^{10}$B(n,t)2α process about 200 mb. In the case of $^{14}$N(n,t)$^{12}$C reaction the cross section fluctuates which is attributed to the decay properties of the excited nuclear levels involved. A summary of those measurements is given separately [32].

In FRT the $^6$Li(n,t)$^4$He and $^7$Li(n,n′t)$^4$He reactions are of key importance for tritium breeding. The status of the $^6$Li(n,t)$^4$He reaction cross-section data is adequate. The data for the $^7$Li(n,n′t)$^4$He process, however, were discrepant. Some new measurements were done recently at Jülich and all the data obtained via tritium counting were reviewed [33]. In the various reported studies $^7$Li samples of various enrichments and chemical compositions were used, and tritium assay was done via two distinct methods, viz. gas counting and liquid scintillation counting. The neutron flux densities were determined using six different detectors. The cross-section results are reproduced in Fig. 5. Apart from some deviations in the early measurements, the agreement within the data is remarkable. The data from threshold to 9.5 MeV are now in good agreement. The data base between 10.5 and 13 MeV is still weak. The data around 14 MeV show some scatter. However, there appears to be no serious discrepancy. The Los Alamos 1981 evaluation describes the

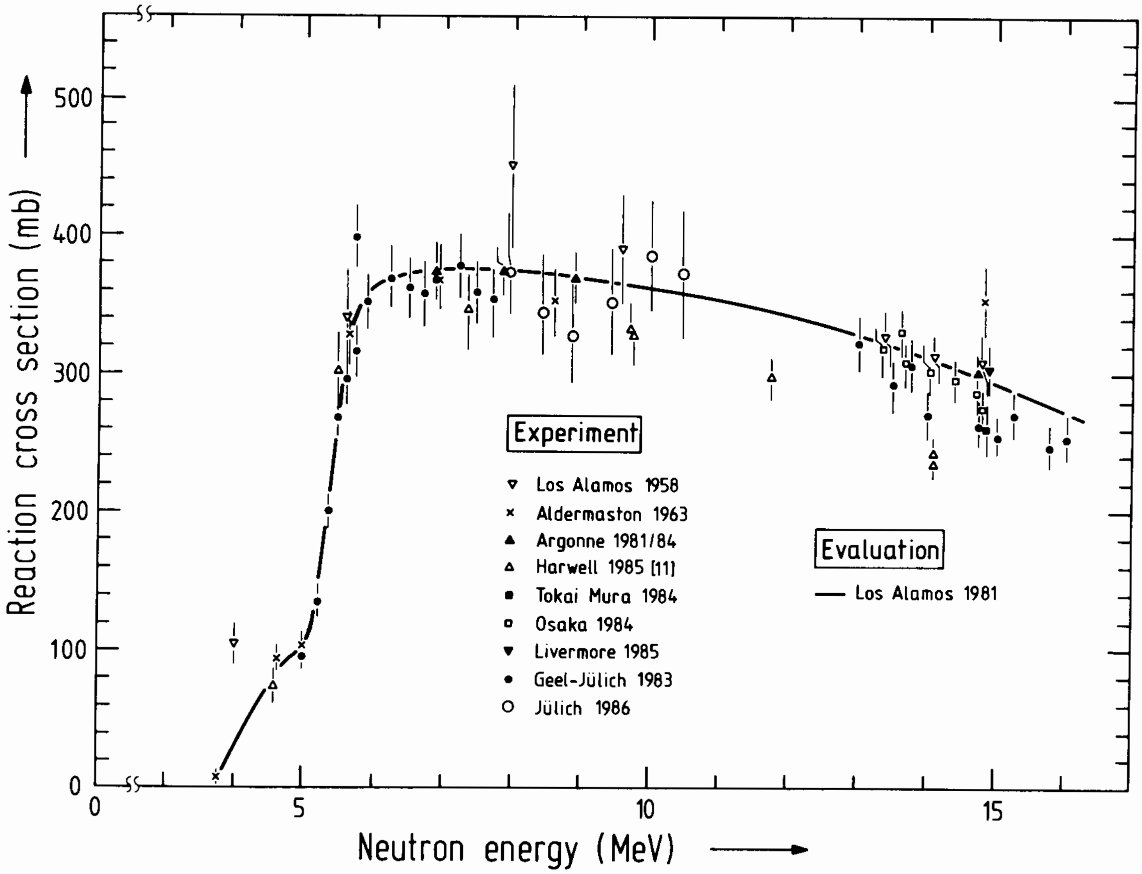

Fig. 5 $^7$Li(n,n′t)$^4$He reaction cross sections (determined via tritium counting) as a function of incident neutron energy [cf. 33].

trend well up to 10.5 MeV. In the range of 13 to 16 MeV, however, it appears to be rather high. In view of the large body of experimental data reported in recent years, new evaluations are presumably underway.

The discrepancy in the $^{7}Li(n,n't)^{4}He$ cross section seems to have been solved. However, the demanded accuracy of 3% is at present not achievable. It appears that with the presently available techniques, in several energy regions the cross section cannot be determined with uncertainties < 5%.

## Activation and Transmutation

Activation of reactor components is an important consideration in design calculations. Cross-section data are needed for estimating long-lived activation products as well as for characterization of neutron fields via multiple foil activation and spectrum unfolding technique. The status of data was recently reviewed [cf. 2,34,35].

Activation measurements have been performed recently around 14 MeV in several laboratories (e.g. Tokai Mura, Beijing, Dhaka, Bratislava, Rabat, Debrecen, Vienna, Argonne, Ann Arbor etc.) and in other energy regions at Beijing, Warsaw, Jülich, Argonne etc. The dosimetry reactions $^{115}In(n,n'\gamma)^{115m}In$ and $^{93}Nb(n,n'\gamma)^{93m}Nb$ were investigated in detail, the former in the energy range of 13 to 15 MeV at Beijing and Debrecen, and the latter between 1 and 8 MeV at Vienna/Debrecen/Geel [cf. 36,37] and Harwell/Birmingham [38]. Measurements on the $^{93}Nb(n,2n)^{92m}Nb$ reaction up to 10.6 MeV were done at Jülich [39] and between 12.5 and 19.5 MeV at Jülich/Geel [40]. For this reaction a large number of measurements existed between 14 and 15 MeV and several studies between 13 and 20 MeV. The data base between threshold and 12.5 MeV, however, was very weak. Recent measurements should provide some useful information.

Because of their importance in waste disposal considerations, studies of long-lived low-activity activation products have been gaining considerable attention in recent years. Furthermore, several of those products (e.g. $^{55}Fe$, $^{59}Ni$) were found to have high thermal neutron (n,α) cross section, leading to the formation of additional helium. Measurements on radioactive products with medium-range half-lives (between a few days and one year) have been underway in serveral laboratories covering various energy regions. Investigations on extremely long-lived products, however, have been limited [cf. 41-45]. Some of the products studied recently are given in Table 1. Measurements were done mostly at 14-15 MeV using high-intensity neutron generators [cf. 41-44]. For several of

Table 1. Cross Sections for the Formation of some long-lived Activation Products

| Radioactive product | Half-life (y) | Nuclear process | Measurement method | Cross section at 14.7 MeV (mb) | Reference |
|---|---|---|---|---|---|
| $^{26}Al$ | $7.2\times10^{5}$ | $^{27}Al(n,2n)^{26}Al$ | γ-ray counting | 30 ± 5 a) | [41,42] |
| $^{55}Fe$ | 2.7 | $^{58}Ni(n,\alpha)^{55}Fe$ | chem. separation; X-ray counting | 125 ± 20 b) | [45] |
| $^{59}Ni$ | $7.5\times10^{4}$ | $^{60}Ni(n,2n)^{59}Ni$ | liq. scintillation counting | 104 ± 25 | [44] |
| $^{63}Ni$ | $1.0\times10^{2}$ | $^{63}Cu(n,p)^{63}Ni$ | chem. separation; liq. scintillation counting | 54 ± 4 | [44] |
| $^{91}Nb$ | $7.0\times10^{2}$ | $^{92}Mo(n,2n)^{91}Mo\rightarrow^{91}Nb$ | γ-ray counting and systematics | 603 ± 119 | [44] |
| $^{94}Nb$ | $2.03\times10^{4}$ | $^{94}Mo(n,p)^{94}Nb$ | γ-ray counting | 53 ± 5 | [43] |
|  |  | $^{95}Mo(n,x)^{94}Nb$ | γ-ray counting | 17 ± 2 | [43] |

a) Investigated energy range was 13.7 to 14.8 MeV.

b) Excitation function was measured from 5 to 15 MeV.

the other expected products like $^{92}$Nb($T_{1/2}$=$10^8$y), $^{93}$Zr($T_{1/2}$=1.5x$10^6$y), $^{93}$Mo($T_{1/2}$=3.5x$10^3$y) etc. no data exist. The cross sections are difficult to measure and radiochemical separations combined with low-level counting methods are mandatory. On the other hand, the accuracy requirements are not very stringent and model calculations could lead to useful information, at least to a first approximation. In the case of long-lived isomeric states, however, the calculations are not very successful.

## Conclusions

Considerable progress seems to have been achieved in recent years in nuclear data measurements. The development and use of pulsed white neutron sources has led to studies of secondary neutron spectra and γ-ray emissions over a broad energy range of incident neutrons. Measurements on hydrogen and helium gas producing reactions have been intensified in the region of 6 to 14 MeV using both counter telescopes and activation technique. Studies of (n,t) reactions on several light nuclei have been completed. The data for $^7$Li(n,n't)$^4$He reaction available are now consistent, except for some fluctuations in the 14 MeV region. The desired maximum uncertainty of 3%, however, is presently not achievable. The importance of long-lived low-activity activation products in waste disposal considerations has been recognised. A concerted effort involving inter-disciplinary studies seems mandatory.

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