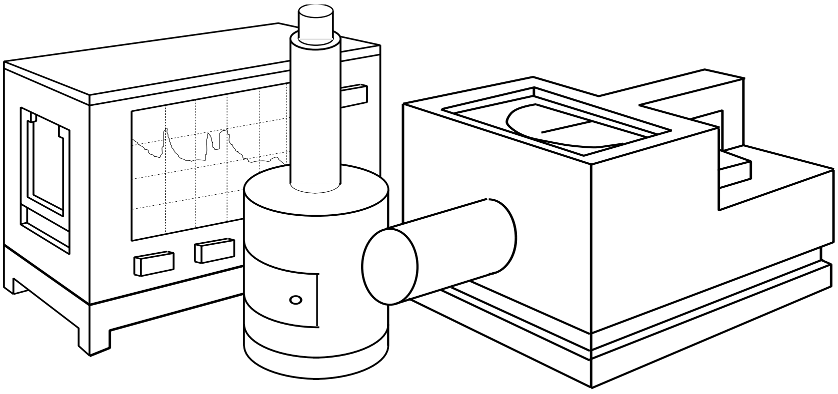
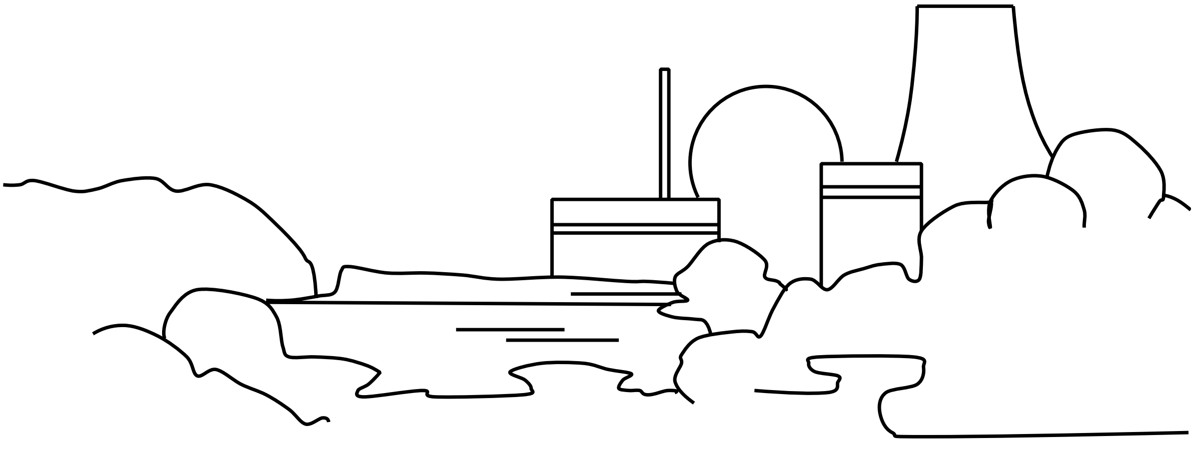
TECHNICAL UNIVERSITY DRESDEN
Institute of Power Engineering
Training Reactor



Reactor Training Course

Experiment

"Neutron Flux Distribution"



Instruction for
Experiment “Neutron Flux Distribution”

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1. Motivation

For any nuclear reactor, knowledge on the spatial neutron flux density distribution is of major interest: in research reactors, it is an input variable for many experiments (e.g. as the source strength for irradiation experiments), in power reactors, it is important for determining the distribution of heat sources. In the given experiment, the radial flux density distribution of the thermal neutrons is measured. The used method, i.e. the activation of suitable detector foils, is one of the most important methods in nuclear technology.

2. Introduction

Figure 1 shows the radial distribution of the thermal neutron flux density. It was calculated by multi-group diffusion calculations (considering both, thermal and fast neutrons). In the fuel region, the distribution approximately fits the cylindric BESSEL function $J_0(2.405 \cdot r/(R_K+\delta))$ that has its first root at $R = R_K+\delta$. The comparison of its shape with the shape of $J_0(2.405 \cdot r/R_K)$ for the bare reactor shows that due to the reflector, the reactor behaves like a bare reactor with a radius that was increased by the distance δ.

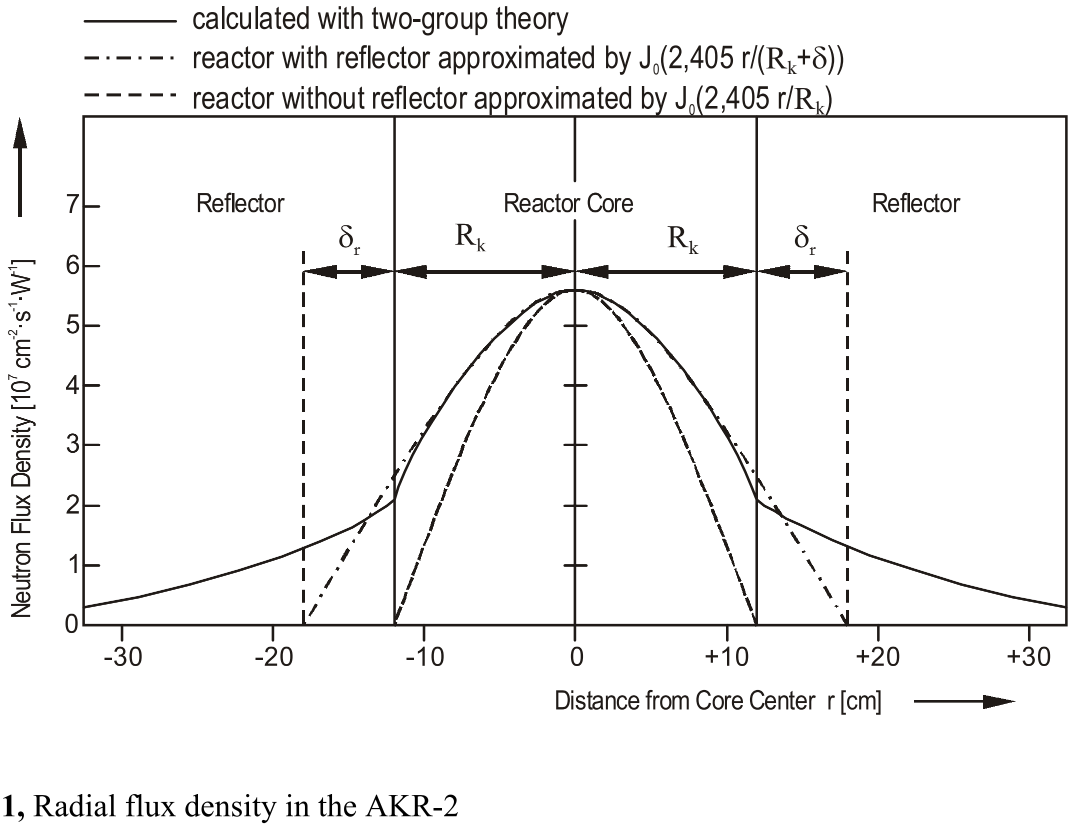

Fig. 1, Radial flux density in the AKR-2

For a reactor with a fixed (material) composition, the critical condition gives the reactor minimum size, which is determined such that the neutron losses by leakage are exactly compensated by the multiplication of the neutron content inside the core.

If adding a reflector, this minimum size, which is in the bare reactor $R = R_K+\delta$, is achieved with a much smaller core volume with the radius R_K. Thus, less of the valuable fuel needs to be utilised for a reactor with reflector than for a bare reactor. The parameter δ is called reflector saving.

Considering the axial neutron flux density, analogous results are found but with the cylinder function replaced by the trigonometric function $\cos(\pi\cdot(z/2)/(Z_K+\delta))$. The parameter Z_K stands for the half of the core height.

The parameters $B_r = 2.405/(R_K+\delta)$ and $B_Z = \pi\cdot(z/2)/(Z_K+\delta)$ of the distributions play a major role for determining the geometry. The quantity $B^2 = B_r^2+B_z^2$ is called geometric buckling because this quantity determines the second spatial derivative in the reactor fundamental equation

$$\Delta\Phi(r,z) + B^2\cdot\Phi(r,z) = 0$$

and, hence, the curvature of the flux.

3. Measurement of the Neutron Flux Density Distribution

Neutron activation samples are used as detectors. These are insensitive to γ-radiation and they can be kept small enough that they are spatially well-defined and do not disturb the reactor neutron flux density.

Several samples can be irradiated simultaneously at different positions inside the reactor such that the measurement of the relative flux density is not influenced by reactor power fluctuations.

For measurements of thermal neutrons, manganese suits well due to the reaction:

$$^{55}\mathrm{Mn}(n,\gamma)^{56}\mathrm{Mn} \xrightarrow{T_{1/2} = 2{,}58\ \mathrm{h}} {}^{56}\mathrm{Fe} + ß^- + \gamma$$

In the thermal energy region, the capture cross section of manganese (σ_0 = 13.3 b) is well proportional to the inverse neutron velocity (i.e. a so-called 1/v-absorber). Resonances exist only for energies higher than 0.337 keV and contribute to the integral cross section less than 5 %. Of course, this value can vary at different positions in the reactor because of spatial dependence of the neutron energy spectrum. But using manganese this effect can be neglected, since it ranges within the achievable error thresholds of the experiment. The half-life of 2.58 h is from the experimental point of view very convenient: On the one hand, it is large enough that time corrections are not essential and, on the other hand, it is small enough that also low neutron flux values give well-measurable activities due to approaching saturation activity. Fig. 2 shows the decay scheme and the typical gamma energy spectrum of manganese.

For the measurement of the activity of ^{56}Mn, the emitted γ-radiation is advantageously used, since the self-absorption within the sample is very low. Thus, perturbations due to irregularities due to the thickness of the sample is avoided.

Due to the design of the AKR-2, the activation samples cannot be placed into the reactor core itself. But the samples can be arranged in the central experiment channel EK1-2, which leads horizontally through the reactor core centre. If aluminium is used as a sample holder, which behaves from reactor-physics point of view like air, the activation detectors are surrounded by materials whose scattering and moderation properties are similar to those of the core and reflector materials. Thus, the measured neutron flux density distribution Φ(r) is identical to that of the reactor core which results from the two-group diffusion theory (Fig. 3).

The neutron activation detectors used in the experiment are disks of manganese having a diameter of about 1 cm. The aluminium sample holder has cuts after every 2 cm for inserting the disks. The weights of all manganese samples range between (0.048 ... 0.051) g and can be considered to be identical with regard to the overall accuracy of the experiment.

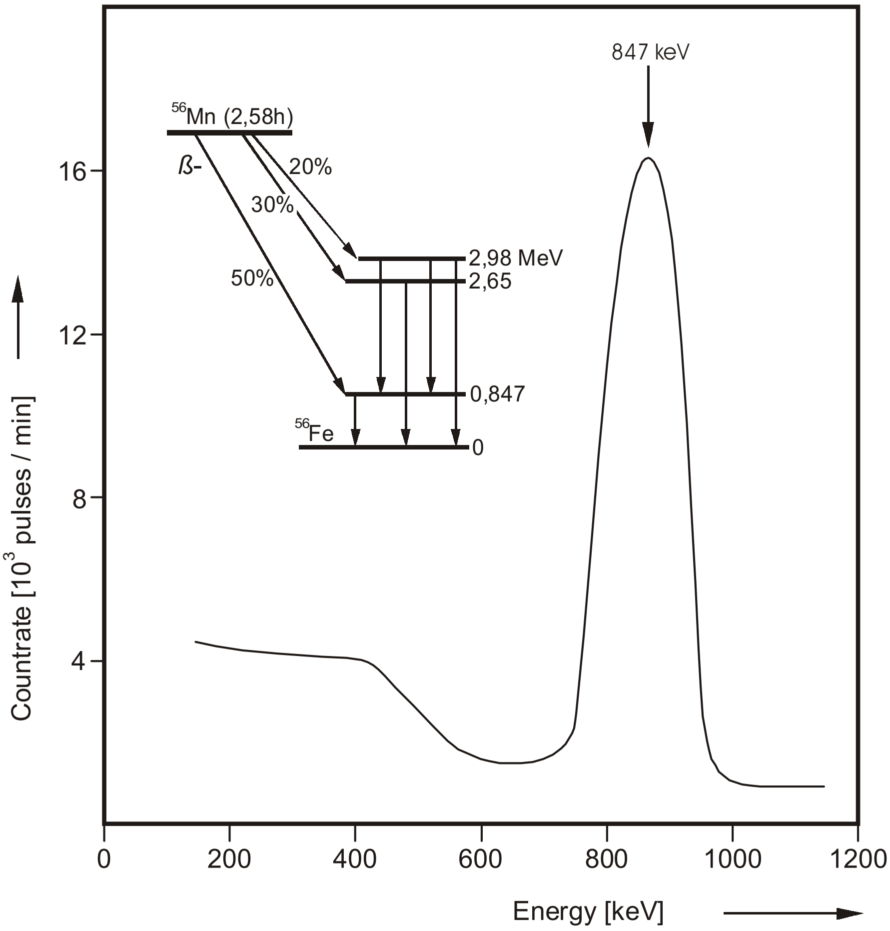

Fig. 2, Decay scheme and gamma energy spectrum of ^{56}Mn

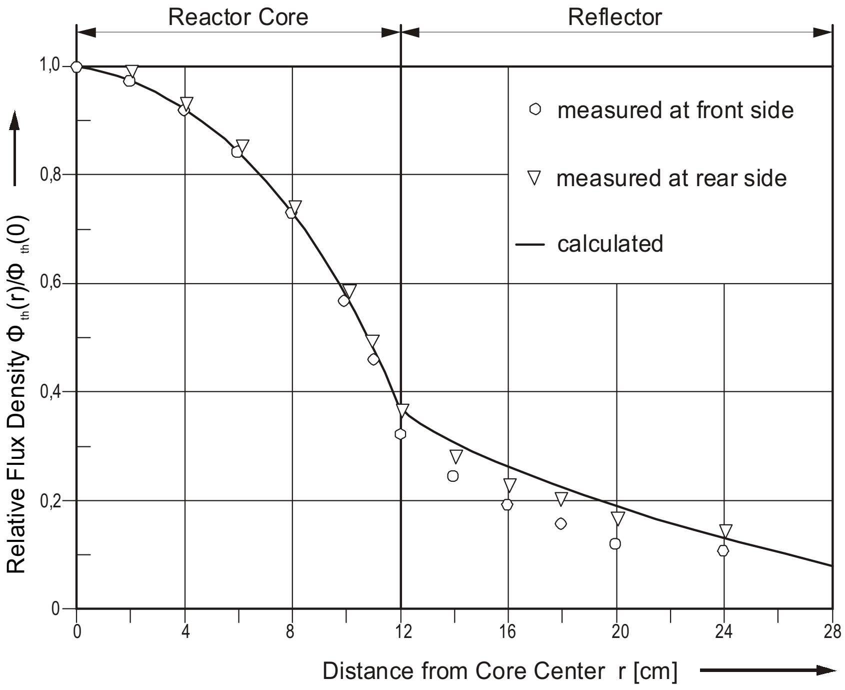

Fig. 3, Typical relative radial flux density distribution in the AKR-2

4. Instructions for the Experiment

4.1. Equipment of the Measurement

The measurement setup is presented in Fig. 4. It consists of the scintillator-photomultiplier-unit, a preamplifier and a computer for the analysis. The activation samples and the aluminium sample holder are visible in the foreground of the picture as well. The scintillator is coupled to a multichannel analyser via a preamplifier and a spectroscopic amplifier. In the preamplifier, the primary charge pulses are converted into voltage pulses (output-voltage is proportional to the input charge). In the spectroscopic amplifier, the pulses are amplified up to a range of 1 ... 10V.

The multichannel analyser recognises the incoming pulses, evaluates them with respect to their height (voltage), which contains the information about the energy, and sorts them into consecutive pulse-height channels. The result is a pulse-height spectrum that contains the energy information of all recognised gamma quants. Each measured gamma quant is a count in the corresponding energy channel of the multichannel analyser.

It should be realised that even discrete gamma energies do not cause sharp lines in the spectrum, because of statistical fluctuations of the elementary processes in the detector and in the post-processing electronics. This phenomenon creates from theoretically sharp lines GAUSSIAN bell-curves (peaks). The mean pulse heights correspond to the energy of the gamma quants. Using a PC programme, the gamma energy spectrum can either be observed on the screen, directly evaluated or saved.

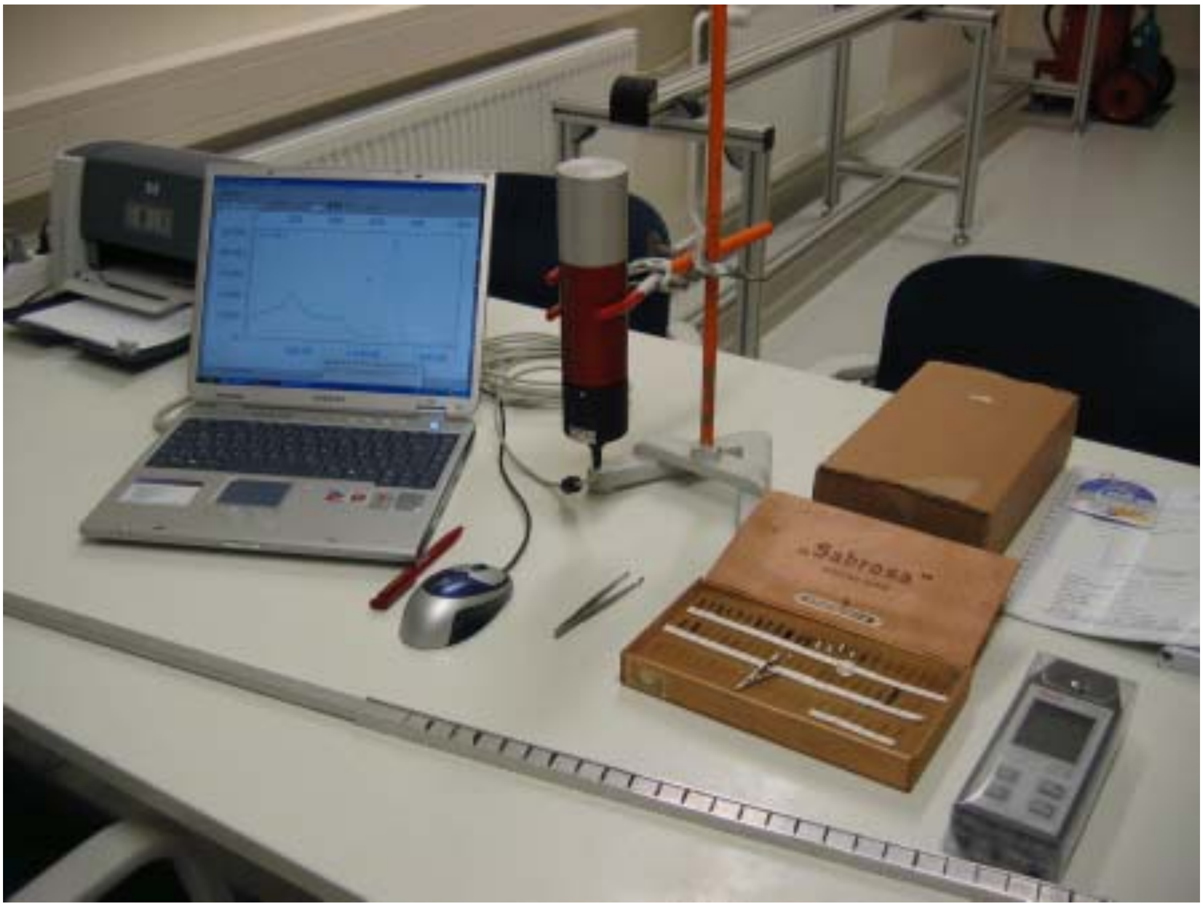

Fig. 4, Measurement equipment

Detectors for gamma spectroscopy are usually scintillation detectors (e.g. NaI) or semiconductor detectors made of Ge(Li) or increasingly high purity germanium (HPGE).

In the given experiment, NaI is used as scintillation detector for the measurements. Scintillation detectors are relatively easy to handle and have a high efficiency. A disadvantage of scintillators is the limited energy resolution, i.e. the ability to resolve two gamma peaks that are located very close to each other.

Scintillation detectors consist of a combination of a luminescent material (scintillator) that is stimulated by ionising radiation to emit flashes (scintillations) and a photomultiplier that converts the flashes into electrical pulses.

Within the scintillator, the absorbed energy of a gamma quant is converted into light by excitation of the scintillator material and its subsequent return to the ground state. For spectrometric purposes, the absorbed gamma energy and the number of emitted light quants and the subsequent pulse height at the output of the photomultiplier must be proportional to each other.

Inorganic mono-crystals made from sodium iodide (NaI) doped with Thallium for activating the light emission has proved a suitable scintillator material in spectroscopy of gamma radiation (NaI(Tl)-scintillators). Because of their high physical density $\rho = 3.67$ g/cm³, their high content of iodine of 85 wt%, and due to the ordinal number of Z = 53, they have a high absorption capability for gamma radiation. Clear crystals that are homogeneously doped and transmissible for their own fluorescent light can be produced in dimensions up to a thickness of e.g. 300 mm or diameter of 400 mm. Also high-energy gamma quants are sufficiently absorbed by these crystals. Commercially available crystals are hermetically sealed (because NaI is hygroscopic) e.g. within aluminium cases, having a glass or plastic window for the light emission. In order to avoid light losses all surfaces of the crystal except for the emission window are not polished but surrounded with a reflecting material, e.g. MgO.

The energy resolution of NaI(Tl)-scintillators is usually given with regard to the gamma line of the radionuclide Cs-137 (E_γ = 662 keV). Best energy resolution obtained with selected NaI-scintillation crystals and photomultiplier combinations are in the order of about 6 %, common values for commercial scintillator crystals and photomultipliers range between (8...12) % FWHM.

The scintillations from the crystal need to be transmitted to the photocathode of the photomultiplier with only as small as possible losses. Immersion layers (e.g. silicone oil) between scintillator surface and photomultiplier reduce total reflection.

By the photoelectric effect, a few free electrons are emitted on the photocathode. Between the photocathode and the anode of the photomultiplier, a graduated high voltage is applied via a voltage divider and a series of intermediate electrodes (dynodes). In the electric field between each two of the dynodes, the electrons accelerate and liberate further electrons by collision ionisation at the next dynode. This effect leads to a low-noise amplification of the initial number of electrons (factor 10^5...10^9). Thus, scintillation flashes are transformed into energy-proportional electric current and voltage signals and are amplified in the photomultiplier. Since ambient light would completely overlap the scintillation effect of the detector and also stimulate the photocathode of the photomultiplier to emit electrons, the entire scintillator-photomultiplier system needs to be light-tightly sealed.

4.2. Irradiation of the Activation Samples

The sample holder is filled with the manganese sample disks. For the experiment, 30 samples are arranged with a spacing of 2 cm each. This allows a full measurement of the neutron flux in the core and reflector region of the AKR-2.

Afterwards, the experimental channel EK1-2 of the AKR-2 has to be opened, inserted radiation protection plugs have to be unloaded and wipe test for checking possible contamination inside the channel have to be carried out. Then, the reactor is started and made critical at 2 W power. For the further experimental procedure, it is reasonable to use the automatic power control. At a steady-state power of 2 W, the sample holder is inserted into the experimental channel.

A label at the sample holder simplifies the positioning. The start time of the irradiation has to be recorded. The irradiation should last about 45 min. During this time, presence in front of experimental channel should be avoided due to reasons of radiation protection.

4.3. Energy Calibration of the Spectrometer

During the time of irradiation, the energy calibration of the spectrometer can be carried out.

Analysing spectra of pulse heights, only the channel numbers of peaks and the respective number of pulses per channel are available. In order to link the channel number of the multichannel analyser to the corresponding gamma energy an energy calibration of the spectrometer is necessary.

For the calibration, pulse height spectra of several well known gamma sources (calibration sources) are measured with the multichannel analyser and the channel numbers of the measured photopeaks are related to the well known photopeak gamma energies. A set of such calibration sources is available at the AKR-2 consisting e.g. of nuclides given in Tab. 1.

Nuclide	Co-60	Cs-137	Kr-85	Ho-166m	Pb-210	Am-241
Energy [keV]	1173 1332	662	514	184, 280, 411, 712, 810	47	60

Tab. 1, Calibration sources and their gamma energies

After booting the PC and connecting the scintillator (type: ScintiSpec) via USB-cable, the program winTMCA32 has to be started. Via the pull-down menu HARDWARE the high voltage can be adjusted and set to an appropriate value. In the given experiment, a high voltage of 681 V is used.

The calibration sources, one after the other, have to be placed onto the scintillator. In the pull-down menu SPEKTRUM the item ENERGIEKALIBRIERUNG has to be activated. The cursor is moved to the first photopeak whose energy shall be calibrated and is set by a double-click. The corresponding energy has to be recorded before continuing to the next line in the calibration table. This procedure is repeated for all further peaks of the calibration spectrum. Afterwards, the button FIT has to be pressed and finally the calibration is fixed with the button SETZEN. Thus, the energy calibration is ready to use for subsequent measurements.

4.4. Evaluation and Protocol

After irradiation of the samples for a time of about 45 min in the experimental channel EK1-2, the reactor has to be shut down (after having deactivated the automatic power control). The time of reactor shut-down has to be recorded. Since the half-life of the aluminium sample holder is 137 s, a high activation of the holder itself can be expected (saturation activity!). Therefore, the sample holder should remain in the experimental channel for about further 10 min after reactor shut-down for decay of its radioactivity. Only after measuring the dose rate, transportation to the evaluation desk is allowed.

For the evaluation of the activation samples, the photopeak of ^{56}Mn of 847 keV energy is used. In the given experiment, the small mass tolerances of the manganese samples are irrelevant. Though in an absolute measurement, the tolerances had to be taken into account.

For the measurement of the particular samples, the live-time of the spectrometer has to be set to 60 s. The particular samples are measured one after the other and the start time of each measurement has to be recorded. This enables a correction of the count rate that has been already decreased since the end of the irradiation. It is reasonable to elaborate a suitable routine to analyse the data.

The determination of the relative activity is done by measuring the peak areas, i.e. said more precisely the net peak areas. After the measurement of each sample, the net areas can be determined by the following functions of the program winTMCA32:

- Open the pull-down menu BERECHNEN
- Mark the peak by using the button PEAKSUCHE
- By repeated use of the pull-down menu BERECHNEN, the spectrum inside the peak limits is integrated (SPEKTRUM INTEGRIERT) and an additional window appears.
- By activation of the flag ZÄHLRATE the net pulse rate is displayed.
- After having recorded the net pulse rate, the window has to be closed and the spectrum to be deleted. Afterwards, the spectrometer is ready for the measurement of the next Mn sample.