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Neutron thermalisation in reactor-grade polycrystalline graphite

Author(s)

W. Bernnat, M. Mattes, J. Keinert

Bernnat@ike.uni-stuttgart.de; mattes@ike.uni-stuttgart.de; keinert@ike.uni-stuttgart.de

Organisation, Country

IKE, University of Stuttgart
Pfaffenwaldring 31
70550 Stuttgart, Germany

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Neutron thermalisation in reactor-grade polycrystalline graphite

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W. Bernnat
M. Mattes
J. Keinert

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ABSTRACT

For polycrystalline graphite the neutron-nucleus scattering dynamics was re-evaluated in considering new remarks concerning the scattering kernel. The proposed frequency distribution $\rho(\omega)$ was compared to the approved one taken formerly for our Scattering law data $S(\alpha,\beta,T)$ integrated in JEF-2 as well as taken for the ENDF/B-VI data. For the new Scattering law data files generated care was taken to have a strong correlation of the revised alpha, beta-grid to the maxima and minima of $\rho(\omega)$. These data sets then were taken to calculate differential and integral neutron cross sections and comparing them with experimental ones. For both models the results agree well within the published accuracy of measurements but the overall agreement of the Young, Koppel distribution seems to be slightly better than the Difilippo model which also does not reproduce the measured specific heat very well. Measured neutron flux spectra in Sm poisoned graphite were reproduced very well by the generated AMPX data sets, delivering for the two models identical neutron temperatures but a slightly softer spectrum in the cold neutron energy range for the IKE/GA data set.

1.Introduction

Reactor-grade graphite as a solid is structured polycrystalline with a hexagonal lattice structure. This lattice structure is highly anisotropic, consisting of the hexagonal basal planes which are only weak coupled. Graphite therefore resembles in many ways as a two dimensional crystal. For calculating thermal neutron cross section data sets in ENDF-6 format /1/ with codes as LEAPR of the NJOY modular processing system /2/ or with GASKET2 /3/ therefore there exist the problem to have a generalised isotropic frequency distribution $\rho(\omega)$ which is the demand for the generation of Scattering law data files $S(\alpha,\beta,T)$ in incoherent approximation with these codes.

To prepare the isotropic $\rho(\omega)$ there exist the possibility to calculate it via a general tensor force dynamical model of the unit cells. In the past this was done by Yoshimori, Kitano /4/ and later improved by Young, Koppel /5/ by the bond-bending and bond-stretching model in adjusting the used force constants to compressibility and specific heat data. Because of the anisotropy of the crystal this procedure delivers the phonon spectra for perpendicular and parallel vibrations of the graphite lattice. The only known code which can handle this is SUMMIT /6/ which has used in the past to produce scattering matrices $\sigma_s(E_i \rightarrow E_f)$. Because this was done very ineffective and time consuming, Young, Koppel have averaged the two parts in Gaussian approximation taking 2/3 of the parallel and 1/3 of the perpendicular one. This isotropic distribution was compiled by Gulf GA in the so-called Kernel Book /7/ being the base for generating the IKE data sets later integrated to JEF-1 and JEF-2 /8/ as well as for the ENDF/B data sets for graphite. MacFarlane /9/ has slightly modified this distribution for LEAPR to prepare improved thermal ENDF/B-VI data.

For the evaluation presented here we have modified our formerly input to GASKET2 especially for the α,β-grid, which is now strongly correlated to $\rho(\omega)$ considering the

multiphonon excitations of the maxima and minima. The new calculations of the thermal data sets now are done with LEAPR, providing the Scattering law data file (as MF=7 and MT=4) as well as the coherent elastic part (as MF=7 and MT=2). These data are thought to be integrated into JEFF-3 /10/.

Alternatively, another case of a general tensor force model was examined by Nicklow et al /11/ calling it axially symmetric model and considering in the calculation atoms up to the fourth-nearest neighbours. This method delivers an isotropic averaged phonon spectrum of the graphite crystal. Difilippo et al /12/ have transformed this spectrum to generate thermal data sets in ENDF-6 format for neutron transport calculations. For our topical evaluation we have also taken this phonon spectrum to generate own ENDF/B-6 thermal data sets for comparison with experimental differential and integral neutron cross sections as well as with measured neutron flux density spectra.

Another theoretical effort was taken by Malik, Kothari /13/ with the so-called unfolding technique in fitting measured specific heat data. From physical aspect this method seems to be a little bit arbitrary because the resulting phonon spectrum must be regarded carefully in deriving differential data from integral ones.

Besides this theoretical work the frequency distribution $\rho(\omega)$ can be derived from measured double differential neutron scattering cross sections. This is because the incoherent Scattering law $S(\alpha,\beta,T)$ /α for α->0 is correlated to the one phonon excitation containing $\rho(\omega)$ via the conservation of energy. In the past many measured $S(\alpha,\beta,T)$ were interpreted to derive phonon spectra for graphite. Some important works are from Egelstaff /14/, Whittemore /15/, Carvalho /16/, Page, Haywood /17/ or Butland /18/. Compared to the theoretical $\rho(\omega)$ those derived from the measured double differential data prove strongly being temperature dependent. But generating Scattering law data with these phonon spectra from mathematical aspect this is not very favourable because each temperature set demands for an own α,β-grid and so it is not possible to store the data in the usually used multi-temperature format of the standard moderator files and each temperature must have its own data set.

2. Considered phonon spectra and neutron cross section comparisons

In a formerly study (Keinert /19/) we have compared neutron cross sections calculated with different phonon spectra $\rho(\omega)$. Taking the Young, Koppel spectrum as the fundamental one the overall agreement of the others with measured data was not very sufficient. So in this study we omit measured $\rho(\omega)$ because, in addition it is very difficult to correct multi-phonon parts in these derived distributions and they are thought to have some uncertainties. Therefore we restrict the comparison to results from the standard phonon spectrum of Young, Koppel which was taken for our scattering law data file for 11 temperatures and later integrated into JEF-1 and then to JEF-2. MacFarlane has later modified slightly the fundamental distribution documented in the KERNEL book /7/ in providing the ENDF/B-VI thermal data sets. For the reevaluation we have taken this altered phonon spectrum to calculate new scattering law data sets. In comparison to the JEF-1 data the α,β-grid was modified. Now the maxima and minima of $\rho(\omega)$ are strongly correlated in considering the multiphonon peaks. In addition the α-grid was increased to very small values.
The second phonon spectra $\rho(\omega)$ considered was that of Difilippo et al /12/. For the calculated Scattering law data sets the same procedure for the choice of the α,β-grid was done as discussed above. The curvatures of the both phonon spectra are presented in Figure 1.

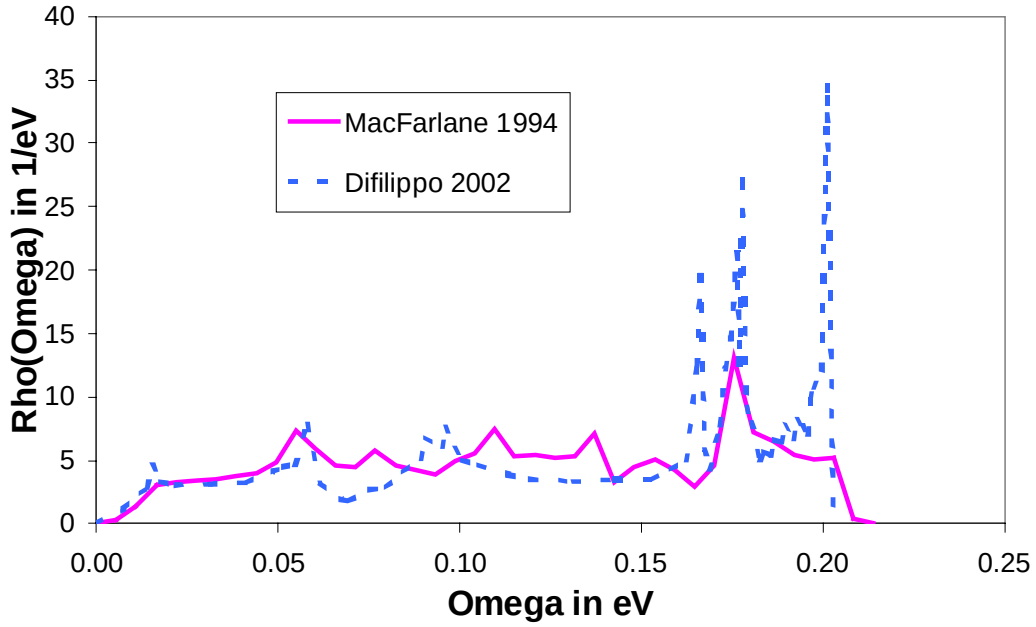

Fig. 1: Updated frequency distributions of polycrystalline graphite

Whereas the Young, Koppel distribution modified by MacFarlane is an average of the solutions perpendicular and parallel to the basal hexagonal plane generated from the dynamical matrix the Difilippo curve is delivered directly from the theoretical treatment of the anisotropic crystal. But for both the results are strongly influenced by

the choice of the taken force constants. Especially Young, Koppel have carefully fitted these to get optimal agreement with measured specific heat from room temperature up to some hundred degrees.
To test the chosen generalised frequency distribution there exist some physical parameters which are simply correlated to $\rho(\omega)$. Among these are ($\hbar$ and k are normalised to unity, so that ω and T are to be read in eV)

- **the specific heat relation**

$$\frac{C_V}{3R} = \int_0^{\omega_{max}} \left(\frac{\omega}{T}\right) \frac{e^{\omega/T}}{\left(e^{\omega/T}-1\right)^2} \rho(\omega) d\omega$$

- **the effective scattering temperature of the neutron scattering nuclei**

$$T_{eff} = \frac{1}{2} \int_0^{\omega_{max}} \omega \coth \frac{\omega}{2T} \rho(\omega) d\omega$$

3/2 T_{eff} is the average kinetic energy of the system of scattering nuclei. T_{eff} is used for supplementation of the finite α,β-grid of the Scattering law data file up to infinity according to the short collision time approximation.

- **the Debye-Waller integral**

$$\gamma(0) = \int_0^{\omega_{max}} \frac{\rho(\omega)}{\omega} \coth \frac{\omega}{2T} d\omega$$

The Debye-Waller integral is used for calculating the elastic coherent and incoherent neutron scattering cross sections. For coherent scattering the Debye-Waller factor exp(-γ(0)*...) describes the height of the cross sections at the Bragg edges and the exponential decrease between them. Also from the Debye-Waller integral the average and maximal atomic dislocation can be derived ($<u^2> \sim \gamma(0)$).

- **the average energy transfer for an excitation** (if allowed)

$$< \omega >= \int_0^{\omega_{max}} \omega \rho(\omega) d\omega$$

Of course $\rho(\omega)$ is normalised to unity. The amount of $<\omega>$ is a measure of the slowing down quality of the scattering material for thermal neutrons.

- **the average square of the energy transfer for an excitation**

$$< \omega^2 >= \int_0^{\omega_{max}} \omega^2 \rho(\omega) d\omega$$

$<\omega^2>$ is correlated to the average $<\Delta V>$ of the potential V of the scattering nucleus.

In Fig. 2 we present our calculated specific heat data for the two phonon spectrum models considered in comparison with experimental data /20,21/.

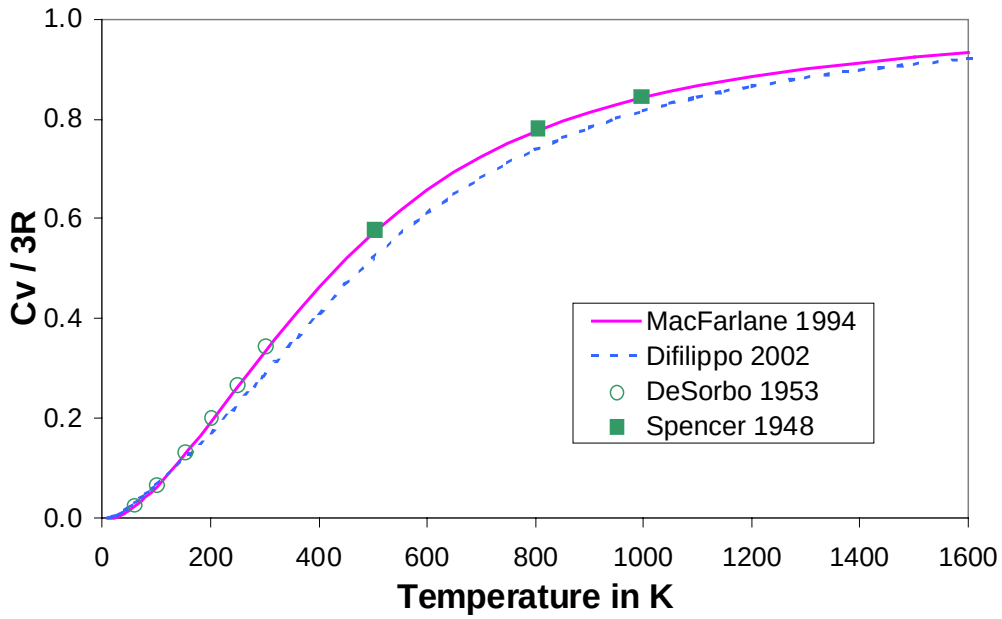

Fig. 2: Specific heat for polycrystalline graphite

As is clearly seen the overall agreement of the data from the ORNL model of Difilippo is not very good, whereas the Gulf GA model of Young, Koppel is within the reported accuracy of measurement. But this is not surprising because they fitted the used force constants to an optimal agreement to the reported specific heat data. For the ORNL model the used force constants should be modified slightly because in the original publication of Nicklow et al /11/ the force constants were chosen to give good results for the specific head in the temperature range from 1 K up to room temperature.
In Table 1 the values of some parameters correlated to the frequency distributions are given for room temperature (293.6 K).

Table 1: Room temperature parameter values calculated from $\rho(\omega)$

Parameter	MacFarlane	Difilippo
$<\omega>/T$	4.596	5.042
T_{eff}/T	2.43	2.64
$<\omega^2>/T^2$	25.81	30.67
$T \bullet \gamma(0)$	0.6586	0.7708
<u> in Å	0.067	0.073

In Table 2 the parameter values are listed which are necessary for the processing of the thermal neutron data sets in ENDF/B-6 format generated from us for JEFF-3 consisting of the Scattering law data file as well as of the coherent elastic neutron scattering data file. As it is usual for thermal ENDF/B data files if the coherent neutron scattering dominates, the incoherent elastic scattering is omitted. For polycrystalline graphite in the energy range below the Bragg edge for the cold neutrons this means an underestimation of the total scattering cross sections of up to 5%. Compared to the formerly generated JEF-1 data sets the temperature grid was unchanged but the chosen α,β-grid was strongly changed by integration of the values correlated to the multiphonon excitation of the maxima and minima of the phonon spectrum. In addition, the α-grid was extended to very small values.
For the ORNL model of Difilippo we have generated an ENDF/B-6 file for 533 K for comparison with measured differential and integral neutron cross sections in addition to the data sets for the temperatures listed in Table 2.

Table 2: Effective scattering temperatures and Debye-Waller integrals for the temperature grid of the thermal neutron data sets

	Gulf GA/MacFarlane		ORNL/Difilippo	
T / K	**T_{eff} / K**	**$\gamma(0)$ / eV^{-1}**	**T_{eff} / K**	**$\gamma(0)$ / eV^{-1}**
293.6	713.72	26.22	775.15	30.48
400	755.68	32.91	812.00	38.87
500	807.58	39.47	858.68	46.98
600	869.22	46.20	915.39	55.25
700	938.40	53.04	980.18	63.62
800	1013.4	59.96	1051.3	72.06
1000	1175.6	73.95	1207.4	89.09
1200	1348.7	88.07	1376.0	106.3
1600	1713.4	116.5	1734.4	140.8
2000	2091.4	145.1	2108.5	175.4
3000	3061.4	216.9	3073.0	262.4

For polycrystalline graphite in the literature many measured double differential as well as total neutron cross sections are published. Among the differential scattering cross section data we have chosen for comparisons the results of Whittemore /15/ measured at room temperature and the data of Carvalho /16/ for 533 K. For both measured Scattering law data $S(\alpha,\beta,T)$ comparisons are made for chosen β values both for the phonon spectrum models of Gulf GA/MacFarlane and ORNL/Difilippo.
In the Figures 3 to 5 the comparisons for room temperature are shown. Fig. 3 shows the Scattering law $S(\alpha)$ for β=2 which describes an energy transfer of 51.7 meV. Following the conservation of energy this is correlated to the first peak region of the

phonon spectra. Compared to the measured data the ORNL model seems to underestimate slightly the experiment in this energy region. Fig. 4 shows the comparison for β=4, which means an energy exchange of 103.4 meV. In this region both models are well within the accuracy of measurement. This energy transfer is correlated to the second peak structure in ρ(ω).

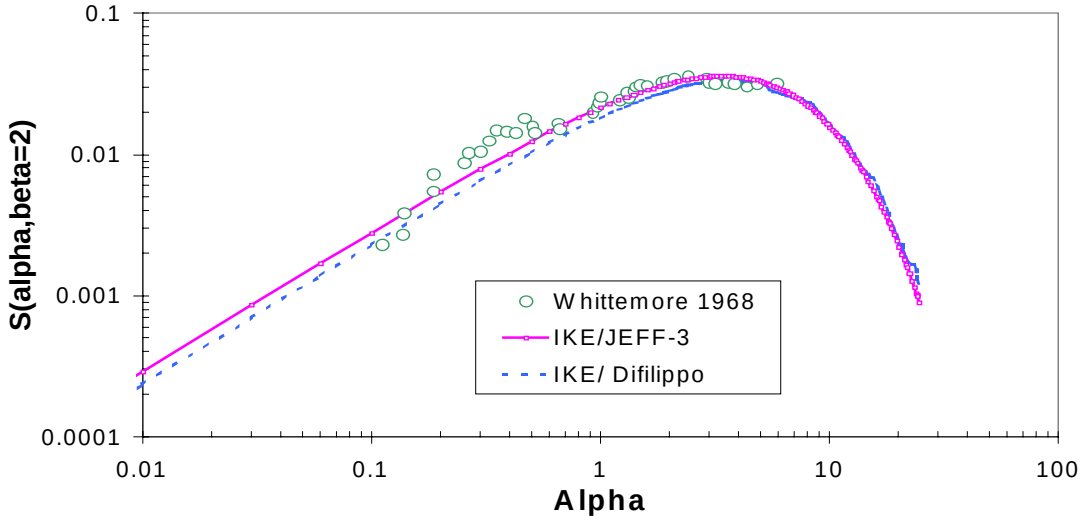

Fig. 3: Graphite scattering law data at room temperature for β=2

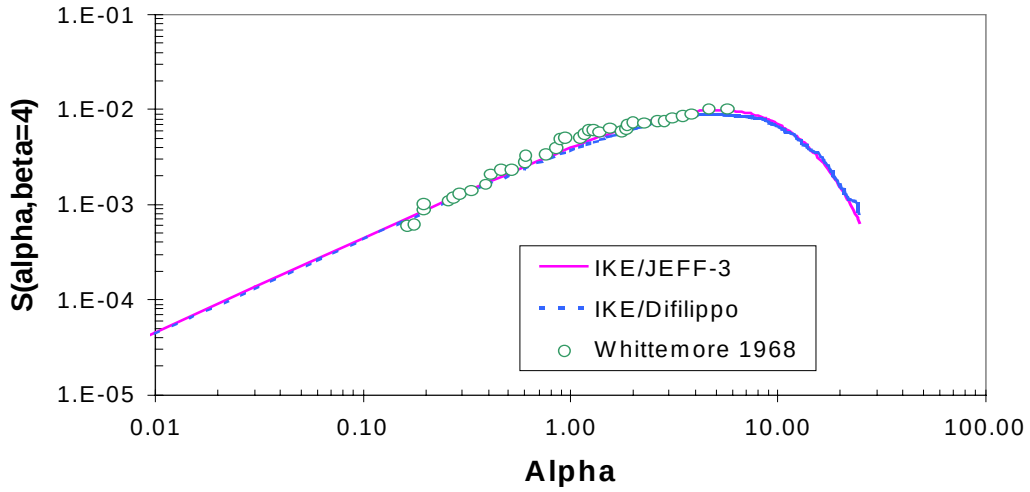

Fig. 4: Graphite scattering law data at room temperature for β=4

In Fig. 5 the Scattering law is presented for β=6. This means an energy transfer of 155.1 meV, which is correlated to the energy region in ρ(ω) before the large peaks.

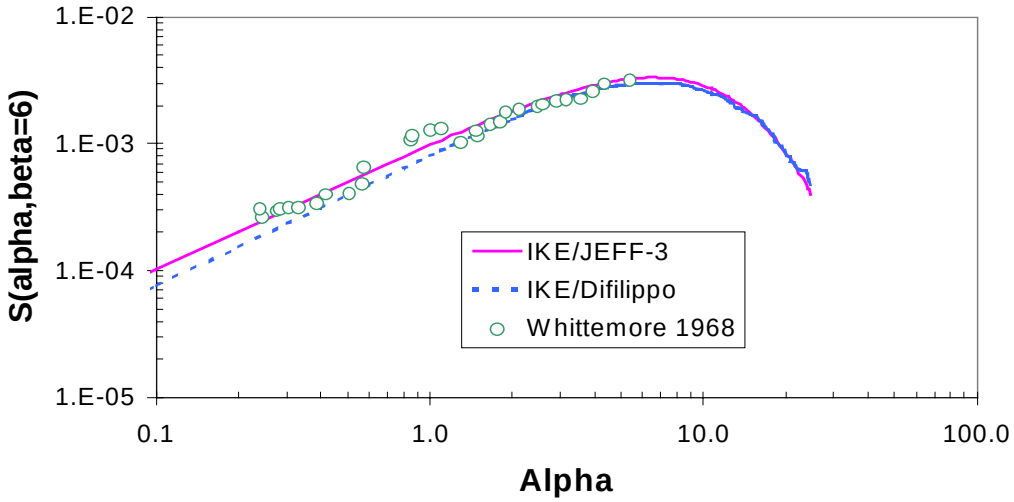

Fig. 5: Graphite scattering law data at room temperature for β=6

Other measured β values are not very favourable because of they describe energy transfers which are correlated to regions where the phonon spectra have only small values. Unfortunately there exist no β value which corresponds to the large peaks.
The Figures 6 and 7 are showing comparisons of scattering law data at T=533 K.
The measurement is from Carvalho /16/. Fig. 6 presents the results for β=0.15. This corresponds to an energy transfer of 6.9 meV. For the phonon spectra this means quasi-elastic neutron scattering. Here no theoretical model is able to describe well the measured values. But comparing both it seems that the Gulf GA model underestimates stronger the quasi-elastic neutron scattering. Comparing the relations in Fig. 7 at β=0.9 corresponding to an energy exchange of 41.3 meV we can see a good agreement both of the model results and the experimental data.

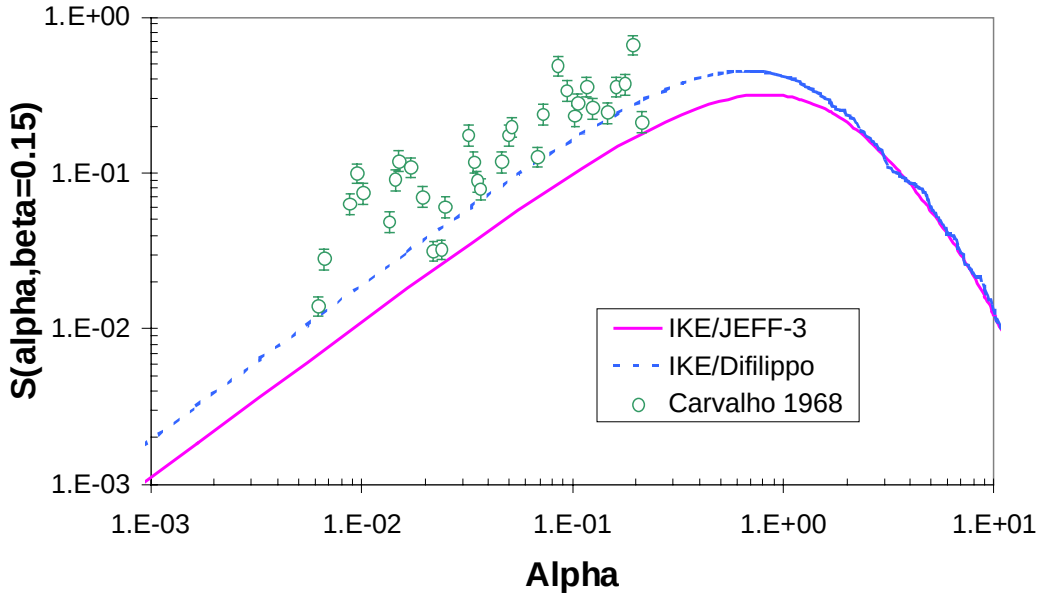

Fig. 6: Graphite scattering law data at T=533 K for β=0.15

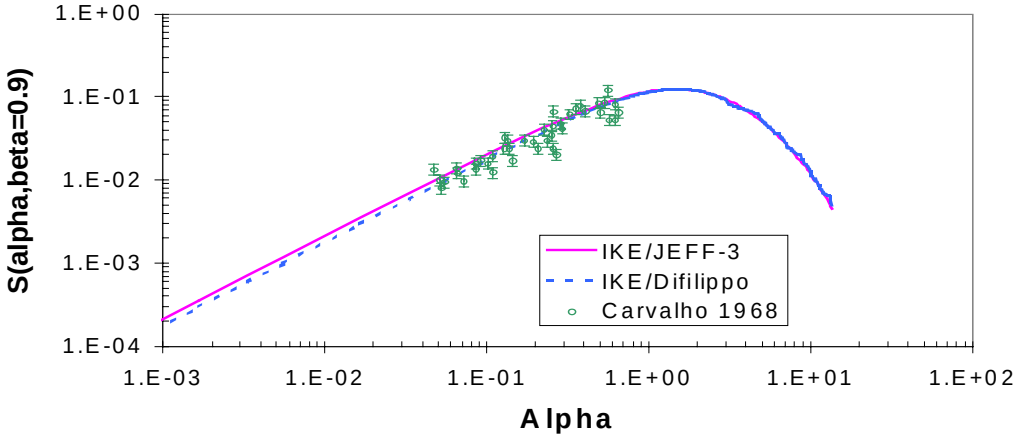

Fig. 7: Graphite scattering law data at T=533 K for β=0.9

Comparing the relations for the different Scattering law data we can state a good overall agreement with the experimental values. Comparing the both scattering models the Gulf GA one seems to underestimate the quasi-elastic neutron scattering whereas the ORNL model produces slightly underestimated inelastic scattering cross sections in the considered peak region. In this study it would be of some interest to know the effect of taking an averaged generalised frequency spectrum. For the precursor of the GA model (the Yoshimori, Kitano /4/ spectrum) Wikner et al /22/ have examined the influence of the Gaussian approximation in constructing an isotropic phonon spectrum for the anisotropic crystal. The anisotropic model results were generated with SUMMIT.
Comparing with experimental results of Egelstaff /14/ for β=0.2 up to 1.6 the results for the Gaussian approximation and the anisotropic graphite differ not very much (about 10% at α≈1). But compared with the experimental data the agreement for the Gaussian approximation always was slightly better. Going to large α the Gaussian approximation can cause large systematic errors. This may play a certain role in neutron thermalisation which we will discuss in chapter 3.

Examining the incoherent approximation for the inelastic neutron scattering it would be desirable to compare differential angular distributions with measured ones. But such experimental data were not available for us.
For comparison of the incoherent total neutron scattering cross section below the Bragg edge of the polycrystalline graphite lattice which is at 1.822 meV we calculated the data from our Scattering law data files for IKE/JEFF-3, IKE/Difilippo and IKE/JEF-2. In contrary to the usual procedure for example with NJOY, which only delivers the inelastic contribution plus a uncertain amount from β=0 for the incoherent elastic part,

we have splitted this by adding the fully incoherent elastic scattering separately. These results are presented in Figure 8.

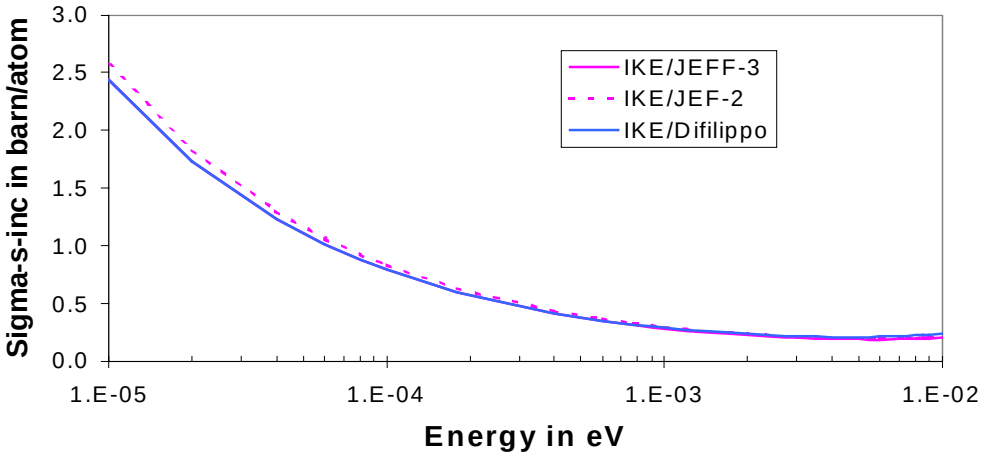

Fig. 8: Incoherent neutron scattering cross section of graphite at room temperature

Comparing the results for JEFF-3 and JEF-2 with identical phonon spectra the improved α,β-grid for JEFF-3 gives decreased values up to about 5 % in the energy range of cold neutrons. Generally, one can say that an inadequate α,β-grid may result in errors of at least some percent in integral cross sections.
In Figure 9 results for the average cosine of the neutron incoherent scattering angle is given and in Figure 10 the ratio of the averaged final neutron energy to the initial energy in the scattering process is presented. This ratio is a measure up to which energy neutron up-scattering dominates.
In Figure 11 we plot the total neutron cross section in the cold neutron energy range in comparison to the experimental data of Palevsky taken from Kothari, Singwi /23/ and from Shamasundar, Kallfelz /24/. Up to the Bragg edge the theoretical data are exact. For greater energies the coherent elastic cross section has a dominating amount.

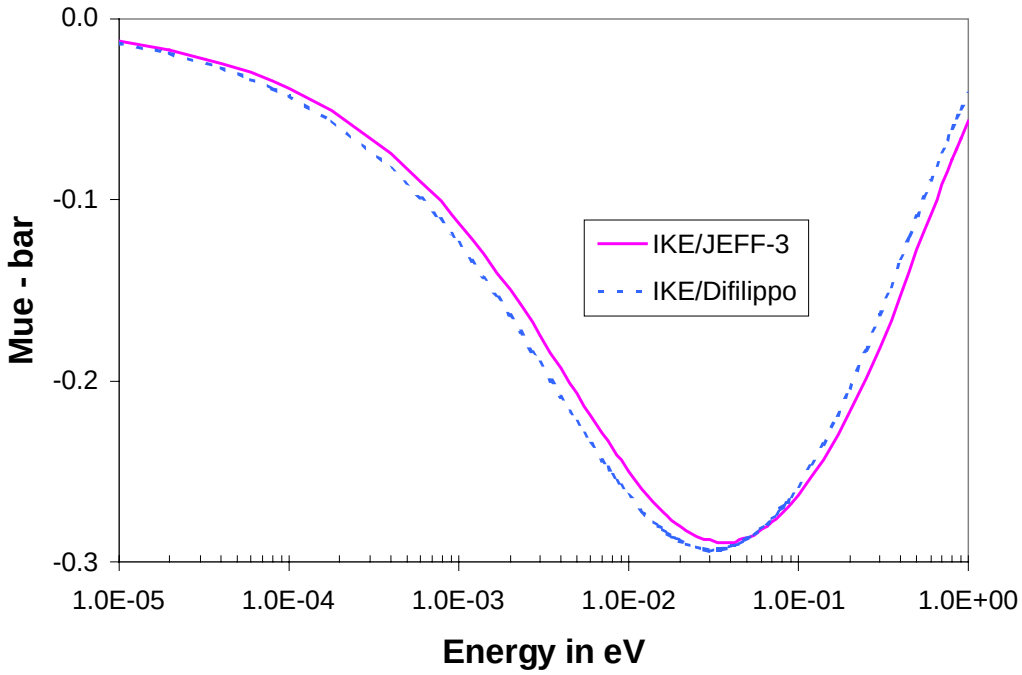

Fig. 9: Average cosine of the neutron incoherent scattering angle at room temperature

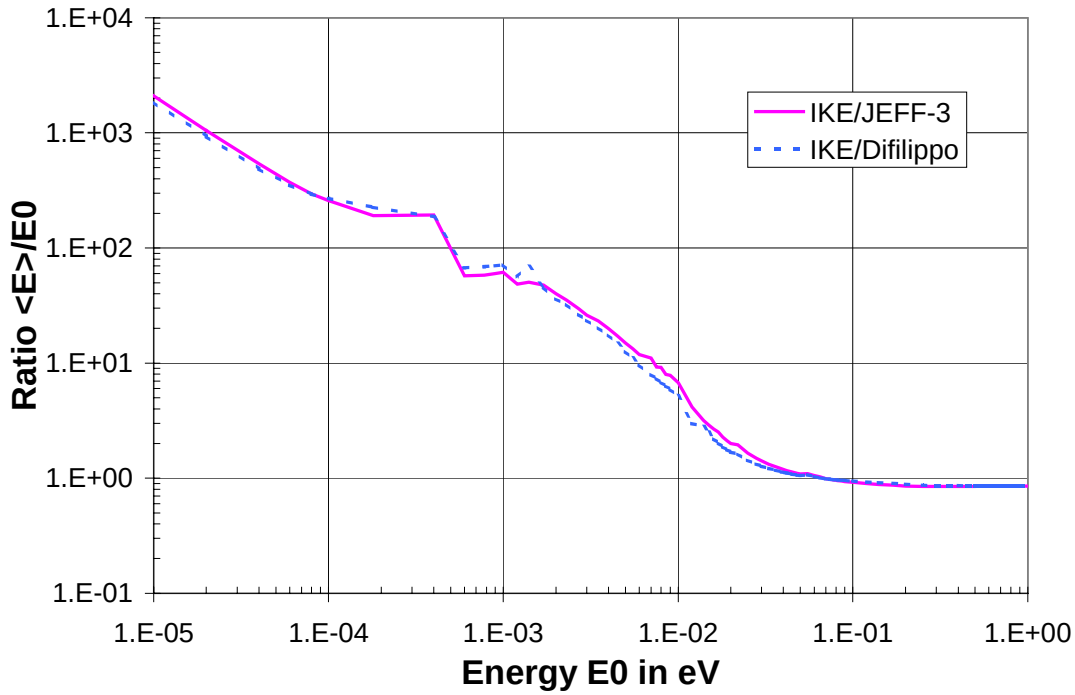

Fig. 10: Ratio average final scattered neutron energy E to initial energy E0 for graphite at room temperature

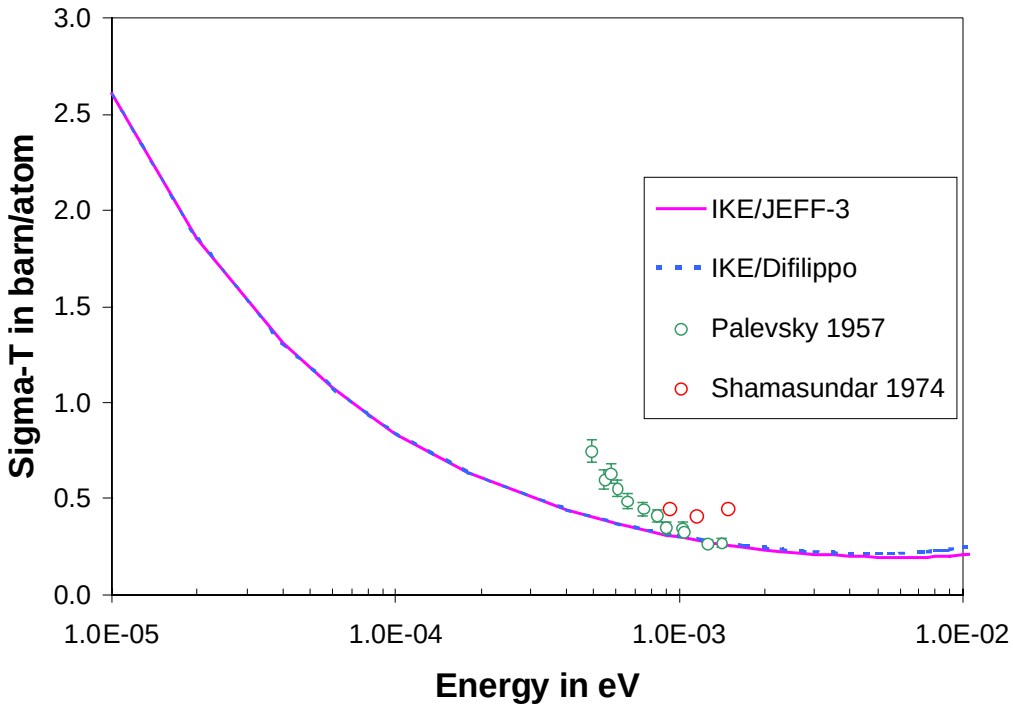

Fig. 11: Total neutron cross section of graphite around room temperature (theory only incoherent scattering)

In Figure 12 the total neutron cross section for the two theoretical scattering models is compared with experimental data /25-27/ covering a wide energy range. Comparing the calculated cross sections one can see a nearly identical curvature over the whole energy range. But working with the thermal ENDF/B-6 files and NJOY one must say that the incoherent elastic scattering is described only insufficient. Although its amount is small the error in $\sigma_S(E)$ for cold neutron energies can be up to 1%. The discrepancy of the theoretical data and the measurement of Steyerl /25/ is thought to be caused by parasitic absorption due to impurities in the used probe. For the other measurements the calculated cross sections agree very well. Especially for the energy range of thermal neutrons this fact is thought to deliver realistic neutron flux density spectra around room temperature and up to some hundred degrees.

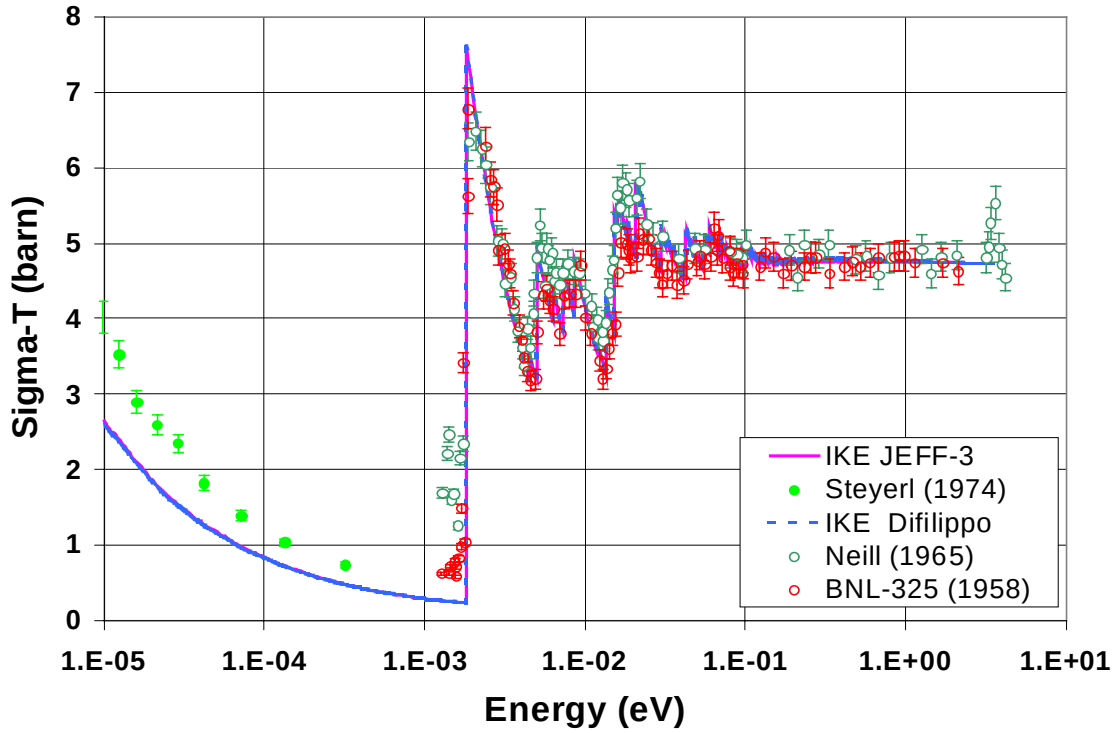

Fig. 12: Total neutron cross section of polycrystalline graphite around room temperature

3. Neutron flux density spectra for GA graphite benchmarks

For neutron transport studies in polycrystalline reactor-grade graphite AMPX and MCNP data sets were generated with the THERMR, GROUPR and ACER modules of NJOY from our thermal neutron data sets in ENDF-6 format containing scattering law data S(α,β,T) as well as coherent elastic data as is shown in principle in the scheme of Figure 13. The neutron transport calculations were done with the IKE code system partially derived from SCALE (AJAX, BONAMI, RESMOD/CGM /28/). The recalculated benchmarks are taken from the Gulf GA so-called Spectrum Book /29/. We have chosen the experiments GA-C-1B and GA-C-1C.

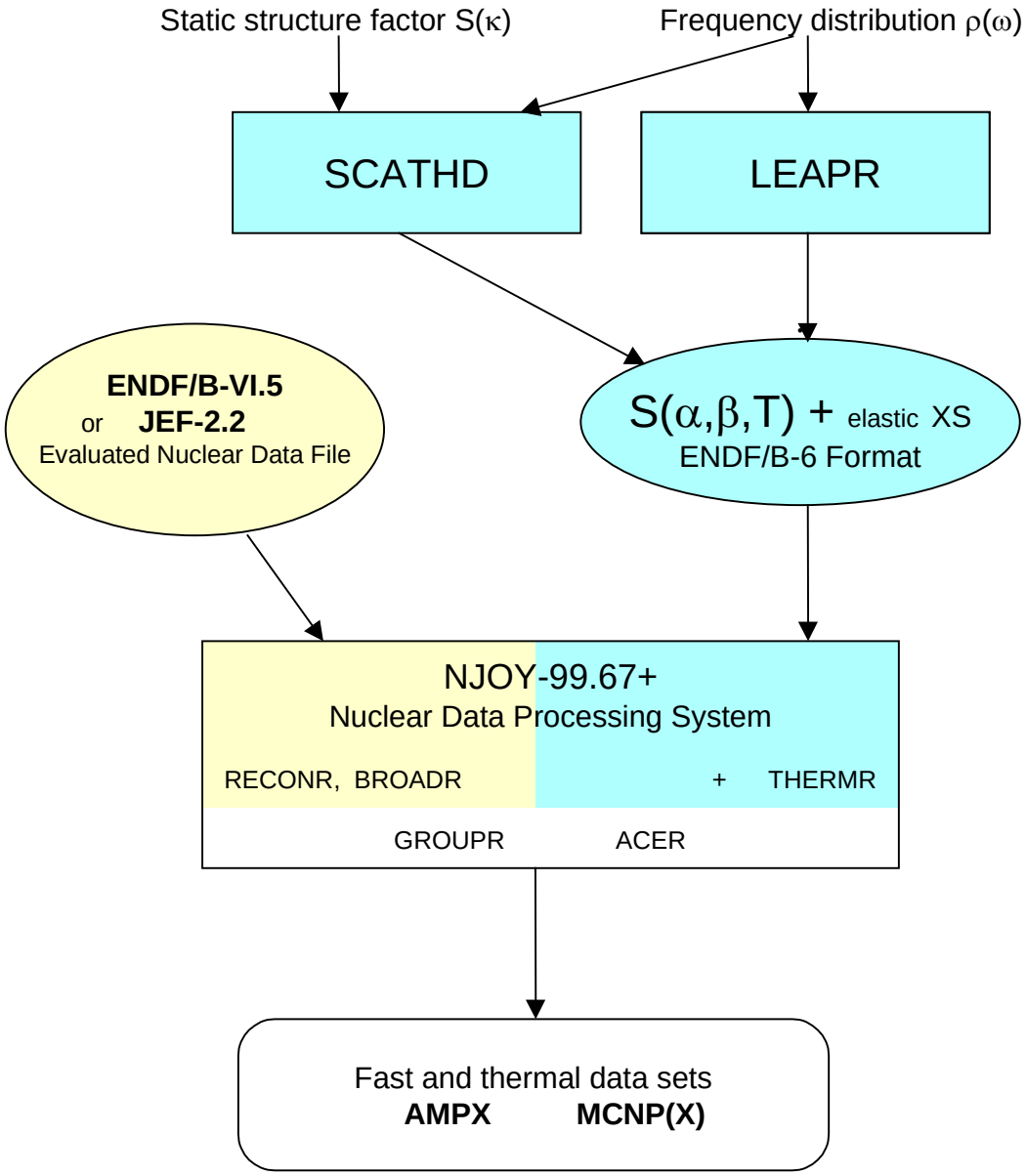

Fig. 13: Scheme of generating MCNP or AMPX data sets at IKE

The finite benchmark geometry was considered in the RESMOD B_3-calculation by a transverse local buckling. In Figure 14 we present our results in comparison to the measurement of GA-C-1B at room temperature.

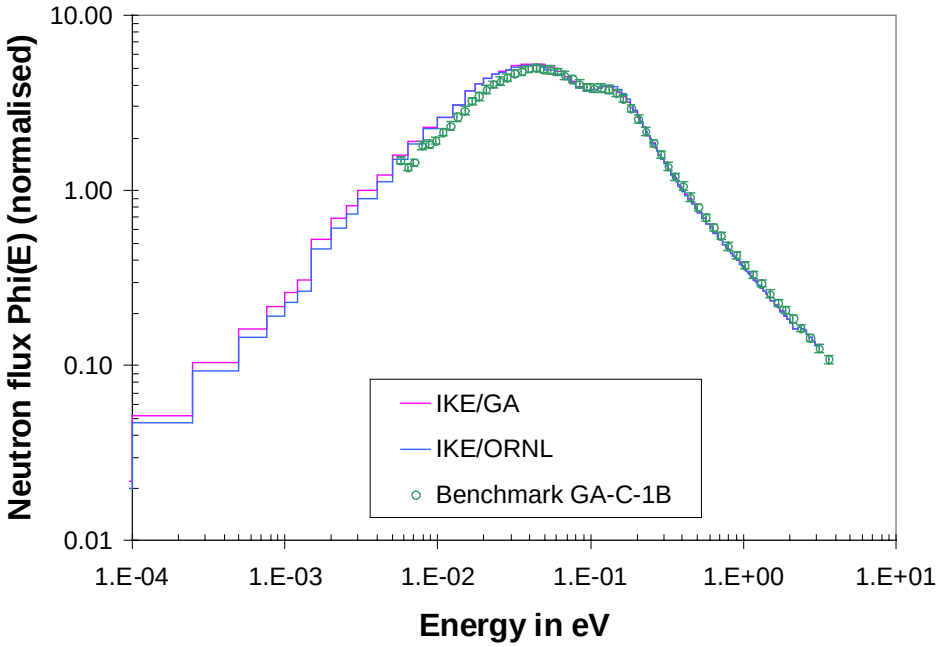

Fig. 14: Neutron flux density spectra for the graphite benchmark GA-C-1B.

The overall agreement of the theoretical spectra is quite sufficient though the B_N-theory cannot describe the geometrical structures quantitatively. Although the neutron temperature of the two theoretical spectra is identical the data set derived from the Gulf GA frequency distribution delivers in the cold neutron energy range a slightly softer spectrum. Therefore it is thought that calculating multiplying systems the k_{eff} for this model would be slightly greater compared with that from the data set of the ORNL frequency distribution.
Discussing the sensitivity of the used Gaussian approximation to the accuracy of calculated neutron flux density spectra in the thermal energy range we can get information from Wikner et al /21/. For large values of α, the systematic error in the use of the Gaussian approximation can be large. We must remember that neutron-scattering events that involve values of $\alpha \geq 1$ play a significant role in establishing the rate at which the thermalisation of neutrons proceeds. Wikner studied systems of an infinite homogeneous mixture of graphite and U^{235} or Pu^{239} having an atom ratio of 5000. For both mixtures the percentage difference in the calculated neutron flux spectra was less than 1.4%, taking the precursor model of the GA distribution, namely that from Yoshimori, Kitano. Generally, this amount is small compared to the accuracy of measurements so that the Gaussian approximation is a tolerable procedure.

In Figure 15 we present our results for the benchmark GA-C-1C at T= 600K.

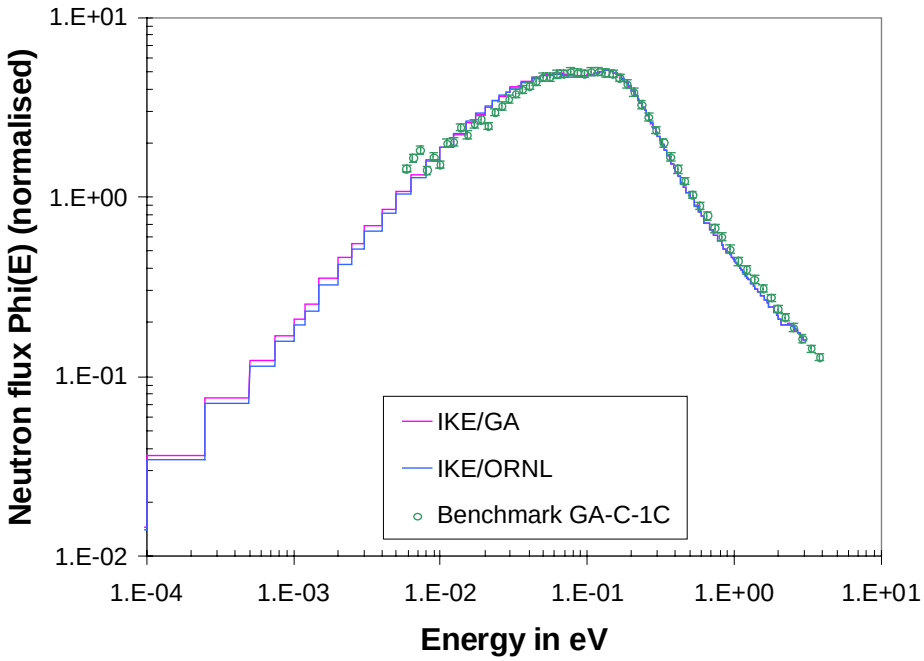

Fig. 15: Neutron flux density spectra for the graphite benchmark GA-C-1C

Compared with the results at room temperature the agreement of the theoretical spectra with the measurement is yet better. Again the IKE/GA model delivers a slightly softer spectrum in the cold neutron energy region but having an identical neutron temperature as the IKE/ORNL model.

In Figure 16 we show neutron flux density spectra calculated for pure graphite but having the same geometry as the two benchmarks. In reality such a composition is not possible because the graphite material always is poisoned more or less with parasitic absorbers. But from aspects of neutron scattering such conditions are valuable for discussing the neutron-nucleus interaction dynamics.

The ratio between the spectra calculated with the IKE/GA model and IKE/ORNL model is shown in figure 17.

Both spectra have the same neutron temperature. But again the IKE/GA data set delivers a slightly softer spectrum in the cold neutron energy domain. Around the Bragg edge near 2 meV one can clearly see the effect of coherent elastic neutron scattering.

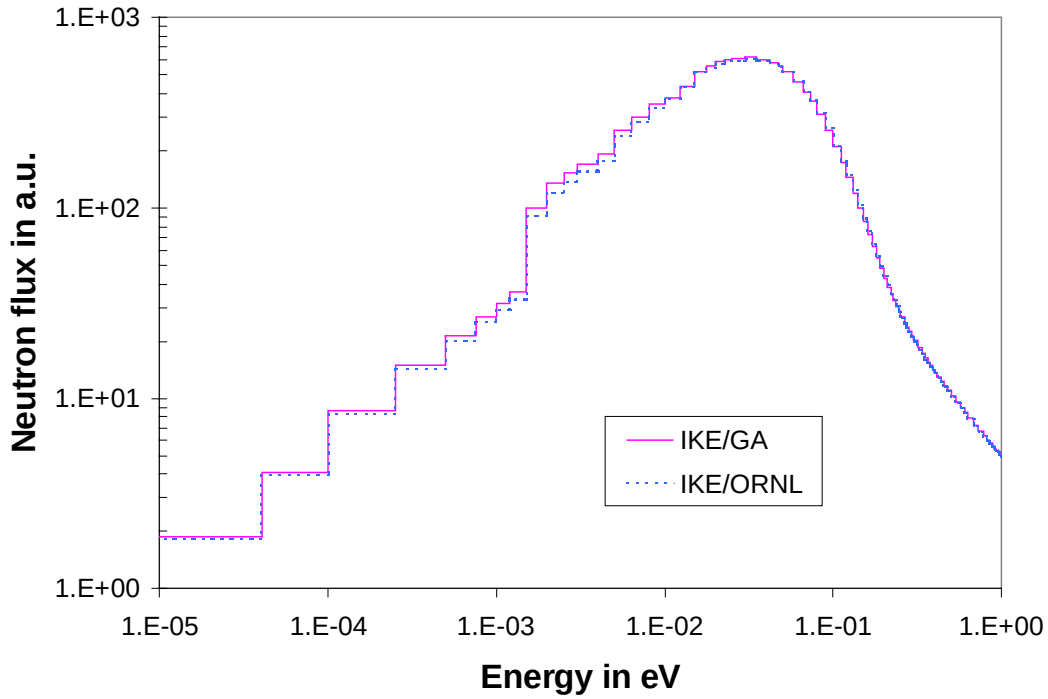

Fig. 16: Finite medium neutron flux density spectra in pure graphite at room temperature

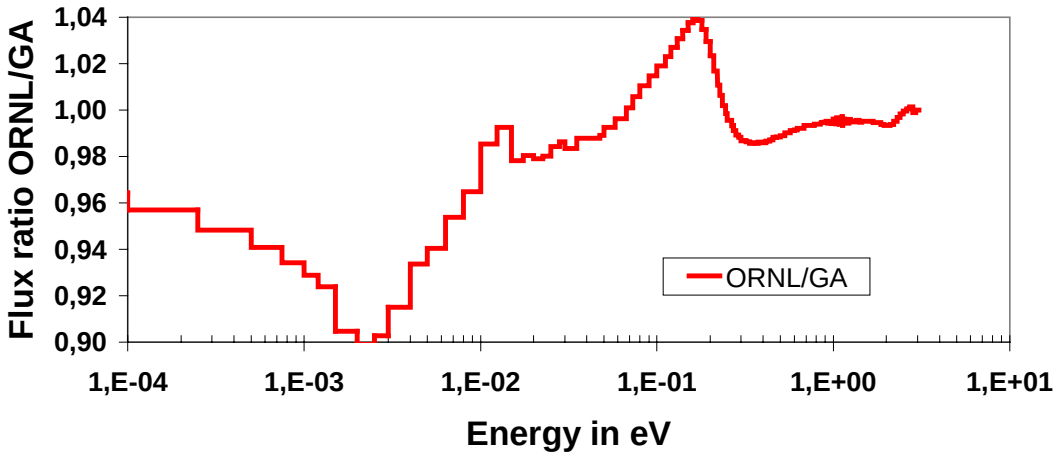

Fig. 17: Ratio of the neutron fluxes generated with the data sets IKE/GA and IKE/ORNL for pure graphite at room temperature

In studying the effect of neutron multiplication in fissionable systems we have recalculated lattices using $^{233}UO_2$-ThO_2 in graphite /31/. In Table 1 our results are compared with the experimental values. Among the published temperatures we have considered the room temperature and 1023K. For both temperatures the data sets IKE/GA and IKE/ORNL for graphite give identical infinite medium multiplication factors. The agreement with the experimental values is quite good. The differences of 0.25 % for room temperature and 0.06 % for 1023 K may be caused by an unknown content of parasitic absorbers in the graphite and an approximated consideration of the extension of the core structure due to the strong temperature increase.

Table 3: Experimental and calculated $k_\infty(T)$ values for a $^{233}UO_2$-ThO_2 HTGR lattice with C/Th=193 and C/ ^{233}U =10470

Temperature in K	Experiment	IKE/GA	IKE/ORNL
293.6	1.0587±0.0014	1.0626	1.0626
1023	1.0245±0.0011	1.0228	1.0229

The fact that the calculated results for the two temperatures agree completely is in contradiction to the remarks of Difilippo /12/ who stated differences up to 0.26 % with their own data sets in recalculating experiments. We suppose the disagreement to be funded in the prepared thermal neutron data libraries in ENDF-6 format. As we have shown for the Scattering law data the chosen α,β-grid and a very strong correlation to the frequency distribution of the moderator is very important. We have no information about the ORNL files but compared to the generated files for ENDF/B-VI our α,β-grid is superior because it contains all multi-phonon excitations of the maxima and minima of $\rho(\omega)$ and the α-range is extended to very small values.
From point of view of our comparisons for the neutron scattering cross sections the different data sets prove sensitivities of some percent. Therefore we have not expected large consequences for neutron flux density spectra or reactivities of multiplying systems.

4. Conclusions

For reactor-grade polycrystalline graphite the neutron-scattering nucleus dynamics was re-evaluated considering new proposals from ORNL concerning the temperature coefficient of graphite moderated HTR. The effect of the basic frequency distribution proposed by Difilippo et al on differential and integral neutron cross sections as well as neutron density flux spectra was compared to that of the approved phonon spectrum of Gulf GA which was taken for the standard data sets in ENDF-6 format of ENDF/B-VI or JEF-2.2. In our formerly study we have shown that the normally temperature dependent phonon spectra derived from measured double-differential neutron cross sections are not favourable to describe all aspects of neutron scattering and neutron thermalisation. So we have reduced our study to the comparison of results generated with the two theoretical models for $\rho(\omega)$ of ORNL and Gulf GA. For differential and integral neutron cross sections both models give very good agreement within the published accuracy of measurement. But the overall agreement of the Young, Koppel distribution seems to be slightly better than the ORNL spectrum which also does not reproduce the measured specific heat in the temperature range from room temperature to some hundred degrees very well. Discussing the effect for double-differential neutron scattering data one can say that the GA distribution slightly underestimates the quasielastic neutron scattering. But for the inelastic scattering the general agreement is better than with the ORNL model. Generating new thermal neutron data sets proposed for JEFF-3 we can say that compared to the data sets of JEF-2.2 the better choice of the α,β-grid for the Scattering law data influences integral scattering cross sections especially in the cold neutron energy range up to some percent.

For neutron thermalisation the measured neutron flux density spectra in pure and Sm poisoned graphite are very well reproduced by the both generated AMPX data sets. Both theoretical spectra agree in neutron temperature but the IKE/GA data sets give slightly softer spectra in the cold neutron energy range. But we do not expect great differences in the temperature coefficient of reactivity for multiplying systems.

Because of lack of measured differential neutron scattering cross sections (known as angular distributions) we could not examine the use of the incoherent approximation for the generated Scattering law data for inelastic neutron scattering. But as assumed from the measured Scattering law curves the coherent inelastic neutron scattering influences the shape of them. Unfortunately, no computer code is known nor available to us to handle the inelastic coherent neutron scattering in providing such Scattering law data. In the past some studies were done (Marshall, Stuart /30/) for polycrystalline aluminium and magnesium to estimate the influence of the incoherent approximation. They have shown that the error for integral scattering cross sections will be less than 3% for energies greater some meV. For cold neutron energies the error will be increased slightly. The amount of the error of course is influenced by the ratio of the free coherent and incoherent standard cross sections. Nevertheless, we conclude that it is quite unlikely that interference effects significantly influence thermal neutron flux density spectra in graphite.

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