Division 6
Ionizing Radiation

Human health and environmental protection are the major fields of work of PTB's Division 6. Here, the task is not only to render direct metrological support for medical applications (e.g. dosimetry for computed tomography), but also to carry out investigations on the fundamental understanding of the interaction of ionizing radiation in biological tissues, to deal with issues of radiation protection for personnel and patients, and to monitor our environment reliably in order to protect our citizens from the dangers of radioactive substances. By rendering metrological support for important environmental issues, we contribute to preserving and improving our living conditions. By developing modern technologies for the measurement of ionizing radiation – be it charged particles, photons or neutrons – we are involved in projects of scientific fundamental research. In the following, this will be illustrated by several examples which are taken from the period under report.

Low radon concentrations accurately measurable for the first time

Radon (Rn-222) is a radioactive noble gas which builds up especially in granite rock and escapes from the soil. It can, however, also occur in construction materials. Despite relatively low activity concentrations from approx. 50 Bq/m³ to 200 Bq/m³, radon accounts – according to the re-evaluation of the International Commission on Radiological Protection (ICRP) of its biological effectiveness – for the major share of the total exposure rate of the German population. Exposure due to medical applications is comparably strong. Thus, the new European new basic standard on radiation protection aims at reducing radon in buildings. To achieve this objective, many radioactivity measurements are required at low activity levels where the measuring instruments which are currently being used cannot be calibrated.

Thus, a novel facility for the calibration of radon measuring instruments has been developed at PTB. In a measuring chamber with an exactly known volume, a radon reference atmosphere is generated whose temporally constant activity concentration is determined by means of a newly developed transfer standard (see the cover picture of this report). The reference atmospheres are generated by transferring the radon emanated from a radium-226 activity standard into the measurement chamber via a noble-gas-tight circuit. With the aid of the known quantities "radium activity", "emanation degree", and "volume of the chamber", measuring instruments can be calibrated to determine the Rn-222 activity concentration in air at low activity concentrations between 100 Bq/m³ and 1000 Bq/m³ with relative measurement uncertainties of only 2 % in a traceable way. The new facility extends PTB's calibration offer to a – previously not available worldwide, but socially extremely relevant – range. The new calibration procedure will also considerably increase the measurement accuracy of the collected data relating to the exposure rate of human beings.

Cover picture:

Multi-wire impulse ionization chamber for the measurement of the radon activity concentration in air..

Neutron radiation in Gorleben

After the last transports of CASTOR casks to the Gorleben Transport Cask Storage Facility (TBL), it was feared that the radiation level in the village of Gorleben might be increased due to neutrons. The Ministry of the Environment, Energy and Climate Protection of Lower Saxony thus entrusted the Physikalisch-Technische Bundesanstalt with neutron radiation measurements in the centre of the village of Gorleben. The neutron ambient dose equivalent was determined at "Reference measurement hut" No. 5 (MH5), which is located approx. 2 km from the transport cask storage facility (TBL) (see Figure 1). In addition, it was checked whether – and if so, to what extent – dose contributions occur at MH5 which are not due to cosmic radiation. This was achieved by comparing the data with measurements carried out at roughly the same time on PTB's site. Ultimately, also the attenuation factor of the measurement hut was determined for the neutron radiation occurring there.

The measurements were carried out with a component of our multi-sphere spectrometer (Bonner sphere spectrometer) NEMUS. NEMUS is PTB's secondary standard for the dissemination of the unit for the ambient dose equivalent for neutron radiation in unknown radiation fields, e.g. at workplaces and in the environment.

The essential criterion for the selection of the spheres resulted from the task consisting in determining the relation of measurement values at different places (PTB in Braunschweig and MH5 in Gorleben) to be able to thereby detect a possible contribution of neutrons of artificial origin and to determine the influence of the "measurement hut" on the display of an ambient neutron monitor. It was not necessary to use the complete NEMUS spectrometer.

Fig. 1: Measurement set-up at the measuring hut MH5. The measuring hut can be seen at the back, on the right-hand-side.

Accordingly, three suitable moderating spheres of the spectrometer were chosen for the measurements.

- The core component for the investigations was the 12" sphere (diameter: 30.48 cm). Of all spheres of this spectrometer, it has the dose response with the lowest energy dependence. Thus, the 12" sphere was used for the measurement of the ambient dose equivalent on PTB's site as well as outside and inside MH5.

- The 5" sphere (diameter: 12.70 cm) has a fluence response that exhibits a maximum in the presence of low-energy neutrons. It was used as an indicator for possible changes in the neutron spectrum. It was also used on PTB's site as well as outside and inside MH5.

- The 8" sphere (diameter: 20.32 cm) was used outside MH5 in Gorleben as a monitor, unchanged during the total measurement time in order to be able to detect possible temporal variations of the radiation intensity.

In all measurements, the influences of the intrinsic background of the detectors used, of the ambient pressure prevailing during the measurements, and of the intensity of the cosmic neutron radiation were taken into account.

The measurement results of the 12" spheres show that the dose rate near MH5, 1 m above the ground, is in agreement with the value measured on PTB's premises. Thus, no contributions to the neutron ambient dose equivalent can be seen at MH5 which do not stem from cosmic radiation. The measurement results in the case of the smaller spheres seem to suggest that the different environmental conditions have a slight impact on the share of low-energy neutrons in the neutron spectrum. This, however, has no influence on the ambient dose equivalent. When comparing the measurements carried out inside with those undertaken outside the measurement hut, it turns out that no influence of the measurement hut on the neutron ambient dose equivalent of the neutron radiation occurring there can be detected.

These results are an important contribution to the concept of dose measurements at the fence of the TBL. They show that measuring instruments can be used inside MH5 to be able to determine the contribution of cosmic neutron radiation for the measurement values at the fence of the TBL.

Calibration of a neutron source for the XENON experiment

The international XENON Dark Matter Project is an experiment which is geared to searching for WIMPs (Weakly Interacting Massive Particles), a variant of Dark Matter. It has been set up in the Gran Sasso underground laboratory and uses liquid xenon as a target material to detect super-symmetrical particles. Numerous universities and laboratories worldwide are involved in this experiment.

In the detector, events are sought in which WIMPs generate a recoil nucleus and which can be detected by means of a certain signature in the measurement signals. Calibration measurements with a neutron source – which is also used to generate recoil nuclei in the xenon – determine whether an event fulfils the required criteria. Furthermore, the analysis of the events recorded has to take into account the contribution originating from the neutrons present in the underground laboratory.

These properties of the detector are investigated by means of particle transport calculations. A measurement with a weak neutron source of known source strength is necessary to validate the calculations. Within the scope of the XENON100 collaboration, a 241Am-Be neutron source was purchased and a precise measurement of the source strength of this source was carried out by PTB. For this purpose, a 3He detector of the Bonner sphere spectrometer NEMUS was used in a moderator arrangement (Fig. 2). The emission rate was determined by comparing the XENON100 neutron source with a PTB calibration source of the same type whose emission rate is traceable to national standards. Thereby, the influence of the orientation of the source inside the irradiation facility as well as its contribution to the measurement uncertainty were investigated. This result, which deviates by approx. 30 % from the nominal value of the manufacturer of the source, yields a very good agreement between the particle transport calculations and the measurements.

Measurement of the differential neutron/deuteron scattering cross section

Besides the nucleon-nucleon scattering, the scattering of a neutron on a deuteron – i.e. on a nucleus of the heavy hydrogen atom 2H consisting of a neutron and a proton – is one of the fundamental processes in quantum-mechanical few-body systems. Furthermore, the neutron-deuteron scattering is of considerable technical importance in nuclear reactors that are moderated by means of heavy water ($2H_2O$). The analysis of experiments with heavy-water-moderated critical and subcritical reactor models has led to variations of the angular distributions of the scattered neutrons between the nuclear data libraries ENDF/B-VI and ENDF/B-VII which, however, could not explain all measurement results. Therefore, the differential cross section for the neutron/deuteron scattering has been included in the High-Priority Request List (HPRL) for nuclear data measurements which is supervised by the Nuclear Energy Agency (NEA) of the OECD. In spite of its obvious technical and scientific importance, only relatively few – and partly inconsistent – measurements from the 1950s and 1960s are available for the neutron/deuteron scattering in the energy range below 1 MeV. Therefore, more recent experimental data are required to clarify the questions which have occurred.

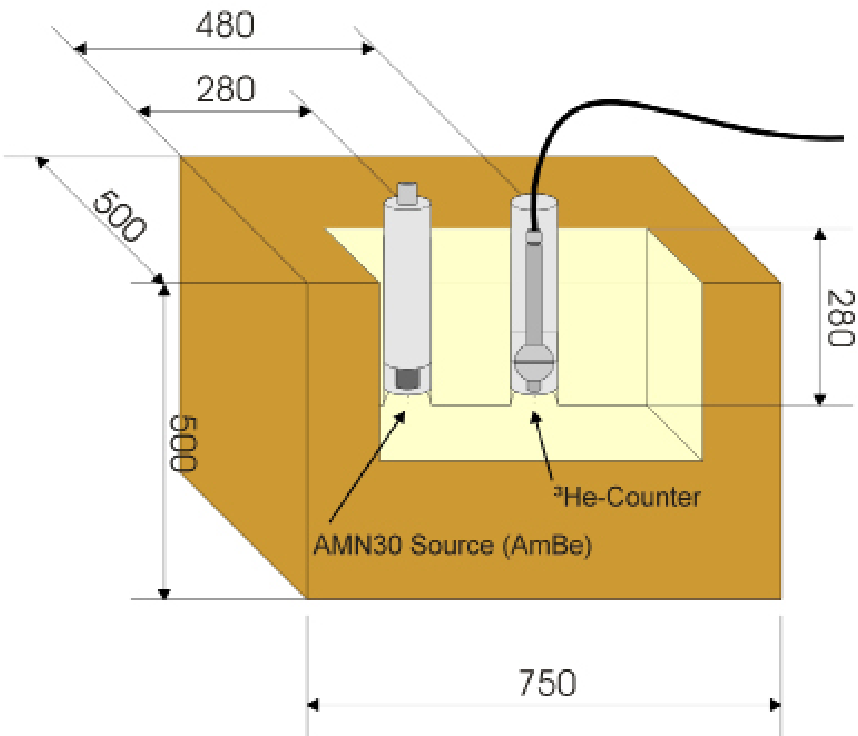


Fig. 2: Set-up for the measurement of the neutron emission rate. The 3He detector and the neutron source under test are accommodated in a moderator made of paraffin wax.

For these reasons, a first series of measurements has been carried out using PTB's proportional counter in cooperation with IRMM in Geel/Belgium. Instead of the mixture of light hydrogen ($1H_2$) and methane (C_1H_4), which is usually used as a counter gas to measure the neutron fluence, a gas mixture of heavy hydrogen (deuterium, $2H_2$) and deuterated methane (C_2H_4) was used. Thereby, the counter gas in the proportional counter is used both as a scattering target and for the detection of the recoil deuterons generated during the scattering of neutrons on deuterium. In an ideal detector, the pulse height distribution would directly reflect the differential scattering cross section in the centre-of-mass frame. In a real detector, however, mainly the finite pulse height resolution and the so-called edge effects – i.e. the incomplete energy deposition of deuterons at the edge of the counting volume – as well as the background of parasitic photons lead to distortions of the pulse height distribution. In a new experiment, the photon underground was suppressed as far as possible by electronic discrimination as well as by shielding. The edge effects as well as the contribution of carbon recoil nuclei from the neutron-carbon scattering have been modelled as accurately as possible by means of a new Monte Carlo simulation program.

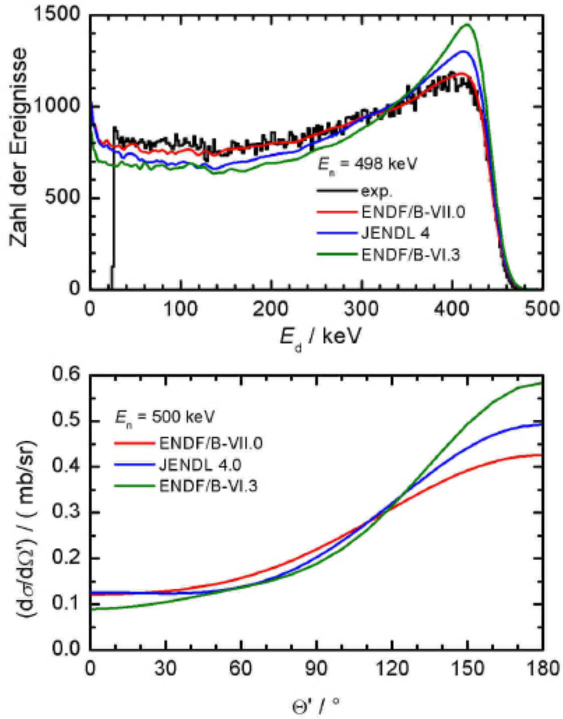


Fig. 3: Experimental (histogram) and simulated (coloured lines) pulse height distributions for a neutron energy of 498 keV (top) and cross sections used for the simulation as a function of the neutron scattering angle in the centre of mass (bottom).

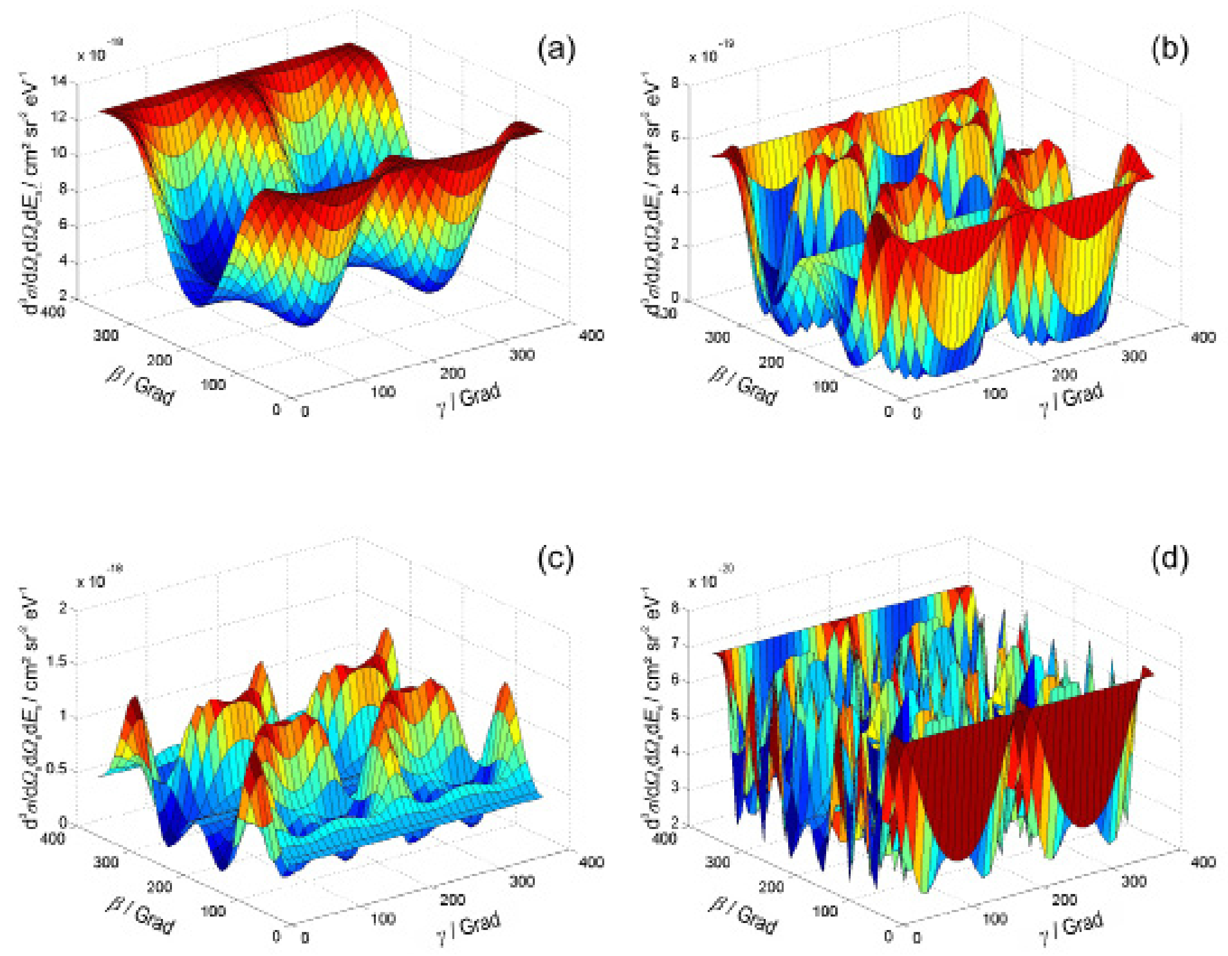
Figure 3 shows the experimental pulse height distribution of the proportional counter for a neutron energy of 498 keV as well as simulated pulse height distributions which have been calculated by means of various data sets for the differential cross section. The data used for the differential cross section in the centre of mass are represented below as a function of the scattering angle of the neutron in the centre-of-mass frame.

The results of the new measurements seem to confirm the data from the more recent library ENDF/B-VII, whereas the angle distributions from the Japanese library JENDL 4 and from the older library ENDF/B-VI show clearly too high an anisotropy at large scattering angles.

Influence of an external magnetic field on electron scattering cross sections for oriented water molecules

In radiation therapy, the attempt is being made to apply a high radiation dose to a tumour volume to kill the tumour cells or to impede their growth, whereby the healthy tissue of the organs at risk should be protected to the greatest possible extent. To increase the quality of the radiotherapy treatment, it is helpful to be able to visualize the target volume and the surrounding tissue during the irradiation. For this purpose, instruments are currently being developed which advantageously combine a linac with a magnetic resonance tomograph. In this context, the question arises as to which influence the magnetic field of the magnetic resonance tomograph has on the interaction between the radiation and the tissue. In a first approach, the influence of a magnetic field on the electron ionization cross sections for the elastic scattering and the ionization on water molecules was investigated. This study, which was carried out within the scope of the EMRP JRP "MRI safety" project [http://www.ptb.de/emrp/mri.html], was aimed at finding out whether the scattering ionization cross sections would have to be modified in a conventional Monte Carlo simulation program for dose calculation if the radiation transport were simulated in a magnetic field.

In order to determine these quantities, the differential cross sections for electron scattering were, in a first step, calculated theoretically on oriented water molecules. The orientation of the water molecule was defined by means of the Euler angles (α, β, γ) which describe a sequence of rotations around the axes of the water molecule and calculate the differential electron cross sections for different values



of the Euler angles from 0° to 360°. The differential cross sections for the elastic scattering were calculated by means of the Independent Atom Model (IAM), whereas for the ionization, an approach was used which is based on the first Born approximation. Examples of the results obtained are shown in Figure 4; they demonstrate the strong dependence of the scattering cross sections on the Euler orientation angles. The mean value of the ionization cross section without a magnetic field was determined by an integration over the three Euler angles. In a second step, the presence of a magnetic field was taken into account. The magnetic field leads to an energy difference between different orientations of the water molecules with regard to the magnetic field. To determine the mean value of the differential cross section in the magnetic field, the statistic distribution of the relative number of molecules with a specific orientation was taken into account by means of a Boltzmann factor.

The results of the calculations show that there are no significant differences between the mean values of the differential cross sections for oriented water molecules with and without a magnetic field. A modification of the ionization cross sections in the Monte Carlo simulation program for dose calculation is thus not necessary if a magnetic field is to be taken into account in the simulation.

Fig. 4: Differential cross sections for the elastic electron scattering on an oriented water molecule as a function of the Euler angles β and β for scattering angles of 30° (left) and 90° (right) and for different energies: 50 eV (a and b), 200 eV (c and d).

Stopping power of liquid water for carbon ions

In radiation therapy with heavy ions, the stopping power of water is the elementary quantity for the calculation of the dose distribution when planning treatment. For high projectile energies, the stopping power can be calculated theoretically by means of the Bethe-Bloch formula, whereas for low projectile energies in the region of the maximum stopping power, complex interactions prevail for which there has not been a valid theory so far. In this energy region, there exist no experimental data with regard to the stopping power for heavy ions. Instead, measurements carried out in water vapour or D2O ice are extrapolated on the liquid phase.

The stopping power of liquid water for carbon ions with energies in the region of the maximum stopping power can be determined by means of the so-called “Inverted Doppler Shift Attenuation Method”. For this purpose, excited carbon ions are generated by bombarding a thin carbon target with α-particles. To this end, a target has been developed which consists of a thin inlet foil made of tantalum on which a 20 nm thick carbon layer has been deposited. The inlet foil serves to separate the water volume from the vacuum of the beamline, with an only minor influence on the energy and angle distribution of the α-particles and a negligible underground production.

While the excited carbon ions move through the water volume, they slow down and decay into their ground state. The energy of the γ-quantum emitted during the decay of the nuclei into the ground state is increased according to the Doppler shift which depends on the velocity vector of the carbon nucleus at the moment of decay and on the emission direction of the γ-quantum. The energy distribution of the γ-quanta is recorded by a high-purity germanium spectrometer.

The measured γ-spectrum, which is a convolution of the start energy distribution of the excited carbon nuclei with the γ-energy-distribution caused by the Doppler shift during the stopping process, bears the information on the stopping power of the target medium. To determine the start energy distribution required for the deconvolution, a Doppler distribution representing the decay of the carbon nuclei in vacuum can be used. For this purpose, the possibility of an area which can be evacuated behind the carbon layer has been envisaged for the new target system. A first experiment was carried out at PTB›s ion accelerator facilities. Thus, the newly constructed target was tested and the underground to be expected was estimated (see Figure 5). The experiment carried out shows that the measurement of the stopping power of water by means of the Inverted Doppler Shift Attenuation can, as a matter of principle, be realized.

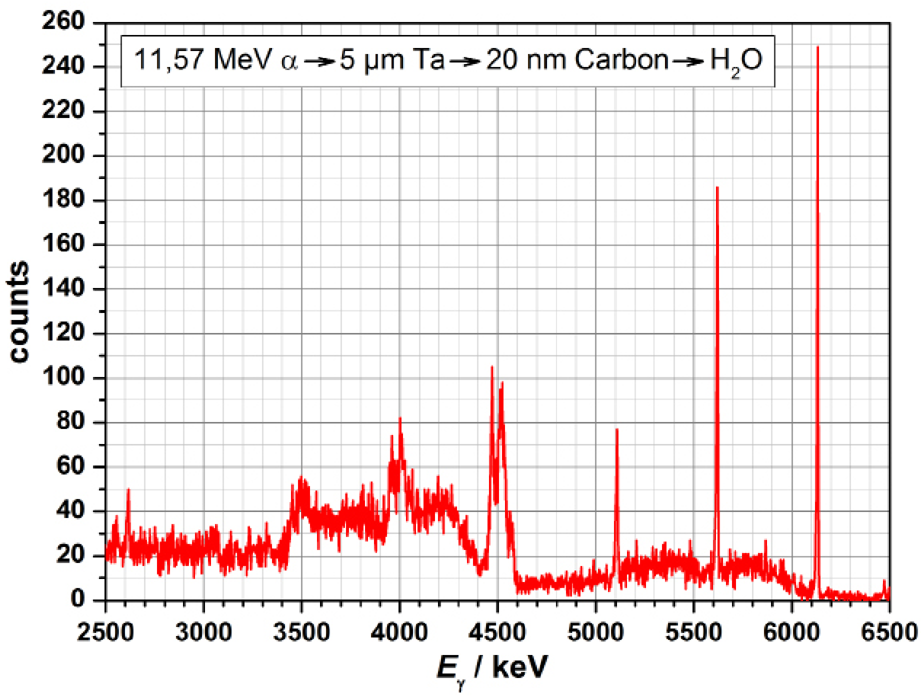


Fig. 5: β-energy-spectrum obtained after approx. one hour of measuring time. The lines around 4.5 MeV represent the energy spectrum of the β-quanta that are emitted when carbon projectiles are slowed down in liquid water and are clearly separated from the remaining background.

Headlines: News from the Division

Fundamentals of Metrology

ICRU Committee on Radon Measurements and Reporting of Radon Exposures

Detection and decision limits: Simultaneous radon/thoron measurements with passive measurement systems

Experimental determination of radiation quality correction factors for frequently used types of ionization chambers

Characterization of an X-ray storage foil system for the 3D measurement of the absorbed dose to water in a miniature X-ray tube

Determination of the spatial response function of ionization chambers in electron and photon radiation fields

Measurement of the differential neutron/deuteron scattering cross section in the energy range from 100 keV to 600 keV by means of a recoil-proton proportional count

New ^{252}Cf source for the irradiation facility with neutron sources of PTB

Calibration of a neutron source for the XENON experiment

Investigation of electron-impact-induced fragmentation processes of DNA components

Doubly differential inelastic electron scattering cross sections of trimethylphosphate

Improving the track structure simulation of alpha particles in nitrogen and propane

Track structure of carbon ions of different energies characterized nanodosimetrically

Measurement of the stopping power of liquid water for carbon ions

Influence of an external magnetic field on electron scattering cross sections for oriented water molecules

Calculation of the diamagnetic tensor of the water molecule

Metrology for the Economy

Highly sensitive coulometer for the measurement of ionization chamber currents

Metrology for Society

Low radon concentrations accurately measurable for the first time

Low-level radon standard chamber goes on line
A medical CT scanner for dosimetry

Measurements in the scattering radiation field of a medical accelerator

Research project for fundamental improvements in radiation therapy: by means of a microbeam and nanodosimetry

Measuring neutron radiation in Gorleben
Neutron monitor AGREM – test measurements in pulsed radiation fields

Deconvolution algorithm for element reconstruction in neutron resonance radiography