Report on

Development, test and application of neutron detectors within the framwork of the nuclear physics ERANET

The NuPNET, a European Research Area Network in nuclear physics infrastructures aims at performing a collaborative work in the field of nuclear physics. It brings together 18 partners from 14 Eu countries among which Hungary is a funding member. It launched the project called NEDENSAA, NEutron DEtector developments for Nuclear Structure, Astrophysics and Applications, which combines the effort of institutions from 6 EU member states plus 2 associated countries. The NEDENSAA project is an effort to pool available resources and ongoing R&D efforts by various groups throughout Europe with the aim of providing significant improvements in neutron detection. The project is divided in different work packages that cover the various technologies and methods relevant for the improvement of the detection of neutrons. These range from the chemistry for development of new scintillator materials, the characterization of the radiation fields and detection devices, the study of innovative concepts for neutron detection, scintillator readout with SiPM, digital electronics, as well as the study of the optimal geometry of the neutron detectors coupled with other detector arrays. The project was strongly development oriented and left only a narrow margin for the study of nuclear processes with neutron emission.

ATOMKI in collaboration with the Debrecen University and Eötvös University participated in three fields of research:

1. participation in development of the neutron detector array NeuLAND, simulation of the behaviuor of the array and test of SiPM coupling to scintillators,
2. test and characterization of the radiation fields to test detection materials,
3. study of nuclear processes with neutron emission.

1. Contribution to the development of the NeuLAND array

One of the key instruments of the R3B collaboration will be the NeuLAND array which is intended to observe fast neutrons with energies of 200-1000 MeV. Its aim is not only to detect single-neutron events with high efficiency and resolution but also to be able to distinguish multi-neutron events when the nuclear reaction in question involves emission of many neutrons. This is a very difficult task since even a single neutron will produce numerous hits in the array which has to be assigned to the neutrons with as little misidentification as possible not to distort the final excitation spectrum of the emitting nuclei after reconstruction of the event. The existing fast neutron detector arrays could achieve only limited multi-neutron capability therefore the NeuLAND array could open a new era for fast neutron spectroscopy.

NeuLAND is a modular detector array consisting of organic scintillator bars of a dimension of 5 cm x 5 cm x 250 cm coupled to photomultipliers on each end. The array consists of 3000 bars. Its expected properties could only be investigated by simulations.

1.1 Simulations

In order to study the neutron response of the NeuLAND detectors, comparative studies in various simulation frameworks (FLUKA, GEANT3, GEANT4) were undertaken. One key quantity addressed was the deposited energy of neutrons hitting the neutron detector. In an energy range of

200-1000 MeV, a remarkably good agreement is obtained. The simulation packages were compared to relevant neutron response data in order to prove their predictive power for NeuLAND. The 3 simulation codes especially FLUKA and GENAT4 gave rather consistent results as it is shown in Fig. 1.

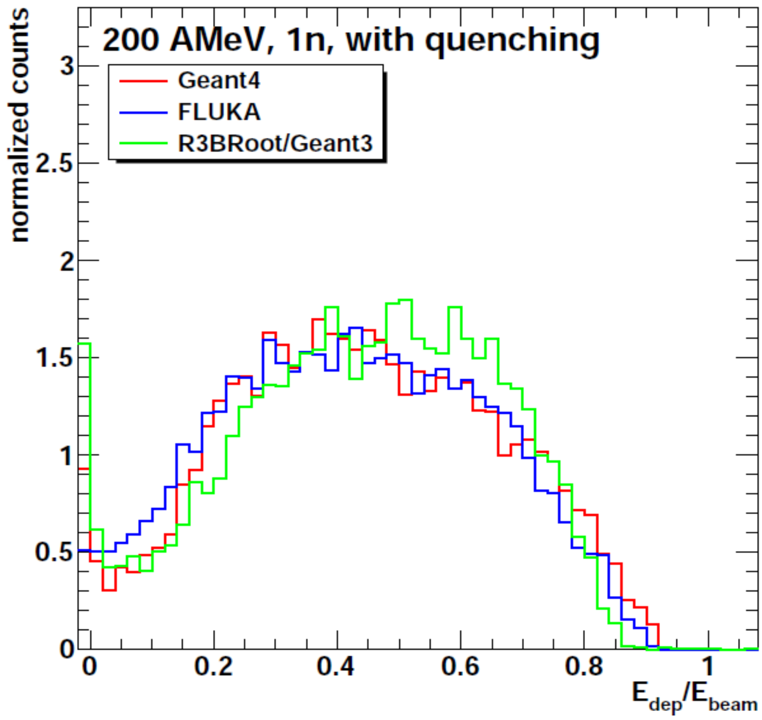

Figure 1: Deposited energy (Edep) divided by neutron beam energy (Ebeam) = 200 MeV.

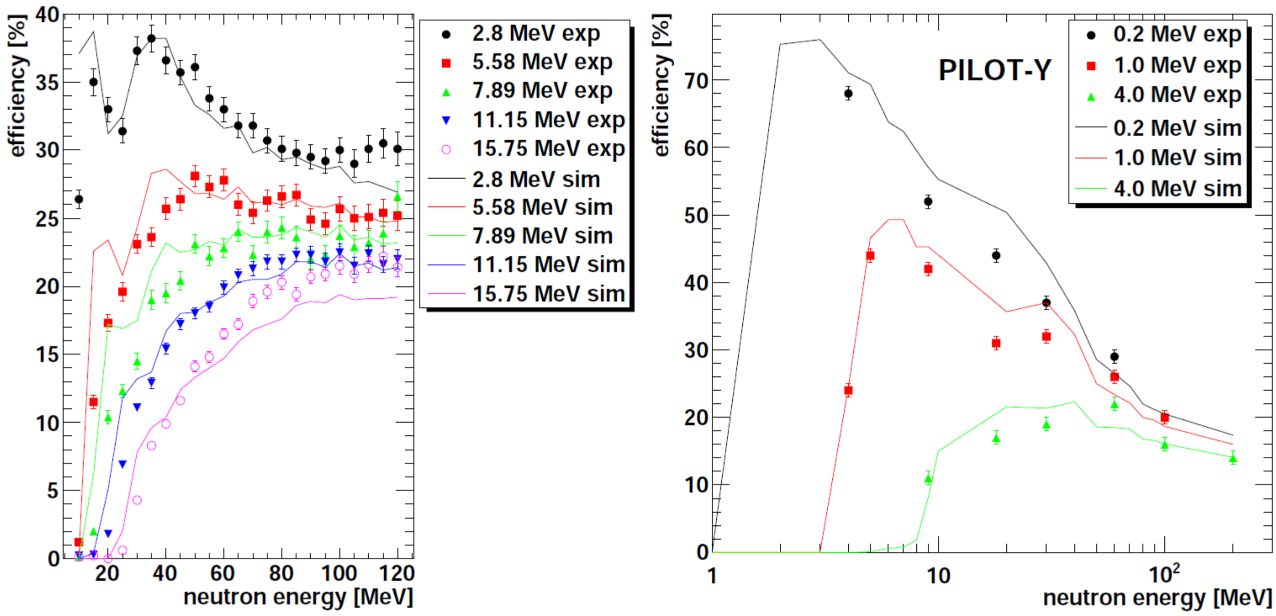

Figure 2: Detection efficiency as a function of the energy of impinging neutron for the two scintillator materials. The data (symbols) for the scintillator NE-110 are displayed on the left hand side [Bet76] and the data for the scintillator Pilot-U on the right hand side [Ede72]. The GEANT4 simulated results are presented as solid curves. The legends detail the different threshold settings in equivalent-electron energies for the experimental and simulated data.

Then, we selected neutron data on two plastic scintillator materials with close similarities to the proposed BC408/RP408 scintillator for NeuLAND. Neutron efficiency as a function of energy thresholds has been measured for neutron energies up to 120 MeV using the scintillation material NE-110 and up to 200 MeV using Pilot-U. Overall, a very good agreement is found for the two scintillator materials, the large range of neutron energies and the various energy threshold settings as it is presented in Figure 2.

Finally, we compared the simulation to the neutron response of the existing LAND detector, which has been used since almost 20 years for the detection of fast neutrons. The most important quantities for the comparison between data and simulation are the multiplicity of modules, the total deposited energy, the energy deposit during the first interaction and the energy deposit in a single paddle. With a single set of parameters the variation of spectra with the neutron beam energy are well described by the simulations.

After these cross-checks we were confident enough to simulate the response of the full array for efficiency and multi-neutron capability. For single-neutron events, efficiency of 90% for 200 MeV energy while 96% for 1000 MeV could be achieved. For multi-neutron events there are two issues which needs attention: (1) determination of the number of neutrons impinging on the array, (2) assignment and selection of the best hit to the each neutron in order to reconstruct the momentum. In addressing the first issue we have exploited a special feature of the setup: the total deposited energy in the array depends on the number of neutrons which can be seen in Fig. 3. Of course, there is a certain percentage of events which are misidentified due to the overlapping of the distributions. However, it is good enough to get about 60 % of the four-neutron events correctly assigned that is never seen for a fast neutron array in the past.

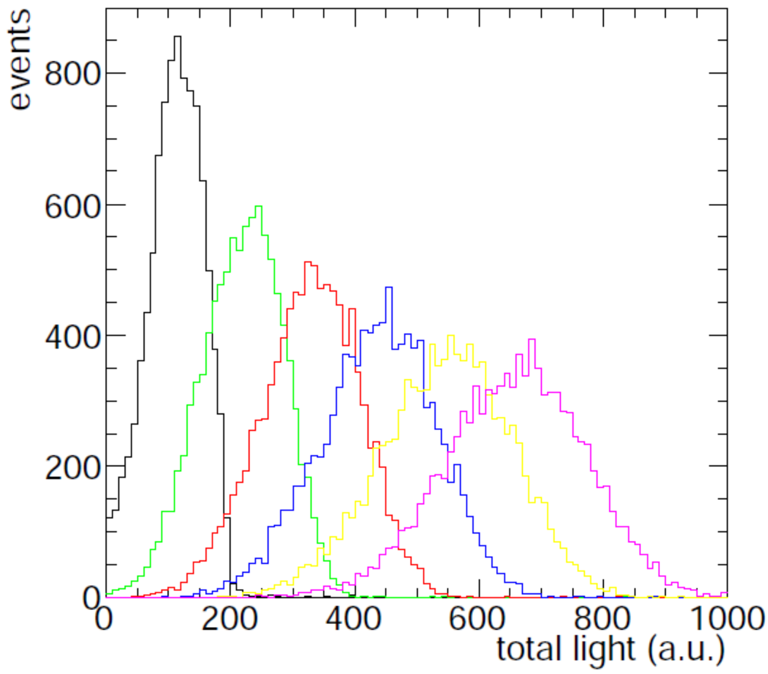

Figure 3: Total deposited energy in NeuLAND from 600 MeV neutrons with number of neutrons 1 (black), 2 (green), 3 (red), 4 (blue), 5 (yellow) and 6 (magenta).

The selection of the best hits for the momentum reconstruction is as important as the determination of the initial number of neutrons. For this purpose, however, we had to find an algorithm that is based on the spatial distribution as well as the causality of the hits. Fig. 4 shows an extreme case when four-neutron events were reconstructed for very large value of relative energy of 100 keV. This means that the hits arrived in the array very close to each other and the sorting was very difficult. However, even for this case a nice peak could be reconstructed with around 40 keV resolution.

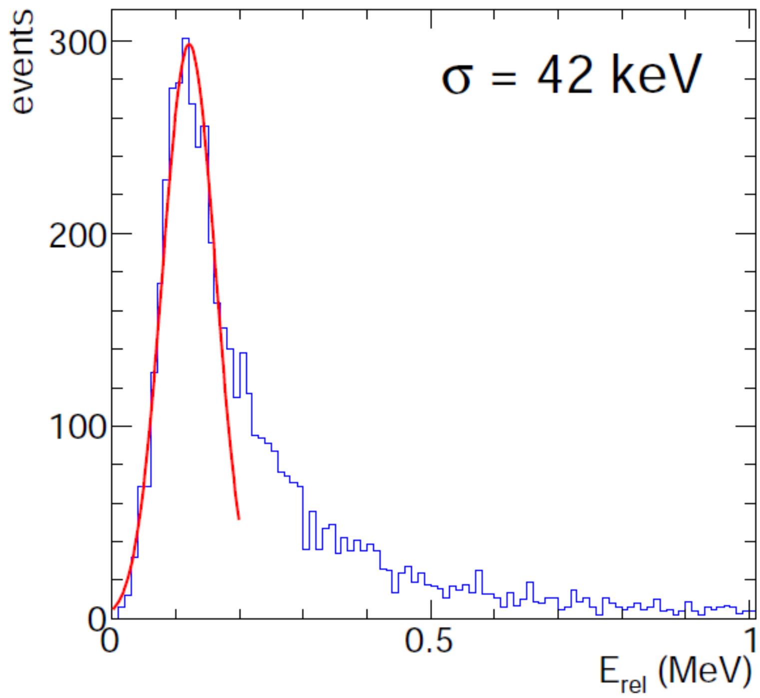

Figure 4: Reconstructed relative energy spectrum for four-neutron events at 600 MeV, simulated with a relative energy of 100 keV with respect to a projectile fragment and the NeuLAND detector in 35 m distance to the origin.

The results of the simulation were used in the experimental proposals submitted to and accepted by the RIKEN PAC.

1.2 Coupling of scintillator detectors to Silicon PhotoMultipliers

The NeuLND detectors are made of a plastic scintillators with conventional photomultipliers on both end. We studied the possibility to replace the traditional photomultipliers with new silicon photon sensitive devices built from avalanche photo diodes (SiPM) which are of great interest for certain applications due to the independence of the signal parameters from external magnetic fields, its extremely compact mechanical design and its low voltage consumption. The aim was to test the matching of standard solid plastic scintillators to silicon photo multipliers (SiPMs), with a focus on reading out scintillator areas on the cm x cm scale, larger than current SiPMs.

Plastic scintillators have been coupled with a standard vacuum PM tube and a highly segmented (60*60 microcell, 5*5 mm) SiPM provided by ST Microelectronics. A two column readout scheme of the SiPM has been used: two corners of the resistor chains and the sum of the comparator rows and columns were digitized. The results show that the readout of the SiPM is possible using only these four ADC channels and even the position map is comparable to the ideal solution.

The main drawback of the SiPM is the high dark current, making the device very noisy. A time slice with dark current pulses is shown below.

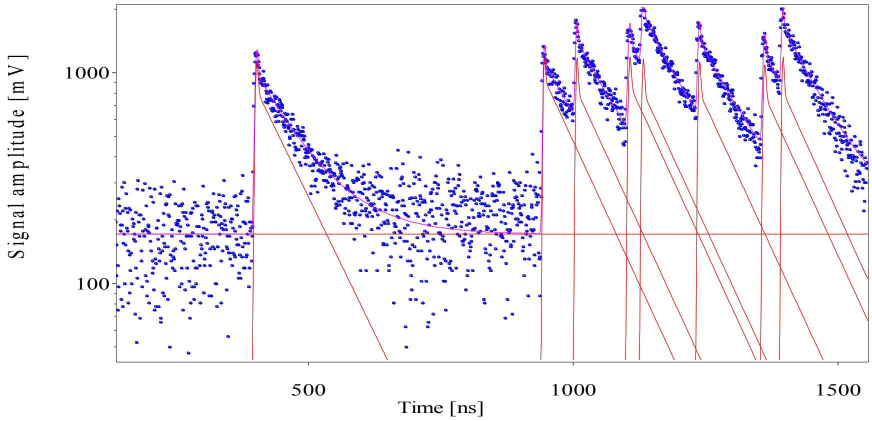

Figure 5. Dark current pulses have very fast rise time (<1ns) and slow (~100ns) decay (recovery) time

Spectrum distortion caused by the noise (dark current) of the device have been studied and compared with traditional PMT measurements. Due to the large noise, low energy threshold is rather high in the case of the SiPMs as it is shown in Fig.6., thus they can be used mainly with scintillators having high enough light yield.

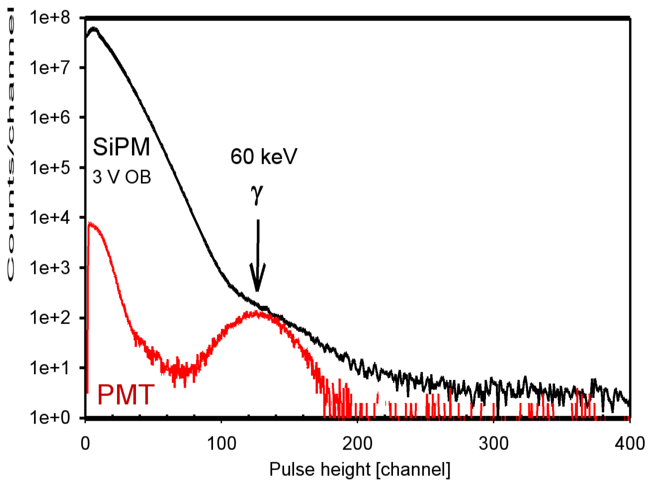

Figure 6. Comparison of the low energy threshold measured with PMT and SiPM

The dark current events cause random pile ups and, as a consequence, the decay time of a scintillation pulse will have a random value, which may be quite high as shown in Fig. 7. below.

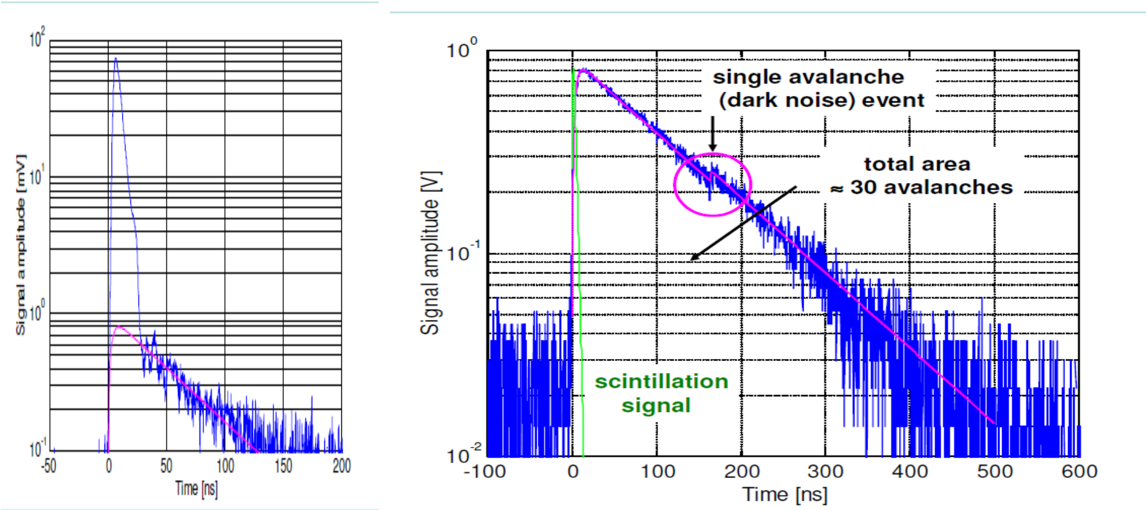

Figure 7. Comparison of the plastic scintillator signal shape measured with a PMT (left panel) and a SiPM (right panel).

A Silicon Photomultiplier (SiPM) matrix array of 9*9 SiPMs has also been built that can be coupled to the 5*5 cm scintillator rod directly. The front-end electronics was designed to be modular, so that different readout concepts could be evaluated. The readout electronics is based on a system-on-module with Spartan-6 FPGA and Gigabit Ethernet connectivity. Different SiPM readout concepts were tested using the module.

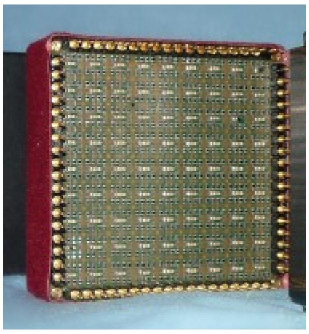

*Figure 8. 5*5 cm SiPM array with 290,000 micropixels.*

It has been shown that the SiPM and the PMT have comparable performance in time and energy resolution. Thus, SiPM may be used in time of flight studies, a common method in neutron spectroscopy. SiPM has a compact size, works on lower voltages and has a small power consumption, which may be important if thousands of PM devises are in use. On the other hand due to the slow decay time it cannot be used for pulse shape discrimination and in high count rate environments. The results have been presented at the 2nd NEDENSAA collaboration meeting.

1.3 Pulse shape discrimination

A system based on a 150MHz ADC and an FPGA has also been built. The signal from different detectors have been digitized and analyzed. Based on the time and amplitude characteristics of the signals an algorithm has been implemented in the FPGA, which is able to distinguish between the neutron and gamma signals (fast and slow scintillation components) obtained in NaI and liquid scintillators coupled to fast PMTs. This work was the BSc thesis of Molnar David, a student from ELTE.

1.4 Participation in the construction of the mutidetector setup NeuLAND

The major part of our planned investment consisted of our contribution to the large neutron detector array NeuLAND. At the moment the construction of the NeuLAND array is underway. So far, about 20 % of the setup is tested and completed.

We bought the necessary components for 25 detector units for the NeuLAND array. We participated in assembling and testing the detector units together with other ones bought at this campaign at GSI. This was necessary since the quality of the scintillator bars were not checked by the manufacturer. The light transmission capability, an important characteristics of the scintillator material, was investigated. The detector material got from the supplier scattered very much in light yield. The units to be placed in inner positions of the NeuLAND array should have light transmission of 88 %, while 70% was set for those placed at the edges of the array. Bars having light transmission below 70% were sent back to the manufacturer for upgrade. The test were performed using a light emitting diode as well as cosmic rays.

One of our students spent additional two months at GSI as a summer student. He worked with the NeuLAND people in order to prepare for the final test of the array. They set up the necessary electronics and his specific task was to prepare a software which automatically adjusted the high voltage of the photomultipliers attached to the scintillator bars in order to achieve similar gains for all the units. After the test experiments the detectors were sent to RIKEN where it is coupled to the existing facilities. We have been contributing also to the efforts in Japan in the installation of the setup.

Several experiments based on the NeuLAND setup have been proposed and accepted by RIKEN PAC. The benchmark experiment is the study of the breakup of ^{28}O and search for tetra-neutron systems, which are only accessible with NeuLAND. We expect to perform the first experiments already in 2015 in Japan. The FAIR facility is also under construction. We expect beam time in 2017 again when the demonstrator can be used in a first experiment in Germany.

2. Characterization of the radiation fields

2.1 New results for the broad spectrum p+Be neutron source of MTA Atomki

The main application of the p+Be neutron source of MTA Atomki is production of broad spectrum neutrons for irradiation testing and characterization of neutron detectors and photonics as well as electronics components and devices to be used in nuclear physics and elementary particle physics experiments or in other nuclear applications. While for the E_p = (17.24 – 22.01) MeV proton energy range 12 neutron spectra measured by the time of flight (TOF) method are available in the literature, the lack of broad spectrum data for E_p < 17.24 MeV proton energies is well known.

At the MGC-20E cyclotron the maximum proton energy is E_p = 18 MeV for extracted beams and the highest flux of p+Be neutrons can be achieved at this proton energy. In some technical and radiation protection circumstances, however, only E_p < 16 MeV energy external beams are available. Therefore, it was practical to determine thick target neutron spectra for E_p < 16 MeV energy proton beams, too, to exploit their neutron producing capabilities.

It is important to mention that the spectrum of p+Be neutrons at E_p = 16 MeV proton energy can be used for modeling neutron spectra expected at some sites that will be next to the core of the future International Experimental Thermonuclear Reactor (ITER), where some control and data acquisition systems will be operated. The neutron spectra expected there will cover the E_n = 0 - 16 MeV neutron energy range.

On the basis of the above mentioned motivations we started to study the thick target spectrum of p+Be neutrons at E_{proton} = 16 MeV proton energy. The protons bombarded a 3 mm thick (stopping) beryllium target.

First, the expected neutron spectrum was extrapolated from results published in the literature, and then it was validated by integral measurements via multi-foil activation method using a procedure described in ASTM E1855-05e1. The obtained neutron spectrum is shown in Fig. 9. The results have been submitted to NIM A for publication.

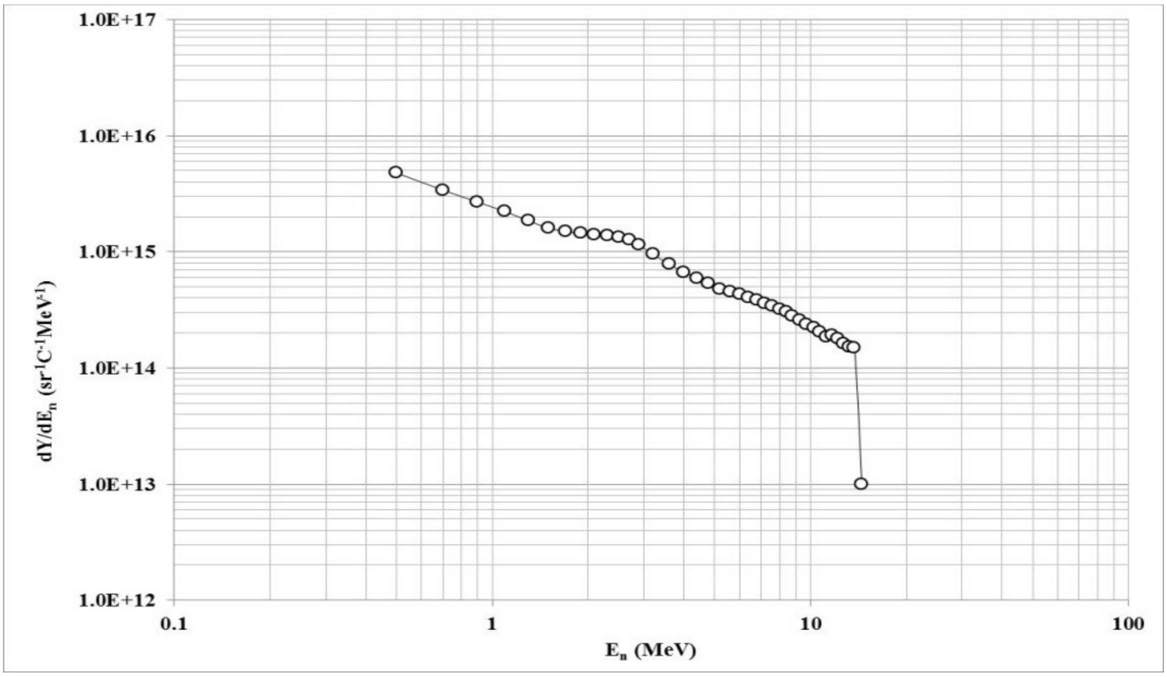

Figure 9. Energy spectrum of the thick target p+Be neutrons emitted by 3 mm thick (stopping) beryllium target bombarded with E_{proton} = 16 MeV energy protons

2.2 Characterization of the high intensity ^{60}Co gamma source of MTA Atomki

A new high intensity gamma photon irradiation facility with a ^{60}Co radioisotope source was commissioned at MTA Atomki in 2013. The irradiation field is conical with bevel angle of $\theta = 34^o$. Characterization of the field of the new setup was done. Monte Carlo simulations and dosimetry measurements were performed using ionization chambers.

Geometry models of the ^{60}Co source and the irradiation vault have been developed for the FLUKA and for the MCNP Monte Carlo codes. Using the geometry inputs we have simulated the energy spectrum of the gamma photons for different irradiation positions and, thus, information has been obtained on the continuous component of the spectrum which is determined by scattering processes in the lead shielding of the ^{60}Co source and in the building environment of the irradiation vault (roof, ceiling, shielding walls, air, etc.). An example of the results is shown in Fig. 10.

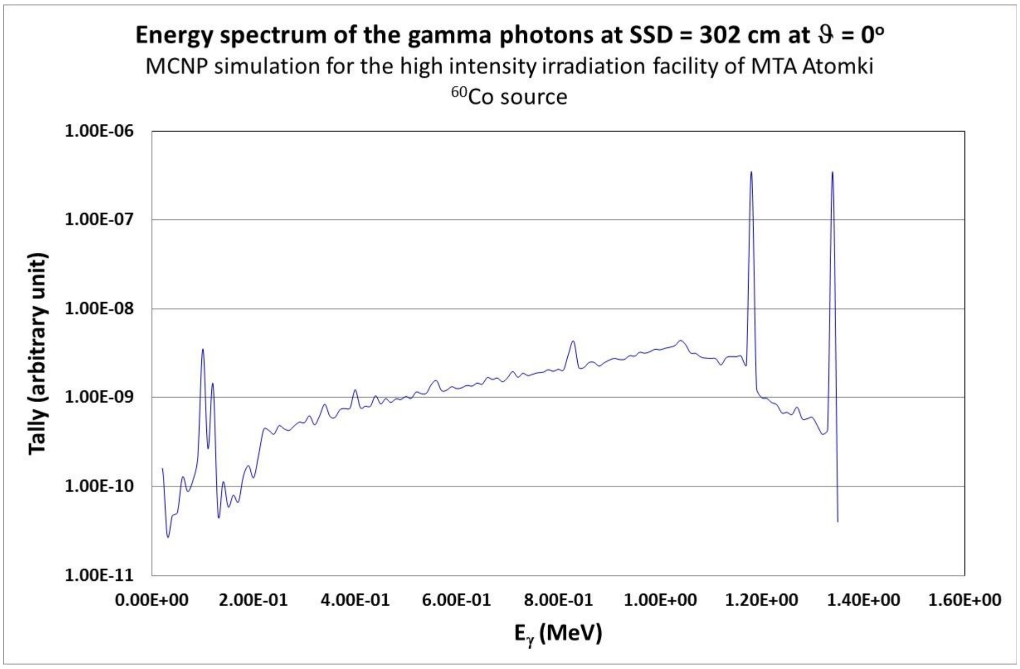

Figure 10. The energy spectrum of the gamma photons at 302 cm Source-to-Sample Distance at the zero degree direction at the high intensity ^{60}Co source of MTA Atomki.

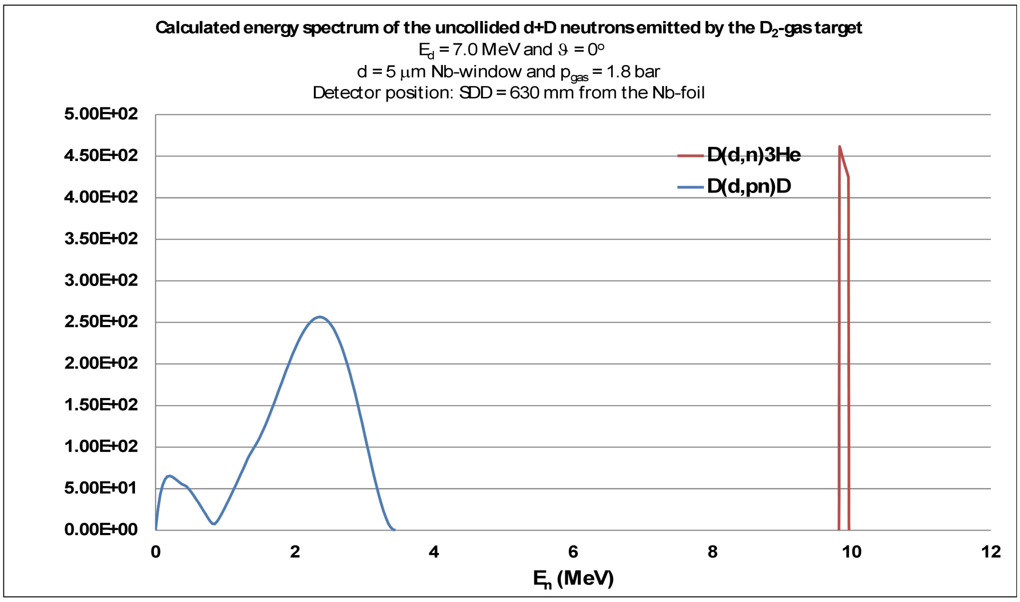

Figure 11. The $\vartheta = 0^o$ zero degree energy spectrum of the quasi-monoenergetic neutrons emitted by the D_2-gas target (p = 1.8 bar) at E_d = 7.0 MeV deuteron energy.

2.3 Monte Carlo simulation frame for the quasi-monoenergetic d+D neutron source

The study of the neutron response of neutron detectors as a function of the neutron energy can be done using well characterized quasi-monoenergetic neutron sources. At MTA Atomki d+D neutrons are produced with a D_2-gas target bombarded by deuterons with energy up to E_d = 9.7 MeV. We have elaborated a Monte Carlo simulation frame for the D_2-gas target.

The energy spectra of the neutrons emitted by the gas target at different angles and the detailed source description card (SDEF) for the MCNP code are calculated by the NeuSDesc code. Then the MCNP code is used for simulation of the neutron transport in the specific experimental arrangements of detector characterizations. As a demonstration of the results Fig. 11. shows the zero degree energy spectrum of the quasi-monoenergetic neutrons emitted by the D_2-gas target (p = 1.8 bar) at E_d = 7.0 MeV deuteron energy.

2.4 Development of a pulse height response spectrometer

Characterization of the mixed neutron-gamma irradiation fields needs spectrometry measurements. The time-of-flight neutron spectrometry is practically not feasible at the MGC-20E cyclotron. However, the pulse height response spectrometry (PHRS) method is feasible. Therefore, in the frame of the OTKA NN104543 project, we assembled a new PHRS system that consists of a scintillation detector with EJ-301 liquid scintillator and a digital signal processing electronics.

The energy calibration of the PHRS spectrometer has been done up to E_{ee} = 2754 keV_{ee} equivalent electron energy. Measurements and Monte Carlo simulations with the GRESP7 code have been done for determining the pulse height response of the PHRS spectrometer for gamma photons up to E_{γ} = 2754 keV gamma energy. Experimental characterization of the PHRS system is done using quasi-monoenergetic neutrons produced by the D_2-gas target. Monte Carlo simulations are in progress employing the NRESP7 and the MCNP-PoliMi codes for reproducing the response functions measured with the PHRS system for quasi-monoenergetic neutrons with energy up to E_n = 12 MeV.

3. Study of nuclear processes with neutron emission

3.1 In-beam studies

Neutron knock out from the very neutron rich nucleus ^{20}C has been studied in Riken by use of the radioactive beam facility. Contrary to the expectations only one excited state has been observed in the ^{19}C nucleus. Even this state has been populated with a very low cross section. These results show that in addition to the $s_{1/2}$ ground state only the $(d_{5/2})^3{}_{3/2}$ state is bound, while the $d_{5/2}$ state itself is not. The result has been submitted to Phys. Rev. C.

Systematic behaviour of inclusive multineutron and multiproton removal cross sections at relativistic energies has been investigated in RIKEN. Cross sections of removal of one more prtoton(neutron) (σ_{k+1}/σ_k) have been compared in Fig. 12. It was found that there is a universal relation for this ratio depending on the difference (ΔC) of the evaporation costs for the weakly and deeply bound nucleons of the nuclus. The cross section for removal of one more weakly bound species drops by a factor of ~5, while to remove more deeply bound nucleon the cross section drops by a factor of ~30. This can be understood considering that for the case of weakly bound nucleons the evaporation plays an important role, while the deeply bound nucleons can be removed only by direct knock out.

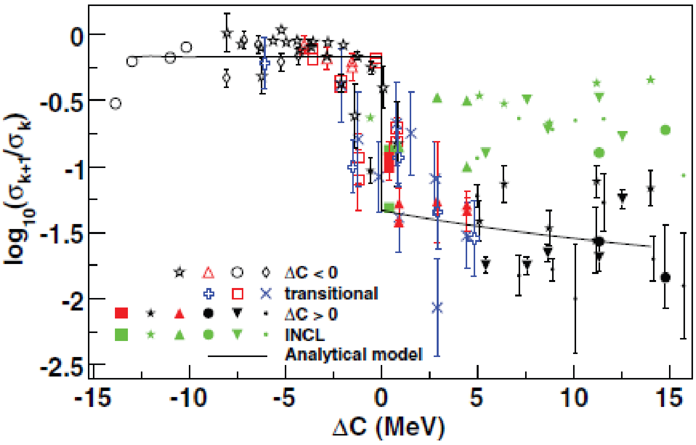

Figure 12. Evaporation cost dependence of the cross section for removing one more particle in fragmentation reaction. The cascade models (green symbols) significantly overestimate the cross section of the removal of deeply bound species.

Multinucleon removal reaction has been performed using a radioactive cocktail beam from in flight fission of a 238U beam in RIKEN. In this study the first 2^+ excited state in the neutron-rich tin isotope ^{136}Sn has been identified at 682(13) keV energy by measuring γ -rays in coincidence with the heavy fragment. This value is higher than those known for heavier even–even N=86 isotones, indicating the presence of the Z=50 shell closure. Our result confirms the trend of lowering of the energies of the 2^+ states in even–even tin isotopes beyond N=82 compared to the known values in between the two doubly magic nuclei ^{100}Sn and ^{132}Sn. The result is published in Prog. Theor. Exp. Phys.

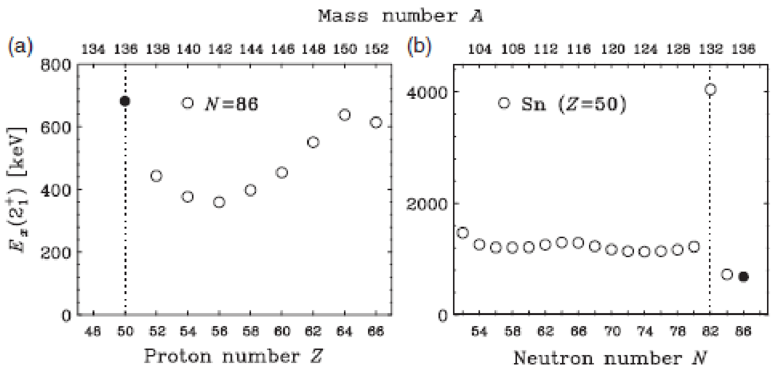

Figure 13. Energy systematics of the 2+1 states in N=86 isotones and Sn isotopes. The value obtained in the present study is shown in a black dot.

3.2 Decay studies

β and β-n studies have been performed in the nuclear region beyond ^{208}Pb, a more-or less unknown region at the moment. The β decays of neutron-rich Tl, Pb, and Bi isotopes have been investigated following fragmentation of a relativistic ^{238}U beam. Level schemes of $^{211–213}$Pb and $^{215–218}$Po have been built from γ singles and γ -γ coincidence spectra and, where possible, spins and parities have been suggested from a coherent assessment of systematics, shell-model predictions, and β-decay selection rules. The β-decay of ^{215}Pb has been also studied, confirming the half-life and the associated 185-keV γ ray in ^{215}Bi. The results are published in Physical Review C.

β, β-n and isomeric decay studies of the ^{78}Ni region, where the stability of the N=50 magic number at Z=28 is in the forefront of nuclear structure studies these days, has been performed in Riken using the EURICA version of the former EUROBALL setup. A short report on the status of the project has been presented at the ARIS 2014 conference. The first result on the β and β-n decay of heavy Mn isotopes is in preparation and will be submitted to Phys. Lett. B. The main result here is the observation of the 2^+_1 and 4^+_1 states in ^{70}Fe for the first time and prove that at mid $g_{9/2}$ shell the deformation of the heavy Fe isotopes is maximal.

Debrecen, 2015. 04. 27

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leader of the project