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INTERNATIONAL NUCLEAR DATA COMMITTEE

PROGRESS REPORT

FROM THE GERMAN DEMOCRATIC REPUBLIC

TO THE

INTERNATIONAL NUCLEAR DATA COMMITTEE

Compiled by D. Seeliger

December 1987

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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C O N T E N T S

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1. Review on nuclear data activities 1986/87

The present report contents a brief review on nuclear data activities in the German Democratic Republic during the period between the XV-th and the XVI-th INDC meetings. This review includes

- abstracts of the most important current nuclear data investigations,
- a bibliography of recent publications and
- a compilation of some original contributions showing the most important results obtained.

In addition to the present progress report the "Annual Report on Nuclear Physics Activities and Applications", ZfK-584, was distributed to the INDC-participants (with the document number INDC(GDR)-046/G) recently. This report contains a complete description of nuclear physics research in the GDR including nuclear data related work together with a complete bibliography.

The national nuclear data coordination group "Arbeitsgemeinschaft Kerndaten" continued its work directed to fulfil the nuclear data requirements of industry as well as different research institutes.

The sequence of the traditional International Symposia on Nuclear Physics organized by the Technical University Dresden was continued with the XVI-th ISNP-Heavy Ion Reactions, Gaussig, November 1986 (the proceedings will be available soon).
The proceedings of the previous meeting, the XV-th ISNP-Nuclear Fission, Gaussig, November 1985, ZfK-592, have been distributed to the INDC members as the document INDC(GDR)-042/G.

Additionally, in co-operation with the IAEA Nuclear Data Section there was organized the Advisory Group Meeting on Nuclear Data for Fusion Reactor Technology, Gaussig, December 1-5, 1986.
The proceedings of this meeting will be published as an IAEA-TECHDOC-publication.

The following data oriented programmes are running at present in the TU Dresden and ZfK Rossendorf in the following directions:

- experimental and theoretical investigations of the 252-Cf spontaneous fission neutron spectrum (nuclear data standard) (TUD);

- measurements of absolute fission cross sections using the TCAPM (TUD);
- measurements and theoretical analyses of DDCS for neutron emission for Pb, 238-U and Ta (TUD);
- development of nuclear reaction models including their tests for 93-Nb and 56-Fe (TUD);
- measurements and theoretical analyses of neutron induced fission neutron and gamma ray emission spectra and angular distributions (TUD and ZfK);
- fusion reactor oriented macroscopic experiments with spheres and blanket assemblies (TUD and ZfK);
- investigations of the influence of lattice vibrations on neutron resonance parameters (TUD);
- calculations of electron shell data for highly ionized atoms (TUD);
- determination of averaged capture cross sections in a zero-power reactor using the pile-oscillator method (ZfK);
- test of different nuclear data libraries for power reactor calculations (ZfK, TUD and others).

The Nuclear Physics Department of the TUD participated in the three IAEA Coordinated Research Programmes on

- level densities
- structural materials and
- 14 MeV neutron nuclear data.

Nuclear and Atomic Data research is carried out in cooperation with the

- IPPE Obninsk
- RI Leningrad
- IAE Moscow
- JINR Dubna
- CRIP Budapest
- Univ. Debrecen
- Univ. Moscow
- IP Bratislava
- INRNE Sofia
- Univ. Frankfurt
- PTB Braunschweig and others.

Of special importance was the close cooperation with the IAEA Nuclear Data Section, which now continues over more than ten years.

Thanks are expressed herewith for a fruitful cooperation to our colleagues from all the institutes mentioned above.

Extended Cascade Evaporation Model and Applications

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The CASCADE EVAPORATION MODEL (CEM)[1] is a complex statistical-model approach to prompt-neutron emission in fission based on the assumption that all fission neutrons are evaporated from fully accelerated fragments. Initial distributions in excitation energy E^x are considered as a function of mass asymmetry A_L/A_H and total kinetic energy TKE of the fragments. Here, the averages $\overline{E^x}(A,TKE)$ have to satisfy the energy balance condition according to the average energy release for a given mass split. The inverse cross section of compound-nucleus formation σ_c is calculated on the basis of a global parametrization of the optical potential yielding a data matrix depending on neutron energy and A. A systematic study of different semi-empirical potentials in CEM applications to $^{252}Cf(sf)$ neutron emission has been finished.[2] We make use of the level density description proposed by Schmitt et al.[3] (including shell and pairing corrections both depending on excitation energy). The center-of-mass system CMS anisotropy due to the fragment angular momentum I is taken into account as a function of A on the basis of average $\bar{I}(A)$ applying a semi-classical approximation.[4] The competition between neutron emission and γ-ray de-excitation is considered by calculating the widths Γ_n and Γ_γ, respectively, depending on E^x and $\bar{I}$.
Using the extended CEM energy and angular distributions $N(E,\Theta)$ of $^{252}Cf(sf)$ neutrons measured in the full 100 keV - 10 MeV / 0 - π range recently[5] have been reproduced satisfactorily.
Specifically, the crucial polar $N(E,\Theta)$ regions corresponding to low-energy neutron emission in the CMS agree with experimental data. Note that the CEM doesn't include any free parameters or arbitrary normalizations. The $^{252}Cf(sf)$ neutron energy spectrum (nuclear standard)[6] can be described quite well in the wide energy range from 1 keV to 20 MeV.

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Energy and angular distributions of ^{252}Cf(sf) neutrons

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A. Lajtai
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A new experimental method[1,2] has been applied to measure the double-differential emission probability of Cf fission neutrons between 100 keV and 10 MeV. The neutron-fragment correlation experiment has been based on neutron time-of-flight spectroscopy combined with a direction-sensitive method of fragment spectroscopy. The angular distributions obtained cover the whole range from 0 to π. The analysis (including data correction) of the data measured in two different experiments, viz.

- (at low energy) by the use of ^{6}Li glass scintillators and
- (at intermediate and high energy) by the use of NE 213 scintillators with pulse shape discrimination,

has been finished. They provide the basis for the further development of theoretical models of prompt-neutron emission in fission. Specifically, the cascade evaporation model (CEM) has been extended.[3] This statistical-model approach (based on the assumption that all neutrons are evaporated from the fully accelerated fragments) is suitable to reproduce the experimental data. There is no indication of a "central component" of fission neutrons[4] due to neutron emission close to the scission point. The upper limit of the yield of such neutrons has been found to be 5 %. However, the characteristics of possible secondary mechanisms of fission neutron emission are not clear. Recent theoretical investigations[5,6] of particle emission in fission indicate a preference of polar emission. Neutron evaporation during fragment acceleration has been studied in the framework of a modified CEM[7] showing the strong influence of the energy dissipation mechanism.

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ENERGY AND ANGULAR DISTRIBUTIONS OF ^{252}Cf(S.F.) NEUTRONS

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The energy and angular distribution N(E,θ) of ^{252}Cf (S.F.) neutrons (N) has been investigated using N time-of-flight technique (NE 213,N/γ discrimination) in conjunction with a direction-sensitive method of fragment (FF) spectroscopy. Both a single and a position-sensitive parallel-plate avalanche counter serve for the measurement of FF direction and FF time of flight. This new type of N-FF-correlation experiment is suitable to measure N(E,θ) in the full θ range (θ=0(1.5) 180 deg) with high precision.

Complex statistical-model approaches are used to calculate N(E,θ) assuming N evaporation from fully accelerated FF: (i) the cascade evaporation model (CEM)[1] and (ii) the generalized Madland-Nix model (GMNM)[2]. As an example, Fig. 1 shows the measured N(E=2 MeV,θ) distribution in comparison with both theories. The measured anisotropy ratios (polar/equatorial) are much higher (up to five times) than the values of Ref. 3 at high energy (> 3 MeV). Within the uncertainties of experiment and theory, no significant indications of secondary emission mechanisms have been found.

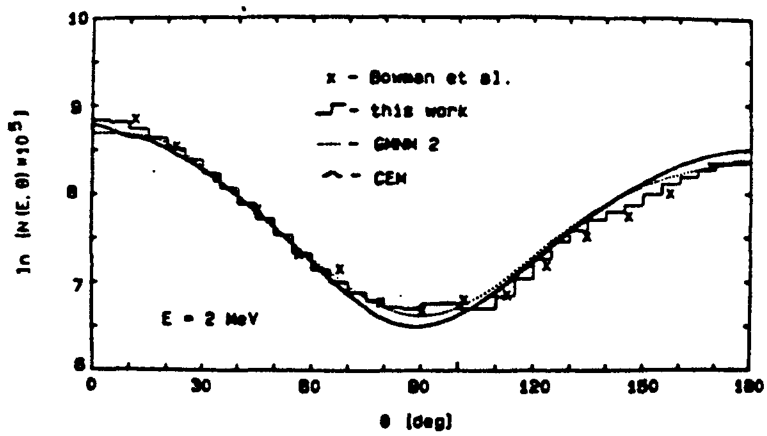

Fig. 1. Angular distribution at E=2 MeV in comparison with complex statistical-model approaches (see text).

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Internat. Conf. Nucl. Phys., Harrogate, 1986

Generalized Madland-Nix Model - Extensions and Applications

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The Generalized Madland-Nix Model (GMNM)[1] is a statistical-model approach to fission neutron emission for applied purposes. It has been combined with a scission point model including semi-empirical shell effects[2] for the prediction of necessary fragment data (kinetic energy, excitation energy) as a function of fragment mass number. Fragment mass yield curves are described semi-empirically on the basis of a 5-Gaussian approximation[3] with parameters depending on the fission reaction and incidence energy. In the case of multiple-chance fission reactions, all the calculations are carried out for the different chances separately in conjunction with a statistical-model analysis[4] of the partial fission cross sections and scattered-neutron cross sections. Compared with the first description of the GMNM[1], the following extensions have been introduced:

- lower limit of the temperature distribution (to account for neutron-γ-competition approximately),
- anisotropy of fission neutron emission in the center-of-mass frame of the fragments,
- use of a semi-empirical level density parameter set,[5]
- calculation of double-differential lab. frame distributions N(E,Θ) in neutron energy and emission angle (with reference to light-fragment direction),
- N(E,Θ) transformation into the emission cross section with reference to incident-particle direction (on the basis of a semi-empirical description of fragment anisotropy as a function of incidence energy).

The complex theoretical scheme provides the basis for the consistent description of fragment data and neutron data for any induced fission reaction in the Th-Cf region. Several applications to neutron-induced fission reactions for incident energies up to 15 MeV have shown that the theoretical results are in quite good agreement with experimental data.[6]

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Scission Point Model with Semi-empirical Shell Correction Energies

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Fission models known don't yield a sufficiently accurate description of fission fragment data (kinetic energy, excitation energy). Therefore, a simple scission point model (two-spheroid model TSM) based on previous studies by Terrell[1] has been used to deduce deformability (stiffness) parameters from well-known fragment data depending on mass asymmetry (Cf, U, Pu). These parameter sets can be related to shell correction energies of deformed fragments at scission accepting the semi-empirical relation proposed by Kildir and Aras.[2]
After their reduction to zero-temperature at scission[3], shell energy sets (as a function of fragment mass number) have been obtained. They agree with Strutinski type calculations qualitatively and reflect the influence of particular closed-shell regions (including deformed shells).[4] The scission point temperature has to be deduced from the sum of the excess excitation energy above the fission barrier (in the case of induced reactions) and an energy amount due to the dissipation during the descent from saddle point to scission. The shell correction energy sets deduced for several well-investigated fission reactions are quite similar. After interpolation and temperature reduction of the shell energies, the inverse scheme described above can be used to calculate fragment energies depending on mass asymmetry for any fission reaction in the Th-Cf region. Using the TSM measured trends[5] of fragment energies and neutron multiplicities as a function of incidence energy have been reproduced. Therefore, the TSM provides a possible basis for the evaluation of fragment data as well as prompt fission neutron data (additional application of a statistical-model approach to fission neutron emission). In the case of multiple-chance fission reactions at sufficiently high incidence energy, the TSM is applied to all possible partial reactions assuming average compound-nucleus excitation energies.

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Revised results of absolute fission cross-section measurements on ^{239}Pu at 4.9 MeV, 8.65 MeV, 14.7 MeV and 18.8 MeV neutron energy

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Absolute measurements of the ^{239}Pu fission cross-section have been carried out at a neutron generator of the TU Dresden and at the tandem van-de-Graaff accelerator of the CINR Rossendorf (GDR) in 1977-1985, using the time-correlated associated particle method (TCAPM) at selected neutron energy spot points /1,2/.
By modifiing the method of P.H. White /3/ and based on the analysis of the fission chamber pulse height spectra, experimental investigations at the PuF_4 fission foils led to absorption corrections of the several fission targets which are 2.7-4.7% higher than the values calculated with the assumed fission fragment range of 7.5 mg/cm^2.
Furthermore, the absolute areal density and nonuniformity of the fission deposites were checked by measurements of the alpha-activity, that correspond to the older results.
Consequently, the correction of the preliminary data published earlier e.g. in /1,2/ results in higher cross-section values: 1.800 ± 0.039 b, 2.433 ± 0.050 b, 2.488 ± 0.038 b and 2.512 ± 0.068 b at 4.9 MeV, 8.65 MeV, 14.7 MeV and 18.8 MeV neutron energy, respectively.
Following these results, a revision of the current ^{239}Pu fission cross-section data files is indicated.

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Absolute measurements of the ^{238}U fission cross-section at 4.8 MeV, 8.4 MeV and 18.8 MeV neutron energies using the TCAPM

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The ^{238}U fission cross-section is considered as the most favourable neutron cross-section standard in the energy region which is important for fusion technology. But there is a lack of experiments determining this cross-section absolutely without any reference to the $^{235}U(n,f)$-standard.

Such kind of absolute measurements were carried out at the tandem van-de-Graaff accelerator of the CINR Rossendorf (GDR) in 1985-1986, using the time-correlated associated particle method (TCAPM). Because of the progress in the neutron flux production and its absolute determination, the properties of the fission deposits became the restrictive factor of the experimental accuracy.

The nonuniformity of the fission foils was determined by Rutherford backscattering measurements with 1.7 MeV ^{4}He-ions. Experimental investigations to check the absolute foil density and the correction of fission fragment counting losses within the foil are in progress. The preliminary data are in good accordance with the ENDF-B/V file and result in values of 0.551 ± 0.016 b, 1.022 ± 0.019 b and 1.351 ± 0.039 b at 4.8 MeV, 8.4 MeV and 18.8 MeV neutron energy, respectively.

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Determination of fission fragment counting losses from the fission chamber spectrum

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The application of fission chambers as fission detectors in nuclear data measurements, but also as neutron flux detectors, requires an accurate determination of the fission fragment detection efficiency. Chemical modifications or contaminations of the target material, the non-linear plateau shap in the fission chamber spectrum near pulse height zero and the influence of surface properties of the backing or microscopic structures within the fission foil are sources of additional counting losses which are considered usually neither in the correction procedure nor in the error estimate. But especially by using extremly thin fission foils, these effects can become the dominating factors of the fragment absorption.
By means of analytic calculations and Monte-Carlo codes the plateau height of the fission chamber spectrum was proved to be a realistic measure of the total counting losses including the effects mentioned above, if surface structures with characteristic dimensions of the fission fragment range can be excluded. In this case, the ratio of the total fission fragment counting inefficiencies of different plane target arrangements analysing isotropic fission is equivalent to the ratio of the corresponding plateau heights, which can be measured easily.

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ATOMIC DATA FOR NEUTRAL AND IONIZED ATOMS

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For the use in basic and applied research an atomic data library with atomic emission and structure data was developed under using the EC 1055/56 computer facility. In the recent time the data files contain for all elements up to uranium or neptunium

- X-ray transition data (transition energies, emission rates, energetic transition widths)
- orbital data (electron binding energies, level widths, fluorescence yields)
- attenuation coefficients in the region from 1 keV up to 150 keV as numerical data and as parameters for data fitting.

The data are stored in a generalized format that allows an optimal data handling considering the features of atomic data sets. All data are available in form of computer listings or as files on magnetic tape. Several subroutines are decided for data evaluation and graphical representation.
As a next step we develope in near future conditions for the creation of Auger data files.
For special applications computer codes for calculations of radiative and radiationless transition probabilities are developed and successfull tested for various configurations of neutral and ionized atoms.

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Nuclear Instr.Methods, B23 (1987) p.278

Neutron data check for fission product nuclides and structural materials

B. Böhmer, K. Dietze, K. Fährmann, G. Hüttel, H. Kumpf, E. Lehmann
(Akademie der Wissenschaften der DDR, Zentralinstitut für Kernforschung Rossendorf)

Based on the highly sensitive pile oscillator method effective absorption cross sections of some fission product nuclides and structural materials in two special fast - thermal coupled systems (RRR/SEG-IV, RRR/SEG-V) have been measured and compared with calculated ones.
The systems were characterized by an energy independent adjoint flux so that the reactivity worths could be directly interpreted as flux weighted absorption cross sections with reference to the standard materials ^{10}B and ^{235}U. Moreover, the dependence on sample size enabled conclusions with respect to resonance self-shielding coefficients.
In this way, group data generated from data files (ENDF(B), JENDL, ENDL, UKNDL, KEDAK) and standard data sets (ABBN, JFS, BARC) for 13 fast breeder fissionproduct nuclides (^{93}Nb, ^{149}Sm, ^{153}Eu, $^{95,97,98,100}Mo$, ^{103}Rh, ^{105}Pd, ^{109}Ag, ^{133}Cs, $^{143,145}Nd$) , stainless steel components (Fe, Cr, Ni, Mo, Mn, Co, W) and some other reactor materials (^{238}U, C, Ta, V, Zr, Cd, Ti, Ca, Al, Pb, Na) have been checked. The obtained results demonstrate inadmissible discrepancies in many cases still to exist.

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THE NEUTRON MULTIPLICATION OF LEAD AT 14 MeV NEUTRON INCIDENCE ENERGY

By T. Elfruth, D. Seeliger, K. Seidel, G. Streubel, S. Unterholzer, D. Albert, W. Hansen, K. Noack, C. Reiche, W. Vogel, D.V. Markovskij and G.E. Shatalov

Abstract

Neutron leakage spectra were measured with time-of-flight and with proton recoil spectroscopy and activation and fission rates were determined for a lead sphere of 4.1 mean-free-path shell thickness fed in its centre with 14-MeV neutrons. The results are compared with calculations based on recent data files and are discussed in connection with previous lead benchmarks. About 10 % more neutrons are observed than predicted by calculations.

(Full article available in "Atomkernenergie-Kerntechnik 49(1987)121-125")

NUCLEAR STRUCTURE AND DIRECT REACTION MECHANISM IN NEUTRON SCATTERING ON ^{28}Si IN THE ENERGY RANGE 6.8 TO 14.8 MeV

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Abstract

The structure of excited states in ^{28}Si as well as the energy dependence of the reaction mechanism are investigated. Angular distributions related to the 0^+_1, 2^+_1, 4^+_1, 0^+_2, 3^+_1, $2^+_2 + 2^+_3$, $3^-_1 + 4^+_2$ levels in the ^{28}Si(n,n') reaction were measured at incident energies 6.8, 7.0, 8.0 ... 12.0 MeV. The analysis was extended up to 14.8 MeV bombarding energy. The experimental cross sections are described by means of a coupled-channel calculation including compound nucleus contributions. The low-lying excited states can be interpreted by a rotational model with prolate but also with oblate g.s. deformation. For the higher-lying states various coupling schemes have been tested. Especially, a second rotational band could be described adopting an oblate deformation.

(Full article available in "Nucl.Phys.A460(1986)265-298")

HYDROGEN AND DEUTERIUM MEASUREMENTS BY ELASTIC RECOIL DETECTION USING ALPHA PARTICLES

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Abstract

This paper presents recoil cross sections for both H and D for alpha particle bombardment in the energy range of 1.6 to 3.4 MeV. For hydrogen and deuterium, a non-Rutherford cross-section was found. For deuterium, a resonance at 2.15 MeV with fwhm of 75 keV was obtained.

Calculations were carried out to find the geometrical arrangement where the maximum information concerning the probing depth can be obtained in the energy range of 1-10 MeV.

In contrast to the generally accepted 30° scattering angle, another configuration is suggested.

(Full article available in "Nucl.Instr.&Meth. B15(1986)486-491")

A SYSTEMIZATION OF X-RAY ENERGIES AND ELECTRON BINDING ENERGIES IN FREE HIGHLY CHARGED IONS

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Single-configuration Dirac-Fock-Slater calculations in the frozen core approximation are carried out for elements up to uranium for all ion ground states to determine X-ray energy shifts and electron binding energy changes in ionized atoms. A summary of the expected energy shifts for the most intense lines and for selected orbitals is discussed. Dependent on the specific electronic configuration, characteristic changes in the gradient of the energy shifts appear. For some configurations the tendency in the X-ray satellite energy shift changes from shifts to the high-energy side of the diagram lines on the low-energy side.

(Full article available in "Nucl.Instr.&Meth. B23(1987)278-283")

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STATISTICAL MULTISTEP DIRECT AND COMPOUND PROCESSES BELOW 30 MEV

FOR 93-NIOBIUM

(Int. Conf. Neutron Physics, Kiev, 1987)

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Abstract

A simple reaction model for statistical multistep direct (SMD) and multistep compound processes (SMC) including quasiparticle and phonon exitations is presented and tested on 93-Nb(n,n') and (n,p) at incidence energies between 5 and 20 MeV.

1. The model

The double-differential emission cross section of this model described in detail elsewhere /1/ is given by

$$\frac{d^2\sigma_{\alpha\beta}(\varepsilon)}{d\varepsilon' d\Omega'} = \frac{1}{4\pi}\left[\frac{d\sigma^{SMC}_{\alpha\beta}(\varepsilon)}{d\varepsilon'} + \frac{d\sigma^{SMD}_{\alpha\beta}(\varepsilon)}{d\varepsilon'}\sum_L (2L+1)a_L(\varepsilon)P_L(\cos\theta')\right] \quad (1)$$

where the incidence nucleon of type $\alpha = \pi$ or ν (proton or neutron) has the kinetic energy ε, and β, ε' refer to the outgoing particle. Here, the SMC-process,

$$\frac{d\sigma^{SMC}_{\alpha\beta}(\varepsilon)}{d\varepsilon'} = \sigma^{SMC}_{\alpha}(\varepsilon)\sum_{n_0=5}^{\bar{n}} \tau_n \Gamma_{n\beta}(\varepsilon')\uparrow \quad (2)$$

is calculated beginning at exiton number $n_0 = 5$ up the equilibrium stage $\bar{n} = (2gE)^{1/2}$. $g = A/13$ and $E = \varepsilon + \tilde{B}_\alpha$ are the single particle state density and excitation energy. The mean life time τ_n is taken from the time integrated (up to $t = \infty$) master equation.

The damping and escape widths are given by the Golden Rule,

$$\Gamma_n^{(\Delta n)}\downarrow = 2\pi\,(3/8)\,\overline{V_{bb}^2}\,\rho_n^{(\Delta n)} \quad , \qquad \Delta n = -2;2 \tag{3}$$

$$\Gamma_{n\beta}^{(\Delta n)}(\varepsilon')\uparrow = 2\pi\,\overline{V_{bu}^2}(\varepsilon')\,\rho_{n\beta}^{(\Delta n)}(U)\,P_\beta(\varepsilon') \quad , \qquad \Delta n = -2;0;2 \tag{4}$$

The factor 3/8 in (3) reduces a two-component to an one-component master equation /2/, whereas the penentration factor P_β in (4) is 1 for neutrons and $\sigma_\pi(\varepsilon')/\sigma_\nu(\varepsilon')$ for protons, and $\sigma_\alpha(\varepsilon')$ are the reaction cross section of particle-type $\alpha = \pi$ or ν. By using (4) there is no reference to the detailed balance principle or inverse cross sections in this model.

The final state densities $\rho_{n\beta}^{(\Delta n)}(U)$ are calculated in two steps: at first, the diagram method /3/ with distinction between protons and neutrons is used, and in the second step the formulas are reduced by a binominal ansatz /2/ to the one-component form. In (3) and (4) the Pauli principle is considered by the usual energy shift. Pairing and shell-effects as well as bound/unbound restrictions are ignored throughout.

With the approximation

$$\overline{V_{bu}^2}(\varepsilon') = \overline{V_{bb}^2}\,\rho(\varepsilon') \tag{5}$$

the bound-unbound matrix element is reduced to a bound-bound one. Here,

$$\rho(\varepsilon') = (2s+1)\,4\pi V_N\, m\,(2\pi\hbar)^{-3}\, m\,(2m\varepsilon')^{1/2} \tag{6}$$

is the state density of a particle in the nuclear volume $V_N = 4\pi r_0^3 A/3$. In this way all $\overline{V_{bb}^2}$ in (2) cancel and the

SMC-model becomes free of matrix elements, i.e., the shape of the SMC-emission is independent of matrix elements at all. Its absolute value is only determined by the "normalization constant"

$$\sigma_{\alpha}^{SMC}(\varepsilon) \equiv \sigma_{\alpha}(\varepsilon) - \sum_{\beta} \sigma_{\alpha\beta}^{SMD}(\varepsilon) \tag{7}$$

which is the difference between the reaction cross section and the energy integrated SMD-cross section.

In (2) the SMC-emission (from $n \geqq 5$) is assumed to be isotropic. The anisotropy comes only from the single- and two-step processes of SMD, whereby the reduced Legendre coefficients $a_L(\varepsilon')$ are taken from the the Kalbach-Mann systematics /4/.

The basic formulas for the SMD-processes are already given by Feshbach e.a. /3,5/. Assuming an adiabatic behaviour of the target nucleus, i.e., the accessible final state density will be the same after each collision, the single- and two-step processes can be written as

$$\frac{d\sigma_{\alpha\beta}^{(1)}(\varepsilon)}{d\varepsilon'} = \frac{2\pi V_N}{\hbar v_\alpha} \frac{1}{2\pi^2} W_{\alpha\beta}(\varepsilon,\varepsilon') \tag{8a}$$

$$\frac{d\sigma_{\alpha\beta}^{(2)}(\varepsilon)}{d\varepsilon'} = \frac{2\pi V_N}{\hbar v_\alpha} \frac{1}{2\pi^2} \sum_{\gamma=\pi,\nu} \int \frac{\rho(\varepsilon_1)}{4\pi} W_{\alpha\gamma}(\varepsilon,\varepsilon_1) W_{\gamma\beta}(\varepsilon_1,\varepsilon') d\varepsilon_1 . \tag{8b}$$

Multiplying (8) by $P_\alpha(\varepsilon)P_\beta(\varepsilon')$ coulomb effects caused by protons in the entrance and/or exit channel are considered.

In contrast to the SMC-processes in the SMD-part we include besides the excitation of non-collective particle-hole states (excitons) also the excitation of low lying collective modes (phonons) /6/. Therefore the transition probability $W_{\alpha\beta}$ is the sum of two contributions,

$$W_{\alpha\beta}^{(ex)}(\varepsilon,\varepsilon') = 2\pi^2 \left\{ \delta_{\alpha\beta} + (1-\delta_{\alpha\beta}) \frac{N\delta_{\beta\nu} + Z\delta_{\beta\pi}}{A} \right\} \overline{V^2}(\varepsilon,\varepsilon') \left(\frac{g}{2}\right)^2 (\varepsilon - \varepsilon' + B_\alpha - B_\beta) \tag{9a}$$

$$W_{\alpha\beta}^{(ph)}(\varepsilon,\varepsilon') = 2\pi^2 \delta_{\alpha\beta} \sum_\lambda \varkappa_\lambda \overline{V^2}(\varepsilon,\varepsilon') \delta(\varepsilon - \varepsilon' - \omega_\lambda) \tag{9b}$$

with the abbreviation

$$\varkappa_\lambda \equiv (\beta_\lambda^2 / \sum_\lambda \beta_\lambda^2) \varkappa . \tag{10}$$

In this simple approximation the relation between the exciton and phonon mean square matrix elements is given by an energy-independent constant $\varkappa$. β_λ denotes the deformation parameter of multipolority λ at energy ω_λ.

The unbound-unbound matrix element $\overline{V^2}(\varepsilon, \varepsilon')$ can be approximated /1/ by an unbound-bound one

$$\overline{V^2}(\varepsilon,\varepsilon') \simeq \overline{V^2}(\varepsilon) g(\varepsilon') \tag{11}$$

if $g(\varepsilon')$ is given by (6).

The energy dependence of $\overline{V^2}(\varepsilon)$ can be obtained directly from the (optical model) reaction cross section for neutrons, $\sigma_\nu(\varepsilon)$. The latter is splitted into a (direct) single-step and a multistep contribution,

$$\sigma_\alpha(\varepsilon) = \sum_{\beta=\nu,\pi} \sigma_{\alpha\beta}^{(1)}(\varepsilon) + \sigma_\alpha^{(M)}(\varepsilon) . \tag{12}$$

$\sigma_\alpha^{(M)}$ includes all processes in which the incomming particle prduces a composite system, and which decay by further collisions to more complex states. Ignoring bound/unbound restrictions in the final state densities all multistep processes (without SMC/SMD-distinction) are considered in , which is given by

$$\frac{2\pi V_N}{\hbar v_\alpha}\left[\left(\frac{A+Z\delta_{\alpha\nu}+N\delta_{\alpha\pi}}{2A}\right)\left(\frac{g}{2}\right)^2\frac{E^2}{2}+\sum_\lambda \varkappa_\lambda\right]\overline{V^2}(\varepsilon)\left(\frac{g}{2}\right) . \qquad (13)$$

2. Results

The following input values are taken for the neutron induced reaction on 93-Nb: B_ν = 7.26 MeV, B_π = 6.57 MeV, r_0 = 1.2 fm. Only three low-lying phonon states are considered (λ^π= 2^+, 3^-, 4^+; ω_λ= 0.93, 2.34, 3.39 MeV; β_λ = 0.13, 0.16, 0.11) which are taken from 92-Zr /7/. All delta functions in (9b) are replaced by Gaussians of width 1 MeV (and 2 MeV for ε = 26 MeV). For $\sigma_\alpha(\varepsilon)$ the reaction cross section of the OM (Wilmore-Hodgson for neutrons; Becchetti-Greenlees for protons) is used in a parametrized form /8/.

The calculated mean squared matrix element can well be approximated by

$$\overline{V^2}(\varepsilon) = \begin{cases} \text{const}/a \\ \text{const}/\varepsilon \end{cases} \quad \text{for} \quad \varepsilon \begin{matrix} \leq \\ > \end{matrix} a \qquad (14)$$

and a $\simeq$ 10 MeV. This qualitative behaviour is almost independent of $\varkappa$ introduced in (10), if $\varkappa \simeq 300 \div 1000$. We take $\varkappa$ = 700 for all calculations, which turns out to by a upper bound (see Fig. 2).

The calculated neutron spectra at incidence energies ε = 5.2, 7.2 and 9 MeV are depicted in Fig. 1. There is a good agreement with experimental data. For ε = 14 MeV neutron and proton spectra are shown in Fig. 2. The only discrepancy in the low energy part of the neutron spectrum is due-to the neglection of (n, 2n) in our calculations at present. Finally the emission spectrum and the first two reduced Legendre coefficients of the double differential cross section, $f_L = \left(\frac{d\sigma^{SMD}}{d\varepsilon'} \Big/ \frac{d\sigma}{d\varepsilon'}\right) a_L(\varepsilon')$ and L=1,2

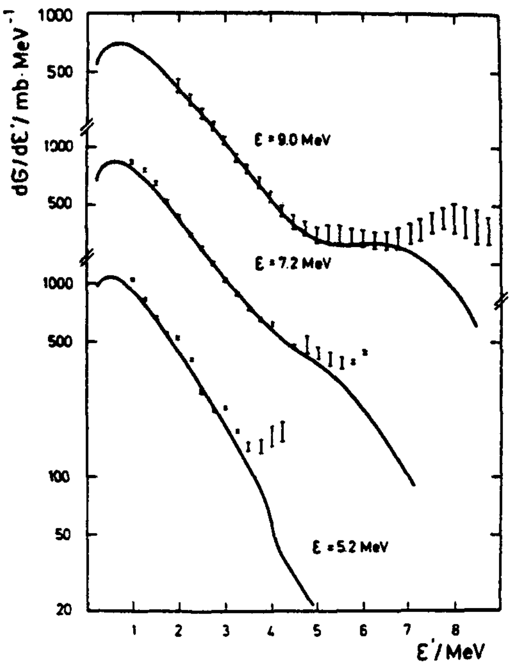

Fig. 1. Energy spectra of 93-Nb(n,n') at incidence energies ε = 5.2., 7.2 and 9 MeV. The broken line denotes the direct single-step contribution. Experimental data from /7,9/.

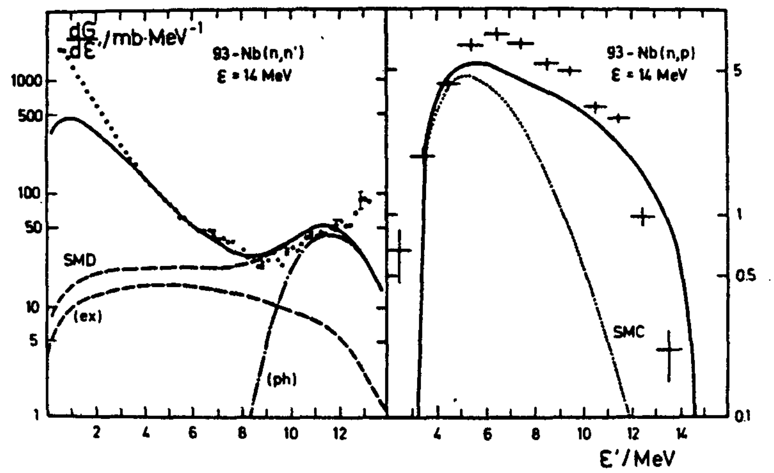

Fig. 2. Energy spectra of 93-Nb(n,n') and (n,p) at 14 MeV. The curves labelled with (ex) and (ph) correspond to the direct single-step excitation of exciton and one-phonon states. The multistep direct and compound contributions labelled with SMD and SMC. The full curve is the sum of SMD and SMC. Experimental data from /10,11/.

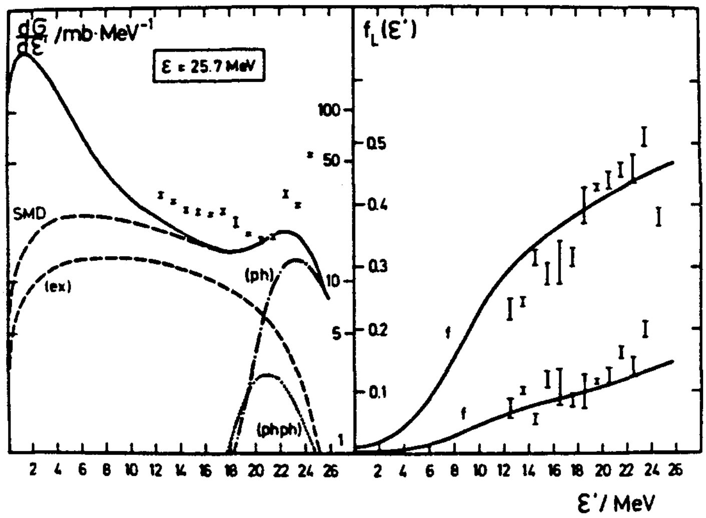

Fig. 3. Energy spectrum and the reduced Legendre coefficients f_1 and $_2$ of 93-Nb(n,n') at 25.7 MeV. The curve labelled with (phph) denotes the contribution of the direct two-phonon excitation. For all other indications see Fig. 2. Experimental data from /12/.

are plotted in Fig. 3.

At high incidence energies ($\varepsilon \gtrsim 20$ MeV) the role of two-step processes of mixing type (in the first step a direct, and in the second step a SMC-process) is still in question. Such SMD/SMC-transitions are discussed in /6/ but ignored in the present model, as yet.

In Table 1 all energy-integrated SMD-contributions for different incidence energies are summarized. The single-step process is divided into a pure exciton and phonon part, denoted by (ex), (ph). In the some way the two-step processes are splitted into four parts: (exex), (exph), (phex), (phph). Also the excitation of three-phonon states are calculated, (phphph).

With increasing incidence energy the direct excitation of phonon states decrease, whereas the contribution of non-collective states increases in this model. Furthermore, the contribution of all direct two-step processes at $\varepsilon \lesssim 10$MeV can be neglected.

The present model reproduces the 93-Nb(n,n') and (n,p) experimental spectra and angular distributions satisfactorily over a broad

Table 1.
Mean square unbound–bound matrix element, neutron reaction cross section, the individual SMD–contributions (in mb) for (n,n'), and the calculated total (n,p) cross section at different incidence energies ε for 93 Nb. For abbreviations we refer to the text.

ε/MeV	5,2	7,2	9,0	14,0	20,0	25,7
$\overline{V^2}(\varepsilon)\ 10^4/MeV^2$	1,94	1,85	1,71	1,31	0,92	0,66
$\sigma_\nu(\varepsilon)$ / mb	2036	1960	1905	1781	1651	1535
(ex)	30,1	54,6	79,3	147	211	149
(ph)	169	166	173	140	102	73,6
(exex)	0	0,2	0,9	10,9	32,1	57,5
2(exph)	0,1	2,5	7,6	49,2	81,8	95,1
(phph)	0,4	7,3	13,6	32,8	24,9	16,9
(phphph)	0	0,1	0,7	6,2	6,0	3,8
$\sigma_{\nu\pi}(\varepsilon)$/mb	1,5	5,8	11,3	36,7	79,7	120

incidence energy range. A particular advantage of this model is its simplicity for practical calculations and its physical consistency. Further work is required to test the model in a broad target mass range.

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ABSOLUTE MEASUREMENTS OF THE U-238 FISSION CROSS-SECTION AT 4.8 MEV, 8.4 MEV AND 18.8 MEV NEUTRON ENERGIES USING THE TCAPM

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Summary

This paper reviews experimental details and preliminary results of absolute measurements, carried out at the CINR Rossendorf by the TU Dresden/RI Leningrad cooperation. Using the Time-Correlated Associated Particle Method (TCAPM), uncertainties of 1.8% and 2.9% were obtained at 8.4 MeV and 18.8 MeV neutron energies, respectively. Because of progresses in the experimental technique, the properties of the fission deposits became the restrictive factor of the experimental accuracy in these measurements. A first short run with poor statistics at 4.8 MeV resulted in a standard deviation of 2.8% for the U-238(n,f) cross-section.

Introduction

The U-238 fission cross-section possesses increasing importance as a nuclear data standard, especially for fusion technology and reactor dosimetry because of its advantages (reaction threshold, smooth function in the plateau regions). Therefore it was already admitted into the IAEA Standards File /1/. But them faces a lack of experimental data, especially absolut measured ones. Thus, the measurements of the TUD/RIL cooperation (U-235 /2-5/, Pu-239 /4,6/) were continued to get a set of precise absolute spot points for the U-238 fission cross-section, too /21/.

Measuring principle

The measuring principle of the TCAPM is well known /7,2,4,6,8/ and will be recapitulated only in its basic ideas (fig. 1):
Accelerated deuterons are focused on a CD_2- or a Ti-T-target foil producing neutrons by the $D(d,n)^3He$- and $T(d,n)^4He$-reactions, respectively. Associated charged particles (AP), which are emitted within a fixed cone $\Delta\Omega_{AP}$ defined by an aperture A, are registered by an AP detector. The neutrons belonging to the registered AP form a cone $\Delta\Omega_n$, which is defined by the reaction kinematics and has to be intercepted completely by the homogeneous fission foils placed inside an ionization fission chamber. Then, the fission cross-section is given by the formula

$$\sigma_f = N_f \,/\, (N_{AP} \cdot n),$$

where N_f is the number of fission events registered in coincidence

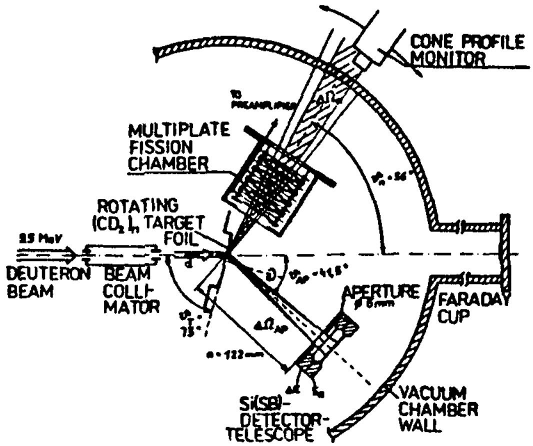

Fig. 1
Experimental set-up of the 8.4 MeV measurement

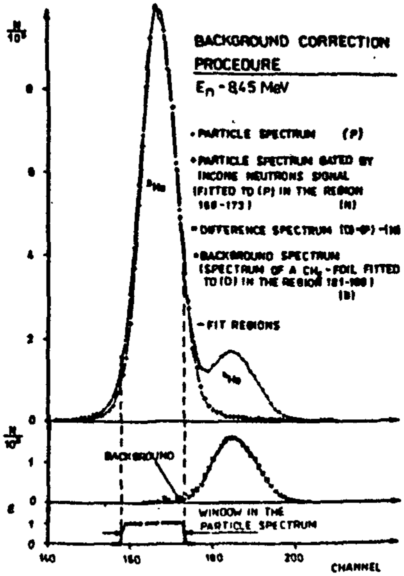

Fig. 2
Background correction procedure at 8.4 MeV

with an AP, N_{AP} the number of counted AP's and n the number of fissionable nuclei per unit area.

AP c o u n t i n g

The AP detection system is based on a telescope of two completely depleted Si-SB-detectors in connection with a fast particle identification circuit /9,2/. This technique allows:

- to suppress rates of scattered deuterons up to $2.5 \cdot 10^5\ s^{-1}$
- to reduce the ^{4}He-background (d(D,n)-reaction) essentially by generating a particle significant spectrum (fig. 2), containing all events inside the former selected window around the ^{3}He-peak in the total energy spectrum.

The remaining background components have to be considered by the analysis of recorded spectra.

4.8 MeV and 8.4 MeV

The portion of the remaining ^{4}He-background not separated is caused by the tail of the ^{4}He-peak and amounts to 0.5...0.6 %. To determine this background underlying the ^{3}He-peak the particle significant spectrum is collected during the whole measurement. In intervals background spectra are collected using CH_2-foils of comparable thickness and besides particle spectra gated by correlated (incone) neutron signals. The background normalization procedure by spectra fitting is illustrated by fig. 2. This procedure is based only on experimental spectra, not on mathematical descriptions of peak shapes.

Unfortunately, this method requires a sufficient large ^{4}He-peak for background spectra fitting. Therefore, the energy window in the total energy spectrum of the detector telescope must be chosen wide enough to admit a sufficient part of ^{4}He events in the particle spectrum. This, of course, will enlarge the ^{4}He amount within the AP window, too. In order to reduce the ^{4}He background as much as possible, a new and independent method of background determination was tested in the 4.8 MeV measurement. In the total energy spectrum the events of a separated ^{4}He peak were counted as a monitor rate during both measurement and background control runs, using CD_2- and CH_2-foils, respectively. The background particle spectra are normalized to the effect particle spectra by means of the ratio of these monitor rates, and in the normalized background spectra the interesting background amount inside the particle window is determined. The results by using this independent method confirm to these by spectra fitting within the error limits of 0.2 %. But for a general application of this method some experimental modifications are necessary to improve the separation of the ^{4}He peak used so that small electronic drifts will not influence the result.

18.8 MeV

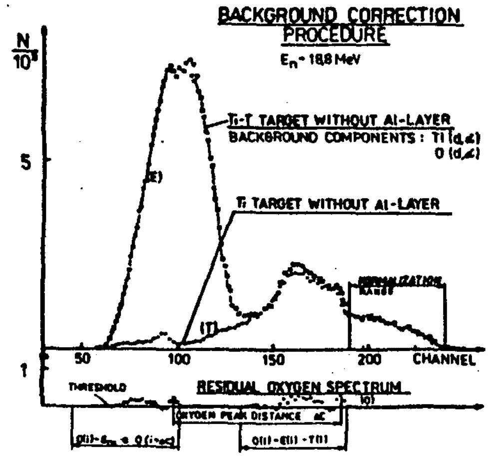

Fig. 3
Background correction procedure at 18.8 MeV

Normalization of the Ti(d,α) and $^{16}O(d,\alpha)$ background components was carried out by fitting the spectra of non-tritiated foils of nearly the same thickness to these registred during the runs considering different ^{16}O-depht-profiles (/2,10,11/ see also fig. 3). *Employing selfsupporting* Ti-T-targets without Al-layer (in contrary to /2,10,11/), the error contribution of background correction in the AP channel was reduced from 1.35 % to 0.60 % because of the absence of the Al(d,α)-component. Using a rotating target holder system at beam-currents up to 600 nA, no T-escape from these targets was detectable.

N e u t r o n   c o n e

The principle of the TCAPM presupposes the complete interception

of the neutron cone by all fission foils. This basic condition was controlled during the whole run by scanning the horizontal neutron cone profile outside the 40 cm in diameter vaccuum chamber with a scintillation detector /12/. Far from the cone maximum this measurement gives no significant information because of the raising amount of events, caused by scattering on fission chamber material and vaccuum chamber wall. Therefore in the 18.8 MeV measurement separate measurements of the proton cone /13/ inside the vaccuum chamber were carried out (protons from the d(^{3}He,p)-reaction; ^{3}He originating in the T-decay). They have shown an exponential slope of the cone edges so that the experimental neutron cone tails can be explained by these neutron scattering processes /14/.
This allowed to open the neutron cone wider in the 8.4 MeV and 4.8 MeV measurements in contrary to former measurements by use of larger AP apertures to reach better statistics. The counting losses caused by neutrons outside the cone were found to be smaller by calculations based on the measured cone profile than 0.02 % in these two measurements.

F i s s i o n c h a m b e r

The necessary increase of fissionable material in the fission chamber results in an increasing number of fission foils. To realize a compact chamber design the facility of decreasing the foil-electrode-distance was investigated. Using an Am-Be-n-source fission chamber spectra with foil-electrode-distances of 2 mm and the former used 3 mm were registered.
Figure 4 shows that the decrease reduces the visible plateau region to a third, which would enlarge the error contribution by spectrum extrapolation to zero, essentially.
Thus, for the foil-electrode-distance of 3 mm given optimum number of foils is nine. In case of a further extension the necessary cone-contraction (because of the raised distance of the last foil from the neutron source target) decreases the amount of fissionable material inside the cone more than the additional foil enlarges it.

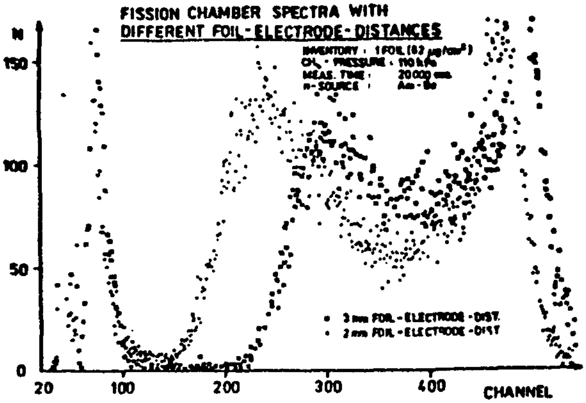

Fig. 4
Fission chamber spectra with different foil-electrode-distance

Our well optimized fission chamber allows to set the threshold in fission chamber spectra at very low energies. Therefore, at the neutron energies of 18.8 MeV a correlated background not negligible was determined explained by the $^{12}C(n,n')3\alpha$-reaction at the chamber gas CH_4 /6,22/. Now, at the neutron energy of 8.4 MeV a correlated background was detected, too. Because of the higher reaction threshold of the $^{12}C(n,n')3\alpha$-reaction it is sure to originate in other reactions at chamber construction materials. In general this correlated background is not ruled out at neutron energies above 8 MeV in dependence on the threshold position. But the amount of correlated background correction is rather small (5.92 % and 0.15 % in the 18.8 MeV and the 8.4 MeV measurements, respectively) compared to the correction values in table 2, which include all events below the threshold introduced with the analysis.

F i s s i o n f o i l s

The fission foils used were prepared at the KRI Leningrad by HF-sputtering (foil II) and by separation from a metal-organic compound (all other foils). The active layers are situated on 0.17 mm thick Ni-Cr-backings contained in brass frames 40 mm in diameter.

Table 1

Properties of the fission foils used

Foil No.	Ø (mm)	manufactured (year)	n ($\frac{\mu g}{cm^2}$)	Δn/n (%)	Inhomogeneity: round points to centr. point (%)	Inhomogeneity: stand. dev. at round points (%)	Mounting position (F = foreward, B = backward): 4.8 / 8.4 MeV (1986)	Mounting position: 18.8 MeV (1985)
II	21	1979	288.6	1.0	+0.16	0.51	4/B	4/B
1	21	1985	427.7	1.0	-0.97	1.79	1/F	3/F
2	21	1985	521.0	1.0	-1.94	2.94	-	1/F
4	21	1985	331.6	1.0	-2.91	1.14	-	2/B
7	21	1985	340.5	1.0	-1.50	0.59	2/B	5/F
1	24	1986	348.2	1.28	-0.38	1.35	6/B	not avail.
3	24	1986	418.9	1.29	-1.31	1.09	3/F	not avail.
4	24	1986	375.6	1.28	+0.11	1.30	9/F	not avail.
5	24	1986	409.6	0.88	-1.27	1.34	5/F	not avail.
6	24	1986	430.7	1.32	+0.35	0.83	7/F	not avail.
8	24	1986	332.4	1.28	+0.20	0.46	8/B	not avail.

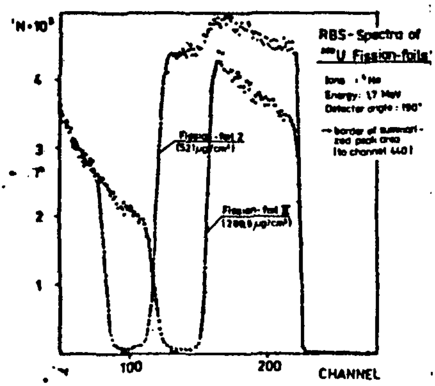

Fig. 5

Typical RBS-spectra of U-238 fission foils

The number of fissionable nuclei per unit area was determined at the KRI by 2π-α-counting, using $T_{1/2}$ (U-238) = $4.468 \cdot 10^9$ y

± 0.11 % /15/.

Nonuniformity of the layers was determined at the van-de-Graaff-accelerator of the CINR Rossendorf by Rutherford backscattering measurements with 1.7 MeV ^{4}He-ions /16/. Figure 5 shows typical RBS-spectra of two fission foils prepared by two different technologies. The brutto area of the effect peak (at right) was used as a measure of Uranium contents in the foils. Nine measuring points 3 mm in diameter were located in the centre of the foil and on a circle (Ø 12 mm) around the centre in steps of 45°. Based on these results nine fission foils were selected from the available 16 ones (for the 18.8 MeV measurement 5 foils) and their true mounting positions in the fission chamber were optimized, so that the inhomogeneities of the round measuring points will compensate each other at a maximum /6/.

The whole inhomogeneity of the complete set of foils was calculated by quadratic addition of the standard deviation of the points outside the centre (0.06 %) and the averaged difference relative to the central point (0.54 %, values for the 1986 9 plate chamber).

Results

Correction values, error contributions and the preliminary results of the measurements presented are given in table 2. Figure 6 presents our results compared to the ENDF/B-V data file /1/.

Small correction values demonstrate the advantages of the TCAPM. In all measurements (except at 4.8 MeV because of the poor statistics) the summarized error contribution from neutron flux determination and counting statistics is smaller than that of foil parameters.

All corrections based on experimental results are derived from spectra recorded during the whole measurement time using a CAMAC-instrumentation system /17/. Correction of the correlated background was realized by setting a threshold in the fission chamber spectrum with the analysis /6/.

Neutron scattering correction is calculated with a Monte-Carlo-Program /18/.

Table 2

Corrections (a) and error contributions (b) of the measurements presented

Neutron energy (MeV)	4.8		8.4		18.8	
	a (%)	b (%)	a (%)	b (%)	a (%)	b (%)
Counting of coincidences						
- Statistics of effect	-	2.22	-	0.87	-	1.81
- Random coincidences	0.48	0.17	1.19	0.11	1.07	0.21
Fission chamber efficiency						
- Pulses below correlated background threshold	1.02	0.07	0.56	0.04	6.34	0.06
- Extrapolation to zero	0.87	0.27	1.24	0.14	1.20	0.20
- Fragment absorption	3.07	0.90	2.74	0.81	2.91	0.90
AP counting						
- Background	3.30	0.60	0.94	0.29	5.65	0.60
Neutron cone						
- Neutron scattering and effective foil thickness due to the cone aperture	1.07	0.40	1.16	0.40	0.54	0.40
- Cone neutrons outside the angular extend of the fission foils	-	0.02	-	0.01	-	0.36
Fissile layer						
- Areal density	-	1.15	-	1.15	-	1.00
- Inhomogeneity	-	0.54	-	0.54	-	1.59
Result (10^{-24} cm^2)	0.551		1.022		1.351	
Standard deviation (%)	2.82		1.82		2.89	

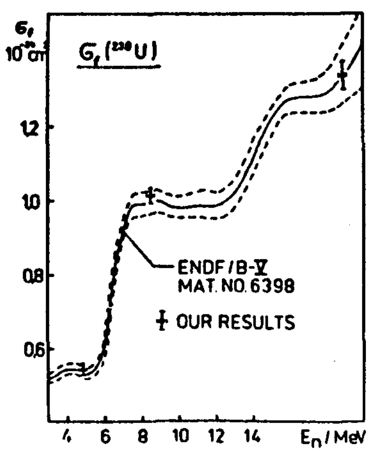

Fig. 6

Results compared with the ENDF/B-V data file

Based on a value of 7.5 mg/cm^2 for the averaged fragment range in U_3O_8 /19/ a value of $(5.5 {}^{+2.0}_{-1.0})$ mg/cm^2 related to the Uranium content (data from the foil manufacturer about microscopic inhomogeneity and about admixtures of other elements considered) was assumed to calculate the fission counting loss caused by absorption /20/. Experimental investigations of the individual absorption parameters of all foils used are planned, and a further decrease of the fragment range may be expected by reason of surface effects, as measurements at Pu-239 foils have shown /21/.

A c k n o w l e d g e m e n t s

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ENERGY AND ANGULAR DISTRIBUTION OF NEUTRON EMISSION IN THE SPONTANEOUS FISSION OF ^{252}CF

(Int. Conf. Neutron Physics, Kiev, 1987)

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Abstract: A new experimental method has been applied to measure the double-differential emission probability of Cf fission neutrons between 100 keV and 10 MeV. The neutron-fragment correlation experiment has been based on neutron time-of-flight spectroscopy combined with a direction-sensitive method of fragment spectroscopy. The angular distributions obtained cover the whole range from 0 to π. Results are presented and discussed in comparison with previous data.

1. Introduction

Fundamental studies of fission neutron emission including the clarification of mechanisms require the precise measurement of emission probabilities $N(E,\Theta)$, i.e. depending on both LS energy E and emission angle Θ with reference to the light-fragment direction.[1] These provide the basis for the further developement of theoretical models for calculating fission neutron spectra.[2] Compared with previous measurements[3], i.e. fragment spectroscopy for a fixed solid angle and consecutive measurement of neutron spectra at selected neutron detector positions, the method used in this work relies on a direction-sensitive spectroscopy of the fission fragments to measure the whole distribution $N(E,\Theta)$ by the use of one or two neutron detectors at fixed positions simultaneously. In this way, systematic experimental uncertainties are avoided. First applications, in particular a measurement of anisotropy of ^{252}Cf(sf) neutron emission, have been presented elsewhere.[4,5] A similar method based on a gridded ion chamber (twin arrangement) has been recently developed at CBNM Geel.[6]

2. Experimental method

As represented schematically in the figs. 1 and 2, a position-sensitive parallel-plate avalanche counter[7] PPAC(PS) has been used for the measurement of fragment direction. The fast timing signal from a single PPAC located close to the fission sample S defines the fission time and , therefore, serves as the input pulse for the measurement of time-of-flight TOF of neutrons as well as fission fragments.

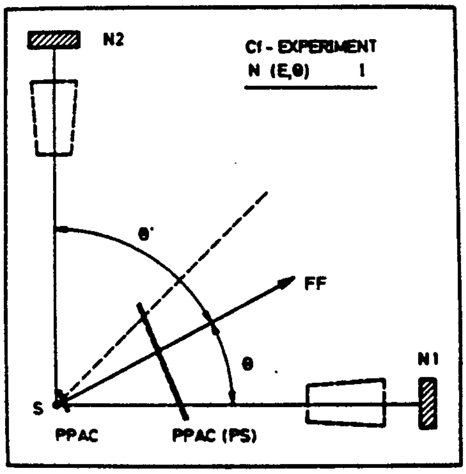

Fig. 1 Experimental arrangement of fragment detectors (PPAC, PPAC(PS)) as well as neutron detectors (N1, N2) for the $\pi/4$-geometry of fragment (FF) direction measurement (Variant I). The shadow cones for measuring the background of scattered neutrons are indicated.

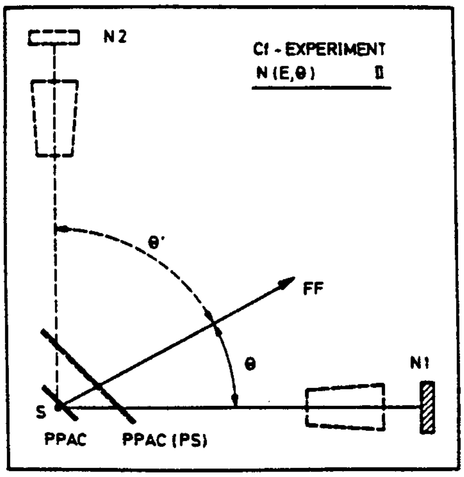

Fig. 2 As for figure 2, but for the $\pi/2$-geometry of fragment direction measurement (variant II).

The multi-parameter data acquisition (position amplitude, fragment TOF, neutron TOF for two neutron detectors) has been realized on the basis of a computer-microcomputer system with magnetic disc and 2D colour display. A typical two-dimensional fragment spectrum is represented in fig. 3 showing two banana-shaped regions, which correspond to the heavy and the light fragment groups, as well as resolved position peaks corresponding to the segments of the PPAC(PS). The distinction between the fragment groups has to be based on a subdividing line obviously depending on position.

The two experimental variants represented in the figs. 1 and 2 have been applied in two experiments characterized in table 1.

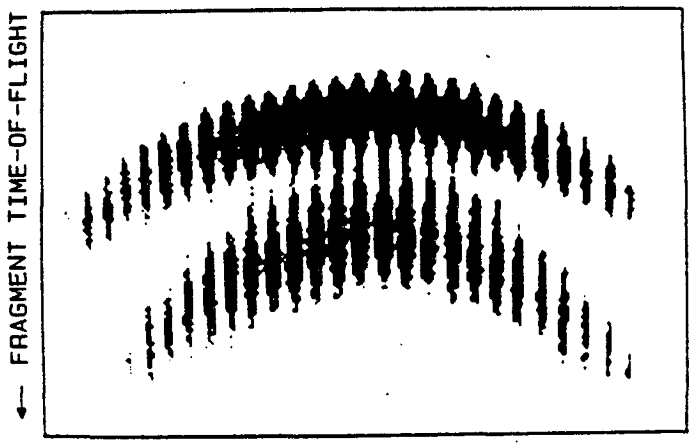

Fig. 3 Two-dimensional representation of a non-correlated fragment spectrum. The black regions include channels with more than 100 counts.

The $N(E,\Theta)$ data analysis includes the following procedures:

i) off-line generation of two-dimensional (neutron TOF, position) spectra for both neutron detectors and for selected fragment groups using a data sorting code,

ii) subtraction of the background components depending on E and Θ after their normalization (random background, spectrum of scattered neutrons from the shadow cone measurement, delayed-γ-ray spectrum in the case of Li glass detectors),

iii) computing the correlated position spectra for eligible neutron energy bins ΔE (corresponding to a certain neutron TOF scale bin) and the following unfolding, which yields the peak areas A_i corresponding to the angle Θ_i of neutron emission (i - PPAC(PS) segment number),

iv) calculation of the neutron emission probability according to

$$N_i(\bar{E},\Theta_i) = A_i \cdot \left[N_{FF} \cdot \bar{\nu} \cdot g_i \cdot \varepsilon(\bar{E}) \cdot \Delta\Omega_n \cdot \Delta E \right]^{-1}, \qquad (1)$$

where N_{FF} -number of counted fragment signals (PPAC(PS)), $\varepsilon(\bar{E})$ - neutron detection efficiency stated

Table 1 Synopsis of two different experiments

Item	Experiment 1	Experiment 2
neutron energy range	100 keV - 2 MeV	1 MeV - 10 MeV (18 MeV in polar direction)
PPAC-PPAC(PS) arrangement	$\pi/2$-geometry (fig. 2)	$\pi/4$-geometry (fig. 1)
angular resolution (fragments)	4.0 deg	1.8 deg
neutron detector type	NE 912 (6-Li glass scintillator)	NE 213 (liquid organic scintillator)
neutron detector size	4.5 cm in diam. 0.95 cm thickness	12.7 cm in diam. 3.8 cm thickness
photomultiplier	56 AVP	XP 2040
flight path	35 cm	1.6 m
time resolution (FWHM γ-peak)	2.55 ns	1.45 ns
background suppression	amplitude discrimination	pulse shape discrimination
additional background measurements	shadow cone arrangement (scattered-neutron background) NE 913 (7-Li det.) measurement (delayed-γ-ray background)	shadow cone arrangement (scattered-neutron background)

for the energy bin average $\bar{E}$, $\bar{\nu}$ - average number of neutrons per fission, g_i - geometrical efficiency of fragment detection (see below), $\Delta\Omega_n$ - solid angle of neutron detection.

Non-correlated fragment spectra have to be measured additionally in order to deduce the geometrical efficiency g_i of the PPAC(PS) segments, which was found to be equal to the solid angle of fragment detection in a given PPAC(PS) strip. The total sum over all g_i has been normalized to 1. (cf. equ. 1).

In addition to the data correction for the different background components as already discussed, the emission probabilities obtained have been corrected for energy resolution and energy bin width, for angular resolution, for accidental coincidences, and dead time losses.

3. Results and discussion

Both variants of N(E,Θ) measurements described in section 2 have been applied to spontaneous fission of ^{252}Cf. The source of about 10^4 fissions per second strength was a 5mm diameter, thin layer on a 0.15 mm thick Ta backing. The two variants characterized by different angular resolutions (cf. table 1) correspond to the typical anisotropies in the energy ranges covered. The variant-I arrangement (with the better angular resolution) was employed to measure N(E,Θ) at medium and high energy, i.e. at high emission anisotropy. In addition, a special diaphragm has been used to reduce the out-of-plane deviation of fragment detection for the PPAC(PS) segments corresponding to polar directions (Θ = 0 and 180 deg) and, hence, to guarantee a sufficiently good angular resolution for the polar regions.[8] The results of the experiments, which have been concentrated for 5 deg bins (120 angle points originally), are represented in the figs. 4 and 5. They can be characterized as follows:

i) For the lowest energy analysed (100 keV), the angular distribution was found to be nearly isotropic (anisotropy ratio 1.1 ± 0.1).

ii) The anisotropy increases as E increases. At 10 MeV, the anisotropy ratio is close to 100.

iii) In agreement with the results of the Geel group[6], the measured polar/equatorial anisotropy ratio is considerably higher than previous data[3,9] at energies higher than 4 MeV.[5] Specifically the precision of N(E,Θ) measurements in the equatorial direction (90 deg) in the case of low emission probabilities and at high energy is of considerable importance for studying emission mechanisms. The efficient background suppression applied in this work was an essential precondition to avoid systematic errors.

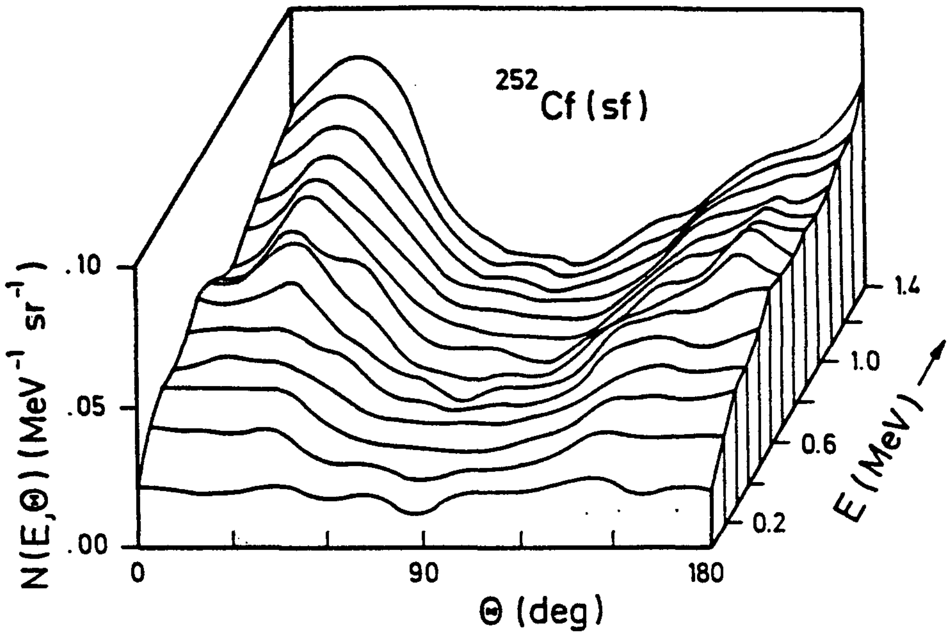

Fig. 4 Angular distributions of ^{252}Cf(sf) neutrons at low energy (E = 0.1(0.1)1.4 MeV) deduced from a variant II measurement with NE 912 scintillators (6-Li glass).

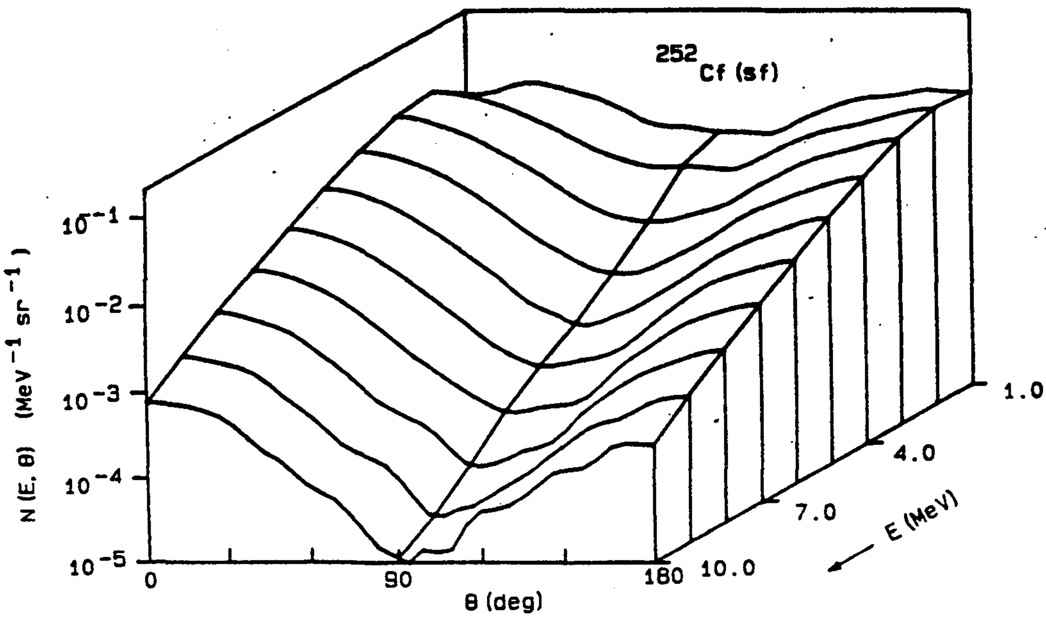

Fig. 5 Plot of N(E,Θ) of ^{252}Cf(sf) neutrons in the MeV range (results of a variant I measurement with NE 213 scintillators).

iv) A significant N(E,Θ) valley appears in the polar region at Θ close to 0 deg and $E \approx 0.95$ MeV. It has to be attributed to neutron emission from the light-fragment group. The position of this valley ($E \approx 0.95$ MeV corresponds to the average light-fragment kinetic energy E_f per nucleon) indicates a kinematic effect due to neutron evaporation from fully accelerated fragments.[2] An equivalent appearance hasn't been found for heavy-fragment neutron emission ($\bar{E}_f \approx 0.56$ MeV) but some indications of structures. The 1 MeV angular distribution is represented in fig. 6.

v) The kinematics of neutron emission from the fully accelerated fragments is the main reason for the differences of both polar spectra. The differential energy distribution at 0.deg is considerably higher than the 180-deg spectrum for $E > 1.5$ MeV (cf. the different E_f values mentioned in item iv).

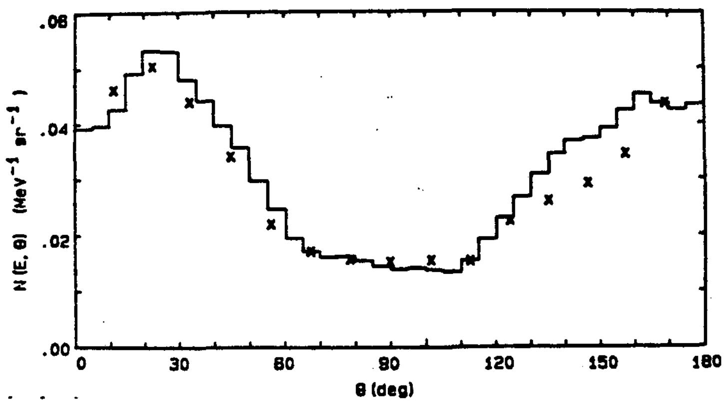

Fig. 6 The angular distribution of 252-Cf(sf)-neutrons at E = 1 MeV (histogram - experimental data of this work, crosses - ref. 3).

4. Conclusion

The experimental method presented enables the precise measurement of double-differential emission probabilities N(E,Θ) of fission neutrons. The measured data on $^{252}Cf(sf)$ neutron emission cover a wide energy range extending from 100 keV (first measurement below 0.5 MeV) to 10 MeV (to 18 MeV in polar direction). The new method is suitable for measuring the full angular distribution with a rather high angle point density simultaneously. Specifically, the shape of the Cf neutron angular distributions in the 0.3 - 1.4 MeV range has been deduced with high accuracy (including the whole polar region, cf. fig. 6), enabling essential conclusions to be reached on theoretical approaches[10].

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