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# Progress Report on Nuclear Data Research in the Federal Republic of Germany \*

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by

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I. Kernforschungszentrum Karlsruhe

A. Institut für Angewandte Kernphysik

## 1. Van de Graaff

#### a. Capture cross section measurements

In the framework of the establishment of an accurate standard the shape of the Au (n,  $\gamma$ ) cross section has been measured by three different methods, 1.) by use of an energy independent "grey neutron detector"  $\int 1,2 \int$  as flux monitor and a large liquid scintillator  $\int 3 \int$  for the detection of capture events in the gold sample, 2.) and 3.) with the large liquid scintillator relative to the B<sup>10</sup> (n, $\alpha_1 \gamma$ )  $\int 4 \int$  and <sup>6</sup>Li (n, $\alpha$ )  $\int 5 \int$  cross sections using respectively a Li-glass detector and a <sup>10</sup>B-slab viewed by 4 NaI-crystals. All three measurements were normalized to the absolute 30 KeV value  $\sigma_{n,\gamma}^{Au} =$ 0.596 b  $\int 1 \int$ . These three measurements were evaluated to a "best" curve with the largest weight attributed to the grey detector measurements. This "best" curve was used to renormalize the former preliminary  $\sigma_{n\gamma}$  results  $\int 3 \int$  in the energy range from about 10 KeV to 150 KeV for the following materials:

Nb, Mo, Pd, Ag, Cd, In, Cs, Hf, Ta, W and Re. By least square fits to the data p- and d-wave strength functions were derived  $\int 6 \int$ . The fits were restricted to energies below the lowest inelastic scattering threshold.

With the grey detector technique also the capture cross section of  $U^{238}$  was measured in the energy range 25 - 500 KeV with normalization to a 30 KeV value of 479 mb  $\int 7_{-}7_{-}$ . Whereas below 100 KeV the agreement with the more recent evaluations of Brookhaven  $\int 8_{-}7_{-}$  and Karlsruhe  $\int 9_{-}7_{-}7_{-}$  is rather satisfactory, the experimental results are lower than these evaluations and the underlying former measurements.

## b. Fission cross section measurements

Preliminary measurements of the fission cross section ratio of  $^{239}$ Pu to  $^{235}$ U were done in the energy range from 30 KeV to 300 KeV by time-of-flight technique with Xenon scintillation fission detectors. Till now no relevant

results could be obtained due to the difficulties of discriminating fission against background caused by response of the multipliers to neutrons and by  $\alpha$ -pile up.

New detectors were prepared which allow to observe both fission products in coincidence and in the near future measurements will be done with these detectors, trying also to enlarge the energy range to below 30 and above 300 KeV.

#### c. High resolution resonance spectroscopy

Measurements and interpretations of resonance total cross sections of separated odd A isotopes in the medium atomic weight range are continuously under way. Particularly  $\sigma_{\rm T}$  of the isotopes  ${\rm Cr}^{53}$  and  ${\rm Ti}^{49}$  was measured in the energy range 20 - 250 KeV, of the Cu isotopes Cu<sup>63</sup> und Cu<sup>65</sup> between 40 and 250 KeV; in the last three months results were obtained for Sc<sup>45</sup> in the energy range 20 - 250 KeV. The broad cross section structure observed earlier in Fe<sup>57</sup> appears now to be successfully interpretable by the two channel formula with due account of the competition of inelastic scattering to the 14.4 KeV level in Fe<sup>57</sup>. Meanwhile the 14.4 KeV  $\gamma$ -radiation could be experimentally detected.

## d. Slow neutron inelastic scattering and Doppler broadening

The evaluation of the frequency distribution for  $\text{ZrH}_{1.08}$  has been completed [11,12]. The scattering of cold neutrons (E = 5 meV) from H<sub>2</sub>O at temperatures of -12 °C and +23 °C has been measured at angles between 16 ° and 110 ° and the frequency distribution extracted from these data using an iterative correction for multiple scattering. The quasielastic scattering from H<sub>2</sub>O (23 °, 45 ° and 75 °C) and D<sub>2</sub>O (23 °C) bas been analysed quantitatively using the LEAP formalism for corrections [13]. The double differential scattering cross sections  $\frac{d^2\sigma}{d\Omega H}$  for liquid H<sub>2</sub> (T = 19.8 °K) and solid H<sub>2</sub> (T = 4.4 °K) have been measured with incident energies of 21.8 and 87 meV for scattering angles between 20 ° and 150 °. The results deviate considerably from the gas model calculations and have been interpreted in terms of a spectral frequency distribution [14].

The Doppler broadening of the 6.68 eV resonance in metallic  $U^{238}$  and  $UO_2$ 

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has been measured as a function of temperature between room temperature and 1000 °C. The line broadening in UO<sub>2</sub> is quantitatively explained using a realistic frequency distribution of lattice vibrations in UO<sub>2</sub> and the scattering law formalism  $\int 15 \int .$ 

#### 2. Cyclotron

Total neutron cross sections of C, O, Na, Al, S, Ca, Fe, Bi and Tl were measured by a time-of-flight method with energy resolutions varying from  $\leq 0.08$  % at the lower energy limit of 500 KeV to  $\leq 0.6$  % at the higher energy limit of 30 MeV. In the lighter and some of the medium weight nuclei a prominent fine structure was observed up to energies of about 10 MeV. So far no resonance parameter analysis was performed, which, above the inelastic threshold, is made difficult by the inelastic component, but in some cases a statistical analysis was performed. This occasionally shows clearly a doorway structure underlying the more rapid compound resonance flucturations  $\int 16 \int$ . At the moment an EANDC publication with a detailed graphical display of the experimental results is in preparation.

### B. Institut für Neutronenphysik und Reaktortechnik

## 1. Measurements with the lead pile spectrometer

The lead slowing down time spectrometer was used to measure the capture ratios of hot-to-cold camples of natural U, W and Ta in a range of energies with the most important Doppler effect contributions, i.e. between about 200 eV and 30 KeV  $\int 20 7$ . Thin samples were heated to two different temperatures ( $U_{nat}$ : 300 ° and 750 °K; W, Ta: 300 and 700 °K) and the capture  $\gamma$ -rays detected by proportional counters.

From the  $U^{238}$  results so far obtained an accuracy of this ratio measurement method of  $\pm 5$  to 10 % appears to be possible. The fact that ratios were measured leaves the knowledge of the neutron flux unnecessary and allows a direct comparison of experiment with Doppler coefficient theory. The theoretical analysis of the experimental results for  $U^{238}$  gives on the average rather satisfactory agreement; above a few KeV the Doppler effect appears to be somewhat larger than predicted by theory.

# 2. Neutron cross section evaluation

In 1967 most weight was given to the transfer of the evaluated nuclear data documented in reference  $\int 9_{-}^{-}7$  to the Karlsruhe evaluated nuclear data file KEDAK. This work is now terminated; a copy of the KEDAK tape in blocked format has been sent to the CCDN Saclay for further distribution upon request; shortly KEDAK will also be available from Saclay in a card image format which is just being developed at Karlsruhe. Now the KEDAK library contains almost complete nuclear data sets for the following most important reactor materials

H (bound in H<sub>2</sub> and in H<sub>2</sub>O), C, O, Na, Al, Cr, Fe, Ni,

Mo. U<sup>235</sup>. U<sup>238</sup> and Pu<sup>239</sup>

Starting from the gaps and discrepancies found during the work on KFK 120/ part I the Euratom request list for nuclear data measurements was carefully revised, particularly concerning the requests for fissionable, fertile and structural materials. In addition new requests pertaining to as yet unknown capture properties of the fission products most important in fast reactor design were incorporated  $\int 18_7$ .

For investigations of the neutron energy spectrum of the Karlsruhe fast zero power assembly SNEAK in the resonance range by means of the sandwich method, "best" values of resolved and statistical resonance parameters for 24 isotopes with atomic weights between 50 and 200 were determined  $\int 19_{-}^{-}$ .

Future work will mainly aim at the critical review and taking over of evaluated nuclear data files from the CCDN/Saclay for some materials of

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secondary importance, at the improvement of the capture and fission cross sections of the main fissile and fertile materials now contained in KEDAK including particularly a revision of the  $Pu^{239}\alpha$  values in the KeV range, at the extension of the present KEDAK data from 10 to about 15 MeV and to a systematic cross section evaluation for those transactinium isotopes built up during fast reactor burn up.

## II. Physik-Department/Technische Hochschule München

Activation measurements of (n, 2n) cross sections at 14.7 MeV have been performed for 16 nuclei with atomic weights between 140 and 204 using neutrons from the D-T reaction. Those target nuclei were selected for which the (n, 2n) reaction leads to product nuclei which decay predominantly by K-shell electron capture. Thus the absolute measurement of the activities produced was done by K-X-ray counting with a thin (3 mm) NaJ crystal calibrated with standardised sources. The neutron flux was determined by activated Al monitor foils using  $\sigma_{n,\alpha}$  (Al<sup>27</sup>, 14.7 MeV) = 111.5 mb as standard  $\int 6_{-7}$ . In addition relative excitation functions (n,p),  $(n,\alpha)$  and (n, 2n) were measured for a series of nuclei in the range 13.5 - 14.7 MeV by the activation method, furthermore for some of these reactions ratios to  $\sigma_{n\alpha}$  (Al<sup>27</sup>) were determined at 14.7 MeV. The accuracy obtained in these experiments is very good, in the energy dependent measurements about 1 %, in the ratio measurements 2 - 3 % [6,21]. The important result is that the observed excitation curves are smooth energy functions and do definitely not show the large fluctuations found by Strohal and Csikai [22].

With the neutron gravitation refractometer at the Garching reactor FRM the coherent scattering length was measured for the bound atom of Bi with the very accurate result:  $a = 8.5682 \pm 0.0012 \int f$ . New measurements have been started to find the precise scattering length of elements in organic liquids, first results have been obtained for C, Cl and Br. Furthermore experiments have been initiated in order to measure the coherent scattering length of elements which are not available in liquid form for direct measurements at the refractometer.

III. Kernforschungsanlage Jülich / Institut für Festkörper- und Neutronenphysik

In recent experiments the incoherent scattering cross sections of Pb and Bi have been measured by determining the intensity of the neutrons scattered by the sample in a large solid angle. The detectors were calibrated with a V sheet as reference sample. Very low neutron energies between 0.4 and 1.3 MeV were used to suppress elastic Bragg and inelastic energy loss scattering. To avoid inelastic energy gain scattering the samples were cooled to temperatures between 3 and 50 °K. At the lowest temperatures the inelastic scattering vanishes and the scattered intensity is only due to  $\sigma_{\rm inc}$ . Results may be found in reference  $\int 6 \int .$  By this method scattering cross sections as small as  $10^{-4}$  b can be measured. The method can also be extended to materials with high absorption or to those materials which are available only in very small amounts.

# IV. Universität Frankfurt/Lain/Institut für Kernphysik

The reaction  $\mathrm{Sr}^{88}$  (n,p)  $\mathrm{Rb}^{88}$  has been studied at neutron energies between 8.0 and 9.2 MeV and at 14 MeV and the reaction  $\mathrm{Pb}^{208}$  (n,p)  $\mathrm{Tl}^{208}$  at 14 MeV and between 17.0 and 18.5 MeV with typical neutron energy spreads of 100 KeV. The estimated uncertainty is about  $\pm$  20 %.

In a further experiment the excitation cross section for the 3.56 MeV level in Li<sup>6</sup> (96 % enriched metallic Li<sup>6</sup> sample) has been measured in the range between threshold and about 7 MeV. The cross section rises from threshold to about 5 MeV, and then remains about constant at  $8 \pm 2$  (mb) between 5 and 7 MeV.

V. Universität Hamburg/Physikalisches Staatsinstitut, I. Institut für Experimentalphysik

As part of continuous systematic studies the excitation functions for some (n,2n) and (n,p) reactions were measured in the neutron energy region 13-19 MeV using the activation technique. Gamma activities were detected by means of a NaJ-well crystal, the annihilation radiation from  $\beta^+$ -activities was observed with a coincidence spectrometer consisting of two NaJ crystals and  $\beta$  -activities were measured with a Methane-flow-counter. Neutrons were produced via the reaction H<sup>3</sup> (d,n)He<sup>4</sup> in thin titanium-tritium targets with the deuteron beam of a 3 MeV Van de Graaff Generator. The neutron flux was measured with a Stilbene recoil proton spectrometer. Results may be found in reference  $\sqrt{6}$  7.

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