Neutron detector development and measurements around particle accelerators

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Various neutron detectors for spectrometry, environmental dosimetry and personal dosimetry have been developed by our group. For high energy neutron spectrometry, spallation detectors of C and Bi, large plastic and NE-213 scintillators, self TOF detector have been used for neutron production and shielding experiments at several high energy accelerator facilities, ISIS of Rutherford Appleton Laboratory, UK, Two-mile Linac of Stanford Linear Accelerator Center, USA, HIMAC of National Institute of Radiological Sciences, Japan, and RCNP of Osaka University, Japan. The response functions of these detectors have been obtained by measurements and calculations. Thick target neutron yields produced from high-energy particles from protons to Xe ions have been summarized, together with shielding benchmark experiments through concrete and iron at these facilities. Neutron measurements over wide energy range including cosmic neutron field were done with Phoswich detector and Bonner sphere spectrometer. For environmental neutron dosimetry, two types of dose equivalent dosimeters, so-called rem counters, high-sensitive type and light-weight type, have been developed and for personal dosimetry, silicon semiconductor dosimeter has been developed for use in nuclear facilities. These dosimeters have good quality to give ambient and personal dose equivalents for neutrons in the mixed radiation fields. The outline of these works will be reviewed in this paper.

Keywords: Neutron spectrometry, Neutron dosimetry, Thick target neutron yield, Shielding benchmark experiment, Induced radioactivity

1 Introduction

For neutron measurements in nuclear facilities, the multi-moderator spectrometer, so-called Bonner Ball, the organic liquid scintillator, the activation detector have been widely used as spectrometers. At present, high-energy and high-intensity particle accelerators are increasingly used for various purpose. Radiation environment around these accelerator facilities is dominated by high-energy radiation, especially high-energy neutrons of strong penetrability. For neutrons of energies beyond 100 MeV, there had been no suitable spectrometers with reasonable resolutions. Our group has then developed the self-TOF detector using the NE102A plastic scintillators, large-scale NE213 organic liquid scintillator and spallation detectors of C and Bi, especially for use in neutron target and shielding experiments. For use in the charged particle and neutron mixed field, the following detectors are realized: (1) Phoswich detector which combines the NE115 plastic scintillator and the NE213 scintillator, (2) Anti-coincidence detector system using $\Delta E$ and $E$ counters.

The neutron dosimetry for surrounding environment and working personnel in nuclear facilities is also important for radiation protection purpose. For neutron dosimetry in the surrounding environment, the dose-equivalent counter, so called rem counter and Bonner ball have been widely used in various facilities. Since the conventional Bonner ball and rem counter using inner thermal neutron detector of BF$_3$ counter, LiI(Eu) scintillator or $^3$He counter had rather low sensitivity to environmental neutrons, we have developed two types of environmental neutron dosimeters, high-sensitivity rem counter and high-sensitivity Bonner ball by using a large volume counter filled with high pressure $^3$He gas, and the former is commercially available from Fuji Electric Co. At present, the cosmic-ray neutron on the ground becomes a serious problem to cause the soft errors in the semiconductor devices, SRAM and DRAM, so the cosmic-ray neutron measurement is strongly required$^1$. Our Bonner ball is now installed as the neutron detector in the Japan experimental module of the International Space Station (ISS). We have also newly developed a light-weight rem counter of only 2 kg without using moderator. This counter uses a mixed gas of methane and nitrogen. For personal neutron monitoring, the passive-type dosemeters have been widely used, but obviously there is a strong need for a real-time neutron dosemeter. We have developed the real-time wide-range personal neutron dosemeter...
using two silicon semiconductor detector, which is now commercially available from Fuji Electric Co. This dosemeter has good characteristics fitted to the fluence-to-dose conversion factor in the energy range from thermal energy to several tens MeV.

Thick target yield (TTY) generally means the angular-energy distribution of secondary neutrons produced from a thick target which has enough thickness to fully stop the incident particles. The TTY data are indispensable for estimating source terms to be used in the accelerator shielding design. A large number of experiments to give the TTY data have been published for various targets bombarded by light particles such as protons and deuterons. The neutron detectors are mostly NE-213 organic liquid scintillator with the TOF method and some with the unfolding technique. Activation detectors are also used in a few experiments. The TTY data for projectile ions heavier than He ions of energies above about 20 MeV/nucleon have been published as a handbook written by Nakamura and Heilbronn.

Many experiments on neutron shielding have been performed using various accelerators. Among them, the benchmark experiments are defined here as follows:

(1) neutron energy spectra penetrated through shields with different thicknesses are given,
(2) source neutron energy spectrum is also given by experiment and/or calculation,
(3) experimental geometry is relatively simple or well-defined.

These benchmark experiments are quite useful for investigating the accuracies of calculation codes, nuclear reaction model and cross-section data, but they are still limited in number. Here in this paper, one representative benchmark experiment for high-energy accelerator facilities using the above neutron detectors is briefly described.

An important component in the design of high-energy and high-intensity accelerator facilities is an accurate estimation of the radioactivities induced by spallation products in accelerator components and in shielding materials. To this end, the production cross-sections are given for various spallation products by high-energy heavy ions measured by our group.

2 Development of Neutron Spectrometers

2.1 Spallation detectors of C and Bi

The spallation reactions of C and Bi induced by neutrons are used to detect high energy neutrons. The activation detectors are useful without a pulse pile-up problem in a burst-pulse field, but have generally low detection efficiencies. Large-volume activation detectors are, therefore adopted in order to obtain high detection efficiencies. The $^{12}\text{C}(n,2n)^{11}\text{C}$ reaction has a threshold energy of about 20 MeV and the cross-section has been measured by Kim et al. up to 150 MeV by using the $p-\text{Li}$ quasi-monoenergetic neutron fields. The $^{12}\text{C}(n,2n)^{11}\text{C}$ reaction has an almost constant value of about 20 mb above about 20 MeV and the half-life of $^{11}\text{C}$ is about 20 min, which makes a good rapidly-activated neutron flux monitor for an energy above 20 MeV. Bismuth detectors using the spallation reactions of $^{209}\text{Bi}(n,xn)^{210-x}\text{Bi}$ ($x=3$ to $12$) are more useful for high-energy neutron spectrometry. The cross-section data were also measured by Kim et al., in the energy range 20-150 MeV and the measured data are in good agreement with the ENDF/B-VI high-energy library data calculated by Fukahori with the ALICE code, as can be seen in Fig. 1. Their threshold energies regularly increase from 14 MeV of $^{209}\text{Bi}(n,3n)$ to 88 MeV of $^{209}\text{Bi}(n,12n)$ with an interval of 8 MeV corresponding to the binding energy per nucleon. The half lives of $^{200}\text{Bi}$ to $^{206}\text{Bi}$ are between 36.4 min. and 15.31 days.

![Fig. 1 — Comparison of measured and calculated reaction cross-sections of Bi(n,xn) ($x=3$ to $12$)](image-url)
2.2 Organic liquid scintillator

NE213 (or BC501A) organic liquid scintillator is widely used for high energy neutron spectrometry because of good quality of neutron and photon discrimination and energy resolution. The physical characteristics of the NE213 scintillator, such as response function, detection efficiency and light output yield, are well known in detail for neutrons below 20 MeV through many studies. For higher energy neutron measurement, a large-size NE213 detector, 12.7 cm diameter by 12.7 cm long, coupled with a photomultiplier (Hamamatsu R4144) has been used in our group. The response functions to neutrons with energies between 50 and 800 MeV measured by Sasaki et al. at the heavy ion medical accelerator facility (HIMAC), National Institute of Radiological Sciences (NIRS), Japan are shown in Fig. 2.

Recently, Satoh et al. also measured the response functions of the 12.7 cm diameter by 12.7 cm long BC501A detector up to 800 MeV. In order to measure high-energy neutrons with higher efficiency and better energy resolution, a bigger 25.4 cm diameter by 25.4 cm long NE213 scintillator is now in use.

2.3 Self-TOF detector

Sasaki et al. developed the Self-TOF detector for high energy neutron spectrometry behind a shield. The Self-TOF detector consists of radiator detectors, a start counter and a stop counter of nine segments. A schematic drawing of the detector is shown in Fig. 3. The radiator, called RAD, is a stack of 20 thin plastic
scintillators (NE102A) of 10 cm × 10 cm with 0.6 cm thickness. Each plastic scintillator is viewed by a 0.95 cm diameter photo-multiplier (Hamamatsu R1635) through a light guide. The start counter, called START, is a plastic scintillator (NE102A) of 10 cm × 10 cm × 0.6 cm viewed by two 5.08 cm diameter photo-multipliers (Hamamatsu R2083) from both sides through each light guide. The stop counter, called STOP, is designed to cover an area of 60 cm × 60 cm and is segmented into nine plastic scintillators (NE102A) of 20 cm × 20 cm × 2 cm, each of which is viewed by a 12.7 cm diameter photo-multiplier (Hamamatsu R1259) through a light guide. The distance between the start and stop counters is adjustable, and is chosen to be 1.2 m for a usual measurement. An in-coming neutron produces charged particles in twenty radiators, and then the charged particles emitted in the forward direction reach any one of nine stop counters through the start counter. The energy of the charged particle is determined by using the TOF (Time-of-Flight) method between the start and stop counters. In this detector, only proton events from H(n,p) and C(n,p) reactions were selected to obtain the detector response function. The neutron energy spectrum can be obtained from the measured proton energy spectrum using an unfolding method with the response functions. The response functions of the Self-TOF detector for high energy neutrons up to 800 MeV were measured at HIMAC of NIRS. This detector has almost constant efficiency of about 10⁻³ % for high energy neutrons above about 100 MeV.

2.4 Multi-moderator detector (Bonner ball)

Various types of multi-moderator spectrometer, so-called Bonner ball, have been widely used for neutron spectrometry due to its simplicity and the usability over a wide range of neutron energies spanning from thermal to MeV. However, the energy resolution is poor and an initial guess spectrum is required for iterative calculation of unfolding. Uwamino and Nakamura¹⁰ developed the two types of Bonner ball. One type has a high neutron sensitivity and another has no sensitivity to gamma rays, and both uses only five polyethylene moderators. The high-sensitivity type uses a 5.07 cm diameter spherical ³He proportional counter filled with 5 or 10 atm ³He gas (manufactured by LND Inc.) which is covered with polyethylene moderators of 0 cm (bare), 8.0 cm (1.5 cm thick), 11 cm (3.0 cm thick), 15 cm (5.0 cm thick), and 23 cm (9.0 cm thick), respectively. The gamma-ray insensitive type uses an indium activation detector. In a cylindrical acryl having a spherical hole of 0.735 cm radius, In₂O₃ powder of 2.875 g is tightly filled. The detector is inserted into the center of polyethylene of 2.02, 3.22, 5.33 and 9.83 cm radii, respectively. The response functions in the energy range from thermal to 1 GeV were determined by Uwamino et al.¹⁰ and by Nunomiya et al.¹¹ using the ANISN¹² and MCNPX codes¹³.

2.4.1 Phoswich detector

In the phoswich detector, the two scintillators are optically coupled to a single photomultiplier tube (Hamamatsu H1949) by Takada et al.¹⁴. A cross-sectional view is shown in Fig. 4. Surrounding the

![Fig. 4 — Diagram of the phoswich detector by Takada et al.](image)
liquid scintillator is a thin slow plastic scintillator (NE115, 5 mm thickness) with a low sensitivity to neutral particles. The inner detector is a liquid organic scintillator (NE213, 58.5 mm diameter × 58 mm length) that has much greater sensitivity to neutrons. Charged particles are detected by both scintillators. The light in the NE115 from charged particles has a long characteristic time constant of about 225 ns, whereas the light in the NE213 by recoil protons from energetic neutrons has a time constant of about 30 ns and that by Compton electrons from gamma rays is about 3.7 ns. These differences in the light-decay time constant make it possible to separate pulses of the three different particle species. Protons, neutrons and gamma rays are detected separately by the use of a pulse-shape discrimination technique based on standard CAMAC charge integration ADCs. The charge integration of the signal is carried out during the time period specified by a gate pulse (total-gate, slow-gate). The total and slow components can be analyzed by a total gate pulse adjusted at the peak of the signal and by a wider delayed slow gate set at the long tail of the signal, respectively.

3 Development of Neutron Dosemeters

3.1 High sensitivity type and light-weight type portable dosemeters

Two types of high sensitivity rem counters were fabricated by using large volume and high pressure $^3$He spherical proportional counters, one filled with 10 atm $^3$He and having a 5.08 cm (2 inch) diameter, the other one filled with 5 atm $^3$He and having a 12.7 cm (5 inch) diameter. They are simply referred to as 2-in.-diam $^3$He rem counter and 5 inch diameter $^3$He rem counter, respectively. The responses of these two rem counters to neutrons of energy from thermal to 15 MeV were also measured in the national neutron standard field. The measured results are shown in Fig. 5 by comparing with the response of the first Anderson-Braun (A-B) type rem counter, Studsvik 2202D, which has been most widely used, and the formerly-used fluence-to-dose conversion factor given by ICRP-21. Our 2 in diameter and 5 inch diameter $^3$He rem counters have about 10 and 70 times higher sensitivities than the Studsvik 2202D rem counter, respectively, and at present, they still have highest sensitivities among the commercially available rem counters in the world. The 2 inch diameter $^3$He portable and stationary rem counters, NSN1 and NDN1, respectively, are now commercially available from Fuji Electric Systems Co. Ltd., as shown in Fig. 5.

Light-weight type portable dosemeter of only 2 kg in weight has recently been developed without using moderator. This dosemeter shown in Fig. 6 uses mixed gas of methane and nitrogen and can measure fast neutrons above several hundreds of keV using the
elastic scattering reaction of hydrogen and slow neutrons using the $^{14}$N(n,p) reaction.

By using these two reactions, the neutron ambient dose equivalent can be obtained using the spectrum-weighting G(E) function method. Neutron detection efficiency is $0.35 \text{s}^{-1}/(\mu\text{Sv h}^{-1})$ for $^{252}$Cf neutron source. It is found in Fig. 6 that the relative responses obtained for mono-energetic and continuous energy neutrons have a good quality of within 50% difference from thermal neutrons to 15 MeV neutrons.

### 3.2 Personal silicon semiconductor dosimeter

The personal neutron dosemeter using two silicon detectors, a fast neutron sensor and a slow neutron sensor, has been developed. Fig. 7 shows the cross-sectional views of the fast and slow neutron sensors.

The fast neutron sensor is a $10 \times 10$ mm $p$-type silicon on which an amorphous silicon hybrid is deposited. The fast neutron sensor is in contact with 80-μm-thick polyethylene radiator to produce recoil protons from the H(n,n) reaction, and can measure neutrons of energy above 1 MeV. The slow neutron sensor is also a $10 \times 10$ mm $p$-type silicon on which a natural boron layer is deposited around an aluminium electrode to detect $\alpha$ and Li ions from the $^{10}$B(n,$\alpha$)$^7$Li reaction, and sensitive to neutrons of energy less than 1 MeV.

This dosimeter is now commercially available from Fuji Electric Co. Ltd., as shown in Fig. 7. This dosemeter can measure the neutron personal dose equivalent by adding the dose equivalent from thermal to 1 MeV neutrons, $H_s$, and that above 1 MeV neutrons, $H_f$, which are measured by the slow and fast neutron sensors, respectively.

### 4 Thick Target Neutron Yield measurements by High-energy Protons to Xe Ions

#### 4.1 TTY (double-differential thick-target yields) by protons

Many TTY experimental results produced by light ions, such as protons, deuterons and alpha particles, have been published. The results are not described here in this review paper due to limited pages. They are published elsewhere.

#### 4.2 TTY (double-differential thick-target yields) by heavy ions

Systematic TTY experiments for heavy ions from He to Xe ions having energies of 100 to 800 MeV/nucleon using HIMAC. The TTY results in the forward direction of 0 to 90 degrees from the HIMAC series of experiments are shown in Fig. 8 for 400 MeV/nucleon C ion on C, Al, Cu and Pb targets. In general, the spectra in the forward direction have a broad peak at the high-energy end. The peak energy usually occurs at about 60 to 70% of the beam energy per nucleon. As the target mass becomes lighter and the projectile mass increases, the high-energy peak becomes more prominent. For example, the dependence on target mass can be clearly seen comparing between C and Pb targets. Most of the neutrons in this high-energy, forward region come from the breakup of the projectile and direct knock-on processes. The peak yield of the knock-on neutrons increases with decrease in the mass number of target nuclei. This is because the ratio of the cross-section of peripheral collision, which is a main source of the knock-on neutrons, to that of the central collision, which is a main source of evaporation process, is inversely proportional to the radius of the target nucleus.
At the high-energy end of the neutron spectra in the most forward direction, the high-energy tail spreads up to 2.5 times the incoming beam energy per nucleon. This can be explained by considering high-momentum components of a Fermi motion in a nucleus. At energies below 20 MeV, the spectra are dominated by the breakup of the target, evaporation process. Because the target remnant is moving slowly in the lab frame, that source of neutrons is essentially isotropic. As such, target-like neutrons can be seen at all angles. As target mass increases, the relative contribution to the overall spectra from target breakup increases. This feature can be seen by comparing 400 MeV/nucleon C + C and C + Pb spectra at low energies.

As can be seen in Fig. 8, the calculation with PHITS gives overall good agreement with the experimental data within a factor of three, except for a few cases. Uncertainties in the PHITS results are not plotted in Fig. 8, and in general are on the order of about 5%-15%, except for the highest energies, where the uncertainties can be greater than 50%. It is noted that the dropping curve at the high energy end of neutron spectra in the most forward direction is reproduced well by PHITS. This means that the QMD (Quantum Molecular Dynamics) model is able to...
trace the behaviour of nucleons inside the nucleus including Fermi motion, and give proper relativistic correction for nucleus-nucleus interaction.

A systematic underestimation, however, appears around the broad peak of knock-on neutrons. This deviation should be further revised by considering the nucleon-nucleon interaction.

5 Shielding Benchmark experiments at High Energy Accelerator Facilities

Above 100 MeV, the neutron shielding experiments have been done only with the white (continuous spectrum) neutron sources at various accelerator facilities. These experiments are summarized in a review article. Here in this paper, one benchmark experiment at HIMAC is briefly described.

5.1 Experiments using 400 MeV/nucleon carbon ions on Cu at HIMAC, NIRS

Neutron energy spectra penetrated through concrete and iron shields were measured by Sasaki et al. at the HIMAC facility of National Institute of Radiological Sciences using three types of detectors: the Self-TOF detector, an 12.7 cm diameter × 12.7 cm long NE213 organic liquid scintillator, and C, Bi activation detectors. The neutrons were produced by bombarding 400 MeV/nucleon $^{12}$C ion beams on thick (stopping-length) copper target. The target size was 10 cm × 10 cm and 5 cm thick. A transmission-type ionization chamber was placed behind the end window of a beam line as a beam monitor. An NE102A plastic scintillator (100 mm × 100 mm and 3 mm thick) was also used as a relative monitor. The Self-TOF detector was placed 506 cm downstream from the target front face on the beam axis. An iron collimator of 60 cm × 60 cm and 40 cm thickness with a hole of 10 cm × 10 cm was set in front of the Self-TOF detector to decrease the accidental signals which were induced by the incidence of fragment charged particles on the stop counters, as well as to inject neutrons almost normally into the detector. The veto counter (150 mm × 150 mm and 5 mm thick NE102A plastic scintillator), was placed in front of the radiator to remove charged particles from neutrons. During the experiment, the Self-TOF detector was fixed at the same position. On the other hand, the NE213 detector was placed both in contact with the shielding surface and 5 m downstream of the copper target on the beam axis. The latter point was selected for comparison with the Self-TOF results. The concrete shield slab has 100 cm × 100 cm and was put onto the steel platform to fix the center of the shield on the beam axis. The assembly of iron shields of 100 cm × 100 cm and 10 cm thickness was put onto the steel platform to fix the center of the shield on the beam axis. The thickness of iron shield assembly was changed to be 20, 40, 60, 80 and 100 cm. The mass density of iron shield is 7.8 g cm$^{-3}$.

Figure 9 shows the neutron fluxes (per steradian per MeV per ion) behind 0, 50, 100, 150, 200 cm of concrete, and 0, 20, 40, 60, 80, 100 cm of iron, using the self-TOF detector and the NE213 detector, together with the source neutron spectrum. The self-TOF detector gives the neutron spectra above the low-energy threshold of 100 MeV because low energy recoils range out in the radiator, and below 600 MeV due to a lack of statistically-significant events. The spectra have a broad peak around 200 to 300 MeV, and little softening of the spectra can be seen with increasing shield thickness. The NE213 detector gives the neutron spectra from 20 to 800 MeV. Both spectra given by self-TOF and NE213 are generally in good agreement with each other, although the broad peaks are not seen in the NE213 spectra. The dashed lines show MCNPX calculations of the spectra.

The calculations, in general, give a harder spectrum than the measurements. Below 100 MeV, the

![Fig. 9 — Comparison of measured and calculated neutron energy spectra penetrating through concrete (a) and iron (b) shields. Broken line indicates the source neutron spectrum measured with the TOF method by Kurosawa et al.](image-url)
calculations overestimate the data as the shielding thickness increases. Between 100 and 400 MeV, the agreement between experiment and calculation is good. The agreement between calculation and experiment is quite good over the entire energy range (20-800 MeV) at 20 cm iron shield, and 50, 100, 150 cm concrete shields.

5.2 Attenuation Lengths of Neutron Flux and Dose Equivalent

These experiments cited in the first part of this section give the attenuation lengths of neutron flux and dose equivalent/ambient dose, but the direct comparison of these attenuation lengths is not possible, because the projectile types used in these experiments are different from each other. For direct comparison, we therefore estimated the source neutron energy spectra produced from the targets and aimed to express the attenuation length as a function of the effective maximum value, $E_{\text{max}}$ of the source neutron energy. The $E_{\text{max}}$ value was approximated as follows: (1) a sharp peak neutron energy for $p$-$\text{Li}$ quasi-monoenergetic source neutrons at CYRIC and TIARA, (2) the neutron energy having 1/100 of the energy at the peak position in the neutron energy spectrum in lethargy unit when the neutron spectrum has a clear peak at the high energy end as in the HIMAC experiment as seen in Fig. 9, (3) the neutron energy at the position having 1/100 of the neutron flux in lethargy unit at 20 MeV when the neutron spectrum has no clear peak as usually seen in the white spectrum for all other experiments.

For the last cases, the source neutron energy spectrum in lethargy unit was estimated by using each experimental condition of the projectile type and energy, and the target type and thickness. In this estimation, the MARS code was used for the ISIS experiment and the PHITS code was used for other experiments.

Figure 10 shows the dose attenuation length $\lambda_D$ for concrete and iron shields as a function of $E_{\text{max}}$. The $\lambda_D$ values for concrete keep an almost constant value of about 30 g/cm$^2$ up to several tens of MeV, and gradually increase above 100 MeV, then reach about 130 g/cm$^2$ beyond a few hundreds of MeV, which might be the high-energy limit. While for iron, the $\lambda_D$ values slightly increase up to about 100 g/cm$^2$ at several tens of MeV, but a big deviation can be seen between about 210 g/cm$^2$ for the HIMAC experiment and 340 g/cm$^2$ for the ISIS experiment in several hundreds of MeV energy region. This may be influenced by the experimental condition. The summarized data of $\lambda_D$ values will be quite useful for the shielding design study of high-energy accelerator facility, since the attenuation length determines the shield thickness of the building.

6 Induced Radioactivity by High-energy Heavy Ions

6.1 Mass-yield distributions

The most systematic results on induced radioactivities were obtained from the HIMAC series of experiments using a target stack comprised of two
to seven 5-mm thick Cu plates. Each plate had a dimension of 10 cm by 10 cm. For each beam, the number of plates was determined such that the total thickness of the Cu target was slightly thicker than the range of the beam. In between each plate, samples of C (0.2-mm thick, 5 × 5 cm square), Al (0.1-mm thick, 9 × 10 cm²), and Cu (0.1-mm thick, 9 × 10 cm²) were placed in order to measure the spatial distributions of spallation products, and to determine the energy dependence on the cross-section. Foils of the same thickness were placed at the front of the stack to measure the reaction cross-sections and mass-yield distributions.

Figure 11 shows the mass-yield distributions (in mb) for the 230-, 400-, and 800-MeV/nucleon Ar, Ne, C and Si ions interacting in a Cu target, as examples. In general, as the mass of the beam increases, the yield also increases.

In Fig. 12, produced nuclides can be divided into the following three groups: (I) target fragmentation induced from a reaction of which the impact parameter is small or projectile fragmentation for heavy projectile, (II) target fragmentation induced from a reaction of which the impact parameter is almost equal to the sum of projectile radius and target radius, (III) target fragmentation induced from a reaction of which impact parameter is in the medium of (I) and (II). The mass yields are somewhat independent of energy, although there appears to be a slight decrease in yield with increasing energy for the higher mass yields. In Fig. 11c, the comparison between the experimental results and the PHITS simulation is shown.
calculations is given, together with the C/E (calculation/experiment) ratios. The PHITS calculations in general agree well with the experimental values within a factor of 2 except for several products. The PHITS calculation gives a large underestimation of the cross-sections, especially for the heavy-mass products.

6.2 Induced activities

The spatial distributions of residual activities of isotopes produced in thick copper target by bombarding various ion beams are also measured. Fig. 12 shows the spatial distributions of residual activities of $^7$Be, $^{22}$Na, $^{38}$Cl, $^{49}$Cr, $^{56}$Mn and $^{61}$Cu isotopes produced in Cu target as a function of Cu depth in the unit of beam range for p, He, C, Ne, Si, Ar ion beams with different energies. The feature of Fig. 12 can be summarized as follows: When the mass number difference between Cu and the produced nuclide is large, nuclides are produced dominantly by the primary projectile reaction. The reaction cross-sections therefore, almost or slowly decrease with the target depth, according to the attenuation of projectile flux through the target. When the mass number difference between Cu and the produced nuclide is small, the fraction of nuclides produced by secondary particles is large. With increasing mass number and projectile energy, the reaction cross-section increases with the depth of Cu target due to the increasing contribution of secondary particle reactions.

7 Conclusions

This paper summarizes many works mainly by my colleagues on neutron detector development for spectrometry and dosimetry, and double differential neutron thick target yield by protons and heavier ions, shielding benchmark experiments for concrete and iron at high energy accelerator facilities, induced radioactivities due to spallation products by heavy ions. These data will be certainly very useful for accelerator shielding design study and radiation protection purpose.

References