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THE DIFFERENTIAL NEUTRON SCATTERING CROSS SECTION OF OXYGEN BETWEEN 6 AND 15 MEV

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Abstract: The elastic and inelastic scattering of neutrons from a water sample has been investigated at 9 energies between 6 and 15 MeV using the $D(d,n)^3He$ source reaction. Special care was taken with the Monte Carlo simulation of sample size effects and multiple scattering corrections and the efficiency determination of the NE213 detectors. Uncertainties of 3...8 % were obtained for the differential elastic cross section resulting in 2.5 % uncertainties for the angle-integrated cross section σ_{el} which was normalized with respect to the simultaneously measured n-p scattering. The differential cross sections show deviations of up to a factor of two from the ENDF/B-V data file, whereas deviations of up to 15 % were found in σ_{el}. The inelastic scattering to the first pair of states in ^{16}O at 6.1 MeV could also be extracted, but with larger uncertainties due to kinematic interference with elastically scattered neutrons from the D(d,np)D reaction.

(^{16}O, E_n = 6 - 15 MeV, scattering cross sections, efficiency of NE213 detectors, time-of-flight spectrometer)

Introduction

The main contribution to the oxygen kerma factor which is needed in particular in the field of radiation protection and neutron therapy, stems from the reactions $^{16}O(n,n)^{16}O$ and $^{16}O(n,\alpha)^9Be$ in the energy range from 6 to 15 MeV. In this energy domain the commonly used ENDF/B-V data file /1/ is weakly based on experimental data, and recent experiments are scarce. This work was started with the aim of providing reference data on the elastic and inelastic scattering cross section for future evaluations which can be also used to fix upper values for the (n,α) cross section taking into account the well known total cross section.

Experimental Set-up

The experiments were carried out at the PTB fast neutron time-of-flight facility /2/ using the movable compact cyclotron to accelerate ns-pulsed deuteron beams with an energy of 3 to 12 MeV. Neutrons with an energy of 6 to 15 MeV were produced via the $D(d,n)^3He$ reaction in a gas target and scattered on a cylindrical aluminum can (wall thickness 0.2 mm) filled with water. The target to sample distance was 175 mm and the sample was 25 mm in diameter and 50 mm in height. One NE213 scintillation detector 102 mm in diameter and 25 mm in length (Det. 1) and four NE213 detectors 254 mm in diameter and 51 mm in length (Det. 2 - 5) detected the scattered neutrons. These detectors were located at a distance of 12 m from the sample behind a massive fixed collimator system. The scattering angle was varied between 12.5 and 160 degrees by turning the cyclotron and the beam line around the sample. Another NE213 detector inserted into a movable shield served as a monitor. The detectors were equipped with standard electronics for n-γ pulse-shape discrimination and an LED/PIN-diode gain stabilization system. Pulse height , pulse shape and time-of-flight were recorded in list-mode by a PDP11/CAMAC data acquisition system. The stability of the detector thresholds were controlled by measuring the time-of-flight spectra of neutrons from a ^{252}Cf fission chamber. The low energy shape of these spectra allowed the thresholds (typically 500 keV equivalent electron energy corresponding to about 1.7 MeV neutron energy) to be determined with uncertainties smaller than 10 keV.

Detector Efficiency

The neutron fluence of the gas target was measured in the zero degrees direction with detector 1, analyzed on the basis of the NRESP5 Monte Carlo code /3/ and compared with the fluence obtained with a Los Alamos type proton recoil telescope set up at a distance of 224 mm from the target. The results for the 9 energies of the oxygen scattering experiment are shown in fig.1 together with results from previous comparisons. The absolute neutron fluences agree within 1.5 %. This confirms the NRESP5 calculation, as well as the description of the neutron production in the gas target and the simulation of the

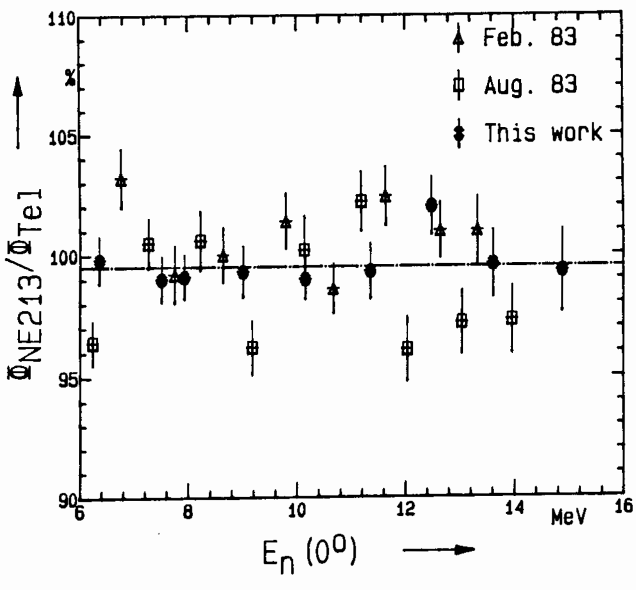

Fig.1: Ratio of neutron fluences measured with Det. 1 (Φ_{NE213}) and the proton recoil telescope (Φ_{Tel})

telescope response /4/. In a comparison of Det. 1 with Det. 2 - 5, an energy independent difference of 2 % was found. In consequence, the calculated efficiencies of Det. 2 - 5 were corrected by a factor of 1.02, thus achieving consistent absolute efficiencies of telescope and NE213 detectors.

Analysis

The peak contents in the time-of-flight spectra of the scattered neutrons were analyzed by comparison with simulated spectra in order to correct for multiple scattering and fluence attenuation in the scattering sample /5/ (fig.2). The simulations performed with the STREUER III code started with cross sections taken from

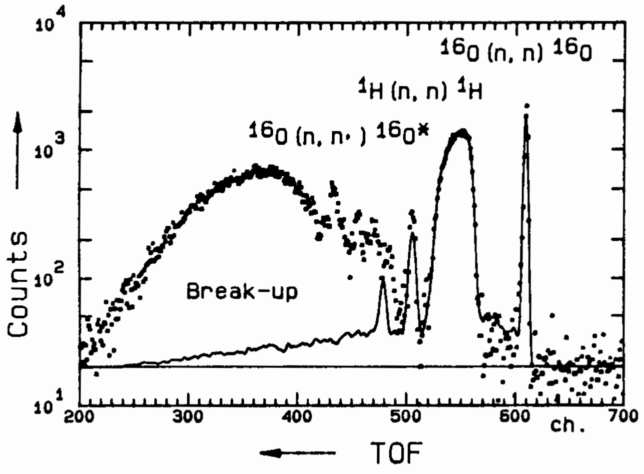

Fig.2: Time-of-flight spectrum of 12.49 MeV neutrons scattered at an angle of 37.7 degrees compared with a STREUER III calculation (smooth line). The first two states of ^{16}O are not resolved.

ENDF/B-V /1/ modifying the oxygen data iteratively until optimum agreement was achieved between experiment and simulation. In addition, the mean energy of the incident neutrons and the scattering angles were varied in the simulation and the resulting peak positions compared with the experimental ones. In this way, uncertainties of less than 0.5 % in the mean incident neutron energy and 0.2 degrees in the scattering angle were achieved. For this analysis all non-calculable background contributions in the time-of-flight spectra had to be subtracted experimentally. This was done by measurements without deuterium gas in the target and measurements without sample (air scattering) and with an empty aluminum can. Special care is necessary when subtracting the contribution of the aluminum can because this contribution differs up to 15 % for an empty and a water filled can. These effects were thoroughly investigated by Monte Carlo simulations in order to apply the proper corrections.

Results

The n-p scattering which was simultaneously measured with the scattering on oxygen provided a conclusive test of the whole experimental procedure. Taking into account the measured fluence of the neutron source, solid angle, sample mass, multiple scattering corrections and the calculated detector efficiencies, the differential n-p cross section is determined and can be compared with the evaluated reference values (ENDF/B-V). The result is shown in fig. 3. It should be noted that the mean values averaged over about 50 data points at 9 energies agree within 1 %. To avoid this small remaining inconsistency, all cross sections were normalized with reference to the n-p scattering. The overall uncertainties of the differential elastic cross section combined mainly from statistical, efficiency, normalization and angle uncertainties can be assessed to 3...7 %, where the greater value

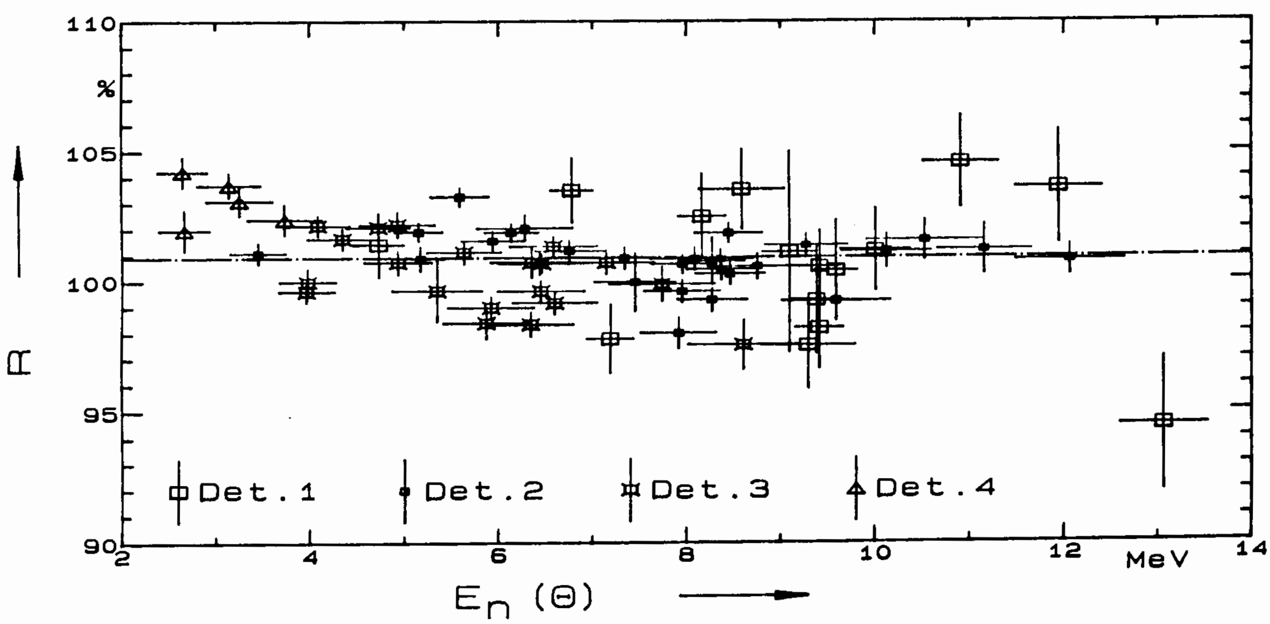

Fig.3: Ratio R of measured differential n-p cross section to reference cross section as a function of the neutron energy after scattering. Only the statistical uncertainties (1 standard deviation) are indicated.

is caused by statistical uncertainties in the minima of some angular distributions, some of which are shown in figs. 4 - 6. The cross sections can be directly compared only with the ENDF/B-V data averaged over the experimental energy distribution on the scattering sample. The results of ref. /6 - 8/ are indicated for informational purposes. Deviations of up to a factor of two from ENDF/B-V occurred.

Only the inelastic scattering to the first pair of states in ^{16}O at 6.049 and 6.130 MeV excitation energy could be analyzed due to elastically scattered neutrons produced by D(d,n)pd whose contribution cannot be subtracted experimentally. According to reaction kinematics these neutrons coincide energetically at backward angles with inelastically scattered neutrons from D(d,n)^{3}He. At angles greater than 90 degrees, this causes additional uncertainties which are difficult to estimate. In consequence, the break-up spectrum of D(d,np)D and D(d,np)NP has been measured but not yet been included in the STREUER code, which would make it possible to reanalyze the inelastic scattering data with higher accuracy.

The differential cross sections were parametrized by Legendre polynomial expansions. To calculate the Legendre coefficients and their correlation matrix, the correlation of the input data was also taken into account. For example, the uncertainties of the five detector angles corresponding to one cyclotron position are fully correlated. Uncertainties for σ_{el} of 2.5 % are

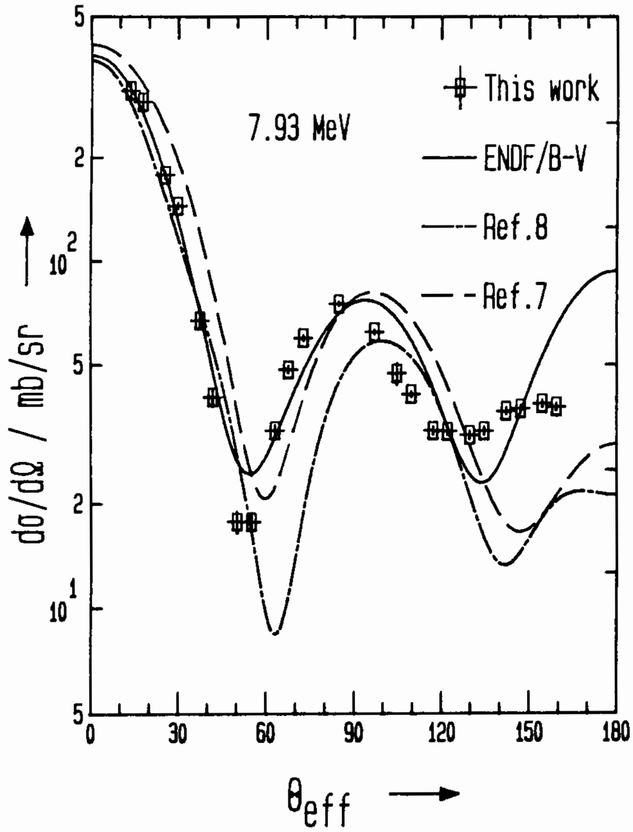

Fig.4: dσ/dΩ versus mean laboratory scattering angle Θ_{eff} at 7.93 MeV compared with ENDF/B-V and measurements from Oak Ridge /8/ at 8.04 MeV and Stuttgart university /7/ at 8.05 MeV

achieved compared with uncertainties of 8...10 % of earlier experiments at 14 MeV /9 - 12/. The integrated cross sections σ_{el} and σ_{inel} are shown in fig. 7. They differ up to 15 % from ENDF/B-V, whereas the agreement with recent data from ref. /6/ is quite good.

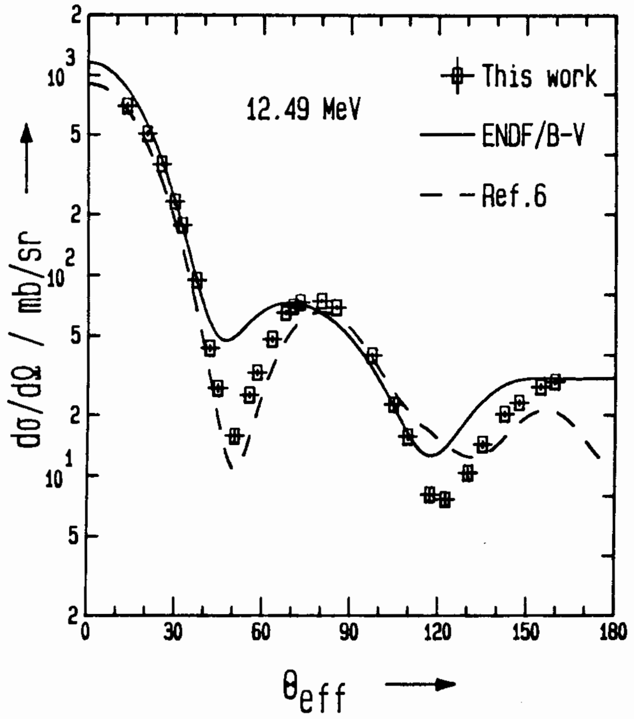

Fig.5: dσ/dΩ at 12.49 MeV compared with ENDF/B-V and a TUNL measurement /6/ at 12.45 MeV

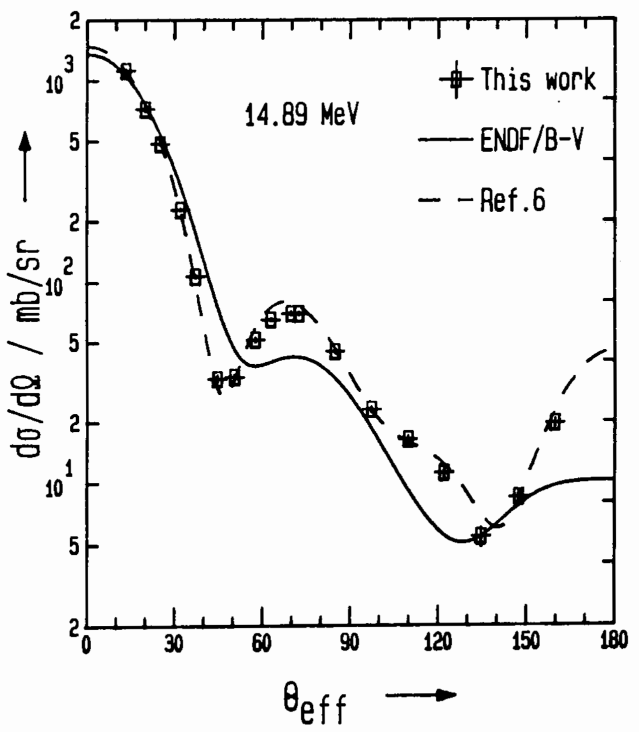

Fig.6: dσ/dΩ at 14.89 MeV compared with ENDF/B-V and a TUNL measurement /6/ at 14.93 MeV

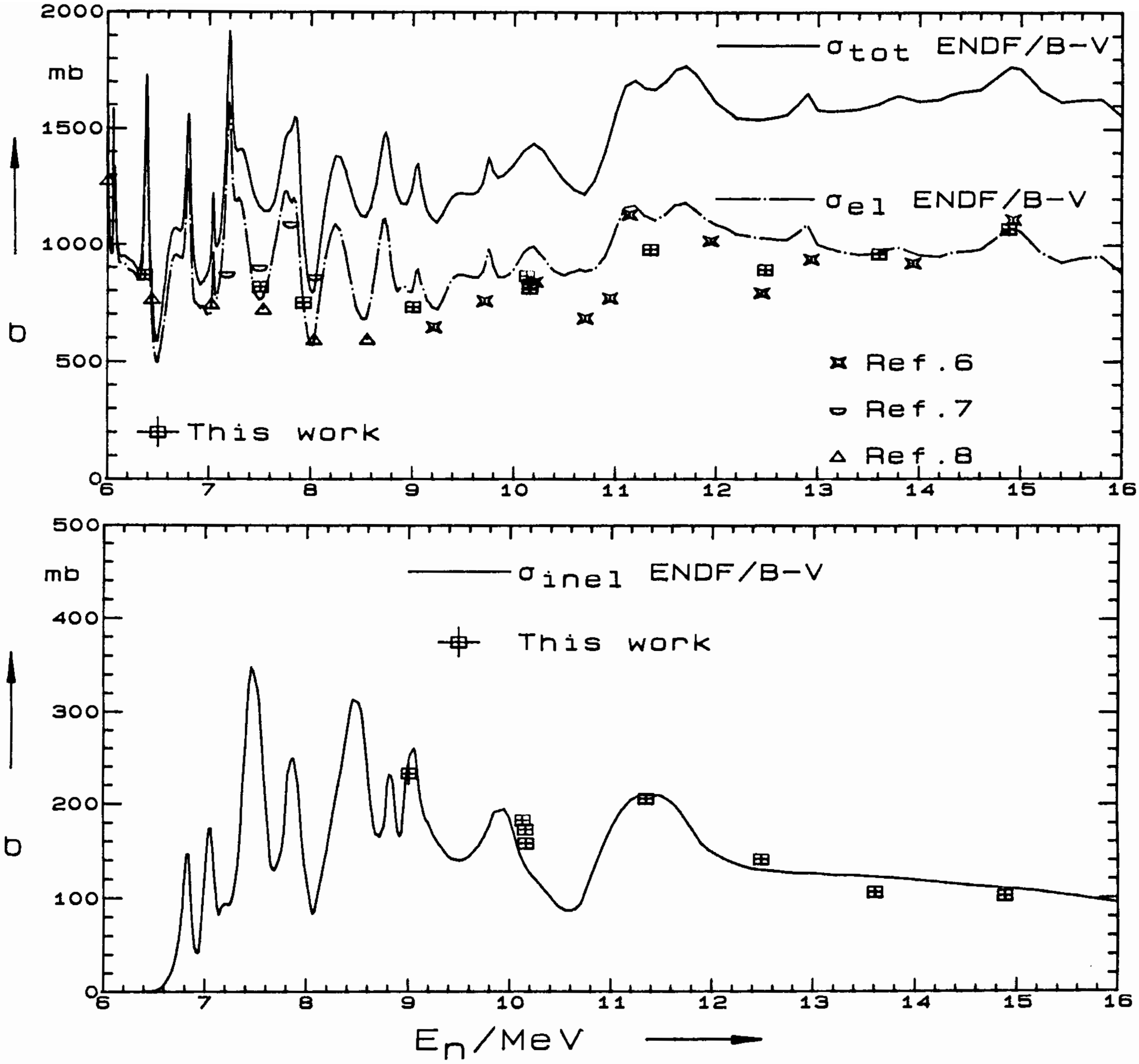

Fig.7: σ_{el} (upper) and σ_{inel} compared with ref. /1/ and /6 - 8/

Conclusion

As a result of careful experimental investigation and extensive Monte Carlo simulation of the relevant effects, highly precise data were obtained for $^{16}O(n,n)^{16}O$. Significant deviations from ENDF/B-V were found. At least in the energy range from 9 to 15 MeV, a common trend with ref. /6/ in σ_{el} and in the energy dependence of the Legendre coefficients offers a possibility of re-evaluating the cross section. Further improvements in the description of the neutron source are in progress to achieve similar accuracy for inelastic scattering data at excitation energies higher than 6 MeV.

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