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Towards an Improved GELINA Neutron Target

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The neutron target of the GELINA time-of-flight facility has been simulated with coupled electron-photon-neutron MCNP4C3 calculations. The main goal is to investigate the feasibility for the reduction of the neutron time spread without significantly compromising the neutron yield. An implementation of new photonuclear libraries into the Monte Carlo calculations was necessary to simulate the neutronics problem accurately.

Absolute flux calculations were performed for both moderated and direct neutron spectra in order to validate the geometry model and the method used to deal with the neutronics problem. These results were compared with the measured neutron spectra at specific flight paths; an agreement within 20% was achieved. The resolution functions of the moderated spectrum currently in use were compared with our Monte Carlo simulations; here an excellent agreement was reached. Finally, the simulated resolution functions for the direct neutron spectrum were calculated with and without the presence of the moderator. This comparison illustrates the negative influence of the moderator on the resolution function for the fast neutron spectrum.

KEYWORDS: electron accelerator, uranium target, photonuclear reaction, neutron flux, resolution function

1. Introduction

The Geel Electron LINear Accelerator (GELINA) is a powerful white spectrum neutron source with a unique high energy neutron resolution [1,2]. Accelerated electrons with energies from 70 to 140 MeV produce neutrons in uranium via bremsstrahlung, mainly by (γ,n) and (γ,2n) reactions. The rotary target currently in use consists of U-$Mo_{0.1}$ alloy cooled by liquid mercury and sealed in stainless steel (Fig. 1). Beryllium tanks filled with water placed above and below the target provide the moderated neutron spectrum. The present target produces ~3.4 x 10^{13} n/s at an electron current of 70 μA and mean electron energy of 105 MeV. The accelerator is operated in pulsed mode at 800 Hz with a pulse duration of less than 1 ns and a peak current of about 100 A. These excellent characteristics accommodate high energy resolution neutron cross section measurements using the Time-Of-Flight (TOF) technique [3].

The main challenge is to design a new target to reduce further the time spread of neutrons of given energy while maintaining the neutron yield. The neutron time spread and the neutron intensity affect the experimental accuracy of the neutron cross section measurements. In view of the many parameters involved, Monte Carlo calculations are prerequisite. In addition, heat deposited by electron beam in the GELINA target must be removed in a reliable way avoiding swelling, stresses and eventual target failure. Therefore the latter issue will be treated in close relation with the neutronics problem.

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Fig.1 The GELINA neutron rotary target

2. GELINA facility

Two flux conditions are available at the measurement stations of the GELINA facility: one optimized for energies below 100 keV using a water moderator and the other one with fast neutrons coming directly from the uranium. Shadow bars placed between the source and the flight-path are used to shield the unwanted part of the neutron energy spectrum.

The energy of the neutrons reaching the detection system is determined using the TOF method. However, due to the scattering processes in the moderator and the rotary target, neutrons of a given energy have a certain time distribution. This time spread together with the Doppler effect, the detector response, the electronics and the electron-gamma shower broadens the experimental width of the resonance.

The time spread is quantified by introducing the so-called Resolution Function (RF) which is usually taken as a function of the delay distance d, instead of the time t. Physically, the delay distance can be interpreted as an effective flight-path elongation (or contraction) that results from the scattering process. The delay distance was first used by C. Coceva et al. [4]. The RF is a very weak function of the neutron energy when expressed in terms of delay distance. In this way the number of neutron energy bins covering the whole energy range can be limited. This is a considerable simplification of the problem. The delay distance is defined by

$$d = v_n(t - t_{ref}) = v_n t - L \qquad (1)$$

where v_n is the velocity of the neutron at the detector and L is the source-detector distance.

3. MCNP4C3 treatment

The MCNP4C3 Monte Carlo code [5] has been chosen to deal with the neutronics part of the project because it can handle the coupled electron-gamma-neutron transport. The geometry model used during the Monte Carlo simulations has been introduced in a previous work [6]. The model was established in such a way that the simplifications significantly speed up the calculations without compromising the MCNP4C3 results.

Photonuclear reactions are the main source of neutrons in the GELINA target. They can be simulated using the MCNP code since version 4C2. However it was necessary to implement new IAEA photonuclear libraries [7] into the MCNP4C3 calculations in order to improve the simulation accuracy.

A photonuclear data library LA150u [8] supplied with the MCNP4C3 code contains the photonuclear cross sections and neutron emission spectra of O-16 and Fe-56. For Be-9, Mo-96 and U-238 we used the photonuclear cross section data from the LA-UR-02-124 data library in END-6 format. After processing using the NJOY99.90 the ACE format libraries were obtained. Since neither of these libraries contains photonuclear data for Hg, the data for Au-197 were used instead. To validate this assumption, a verification was done, which showed the similarity of the photonuclear cross sections for Hg and Au [9].

4. Results

In order to verify the MCNP4C3 modeling of the GELINA facility we compared the calculations with two neutron flux measurements: one measurement was done at an angle of 81° and a distance of 60 m with a moderated spectrum, another measurement was done at an angle of 90° and a distance of 200 m with a fast spectrum. Further, we calculated the resolution functions for the moderated neutron spectrum, and compared them with the RFs introduced by Coceva et al. [4]. Finally, the RFs for the fast neutrons were simulated with and without the moderator in order to demonstrate the influence of the moderator on the resolution functions for the high-energy range.

4.1 The absolute flux of the moderated neutron spectrum

The neutron flux was measured using the flight-path at an angle of 81° with respect to the incident electron beam, and at a distance of 60 m. The experiment covered the neutron energy range from 25 meV to 200 keV. The measurement was done using the $^{10}B(n,\alpha)^{7}Li$ reaction with an ionization chamber with six homogeneously evaporated boron layers enriched to 94.1% in ^{10}B and a total ^{10}B thickness of 210 μg/cm^2. Neutrons coming from the uranium target were shielded using a 10-cm thick, 5-cm high lead bar placed between the flight-path and the target itself. The final accuracy of the measurement is about 11-15%; 5-11% is due to the flux measurement (statistics, amount of ^{10}B in the beam), 10% is due to the electron current normalization.

Fig. 2a shows the comparison of the measured and the calculated moderated neutron flux. An agreement within 20% is obtained in the whole energy range, which manifests the high accuracy of the Monte Carlo treatment. As an additional comparison, Fig. 2a depicts two models dealing with the thermal treatment of neutrons. The S(α,β) takes into account the material effects of chemical bindings, and is applied for hydrogen for the neutron energies below 4 eV. On the other hand, the free gas model is based on the free gas approximation, which accounts for a thermal motion of atoms. The comparison of the results shows that the MCNP4C3 calculation of the thermal peak of the neutron spectrum is in better agreement with the measurement if the S(α,β) model is used. From 0.5 eV up to 4 eV the free gas model shows slightly better agreement with the measured data.

4.2 The absolute flux of the direct neutron spectrum

The experiment was performed in the flight-path at an angle of 90° with respect to the incident electron beam, and at a distance of 200 m. The experiment covered the neutron energy range from 165 keV to 20 MeV. The flux was measured using the ^{235}U(n,f) reaction with an ionization chamber with eight homogeneously evaporated ^{235}U deposits. The ^{235}U is enriched to 99.8268% and has a total areal density of about 3.07 mg/cm^2. The moderated neutrons were eliminated using a 10-cm thick lead and a 10-cm thick copper shadow bar with a vertical opening of 3 cm and a horizontal opening of 12 cm. The flux measurement has an accuracy of about 4%, whereas the electron current normalization has an accuracy of 10%.

Fig. 2b shows the comparison of the experiment with the MCNP4C3 simulation. In the energy region up to 5 MeV there is an agreement within 20%. Above this energy, an increasing deviation is observed. This is probably caused by the (γ,xn) emission spectrum in the photonuclear data library for ^{238}U. The flux calculation was also performed with the JENDL-3.3 library so that the influence of the neutron inelastic scattering data of ^{238}U on the flux simulation could be shown. The JENDL-3.3 library provides more accurate inelastic scattering data than the MCNP4C3 default library ENDF/B-VI. This comparison shows an observable difference only in the region up to 400 keV. However, this change does not explain the difference with the measured data. Also, replacing the simplified MCNP model recently in use [6] by a model with the conical shape of the opening of uranium doesn't explain this difference. An increase by 20% of the temperature parameters that govern the neutron emission spectra would probably lead to an improved agreement with the shape of the measured data.

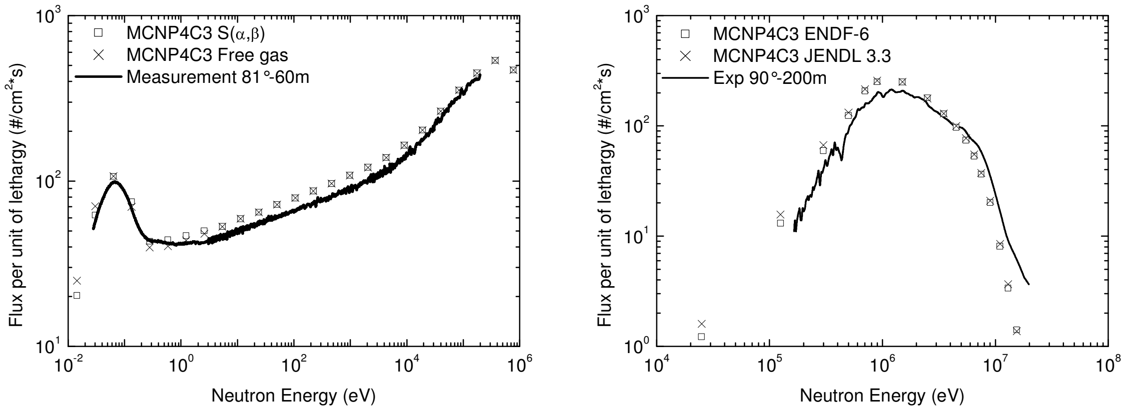

Fig.2 Neutron flux per unit of lethargy in the flight-path a) 81°- 60 m of the moderated neutron spectrum b) 90°- 200 m of the fast neutron spectrum

4.3 The resolution functions for the moderated neutron spectrum

The RF describes the time-dependent behavior of the neutrons of given energy. As mentioned above, the RF is a weak function of the energy, if the delay distance is used instead of time. This simulation was performed at an angle of 81° for the moderated neutrons. Here we divided the neutron energy range into several intervals from 1 eV up to 3 MeV. Fig. 3 shows some of the comparisons of the simulated RFs with those calculated by Coceva using a dedicated program [4]. The RF represents the response of the

GELINA target on a 1 ns electron pulse with an average energy of 105 MeV. Only neutrons coming from the moderator could reach the detector as the direct neutron spectrum was shielded. The RF is given in Fig. 3 as a probability density function, which is a function of the delay distance.

The comparison in logarithmic scale shows excellent agreement. Slight discrepancies can be observed for high delay distance values. It has to be stressed that the quality of the RF for the higher energies are of lower importance compared to those of lower energies, since the direct neutron spectrum is shielded. As soon as the high-energy neutrons are of interest, the direct neutron spectrum should be used with a shielded moderator. In order to obtain the simulation results effectively, we used the so-called point detector, which is a very efficient tool of the MCNP4C3 code to obtain sufficient number of neutrons in the place of interest [5]. All results of the simulations have relative errors below 5%, which is a reasonable limit for use of the point detector in the MCNP4C3 code.

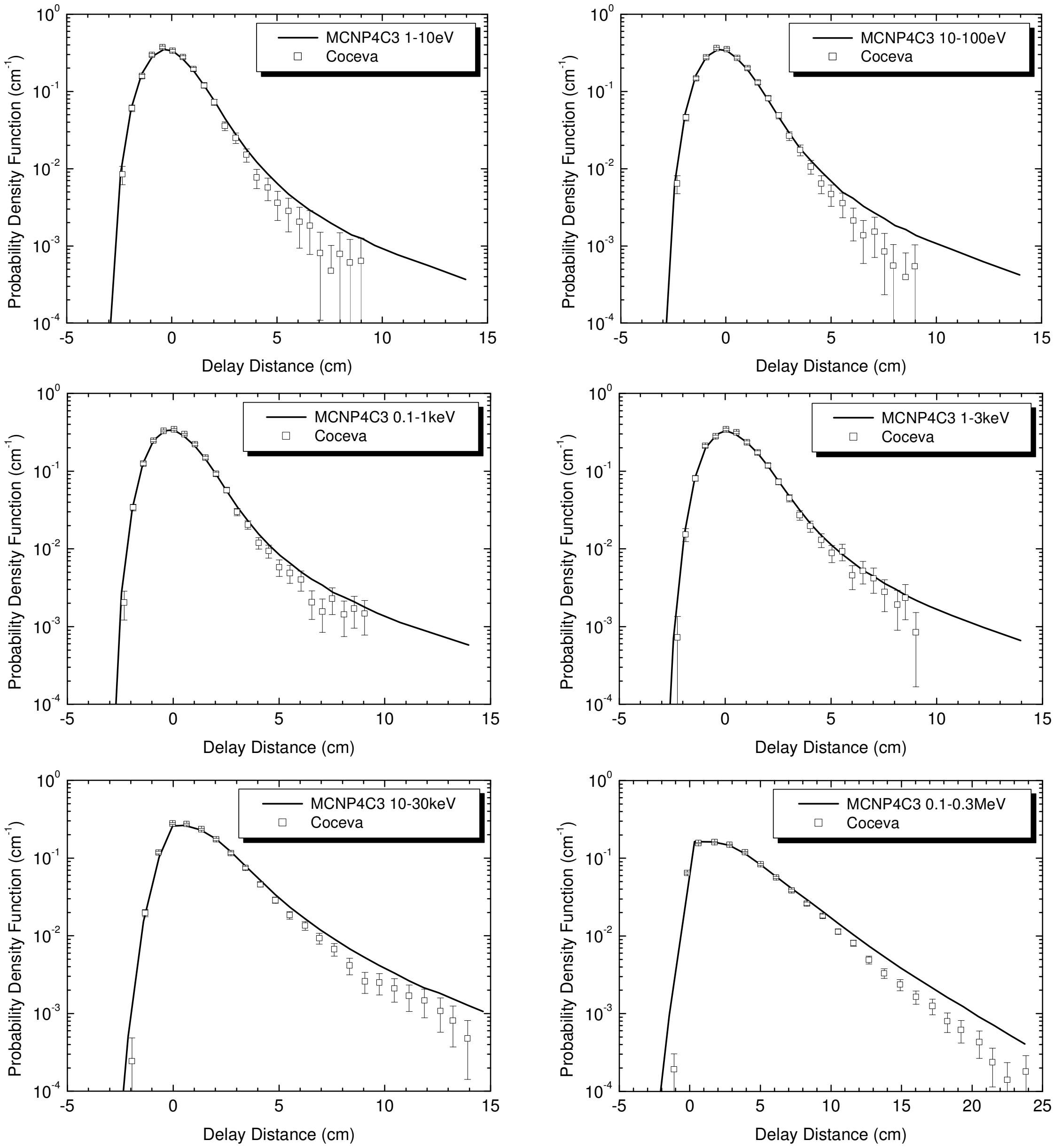

Fig.3 Resolution functions for the moderated neutron spectrum at 81°

4.4 The resolution functions for the direct neutron spectrum

In this case the moderator tanks were shielded in order to allow only the neutrons coming from the rotary target to reach the detector. This simulation was carried out at an angle of 90°. Again, the results presented in Fig. 4 show the neutron response of the GELINA target on the 1 ns electron pulse. Two simulations were performed: one simulation with the presence of the shielded moderator, another simulation without the moderator. In this way the influence of the moderator tanks on the RF can be demonstrated. Moreover, the RFs without the presence of the moderator will be later used as a measure for the direct comparison with the RFs of the new target design.

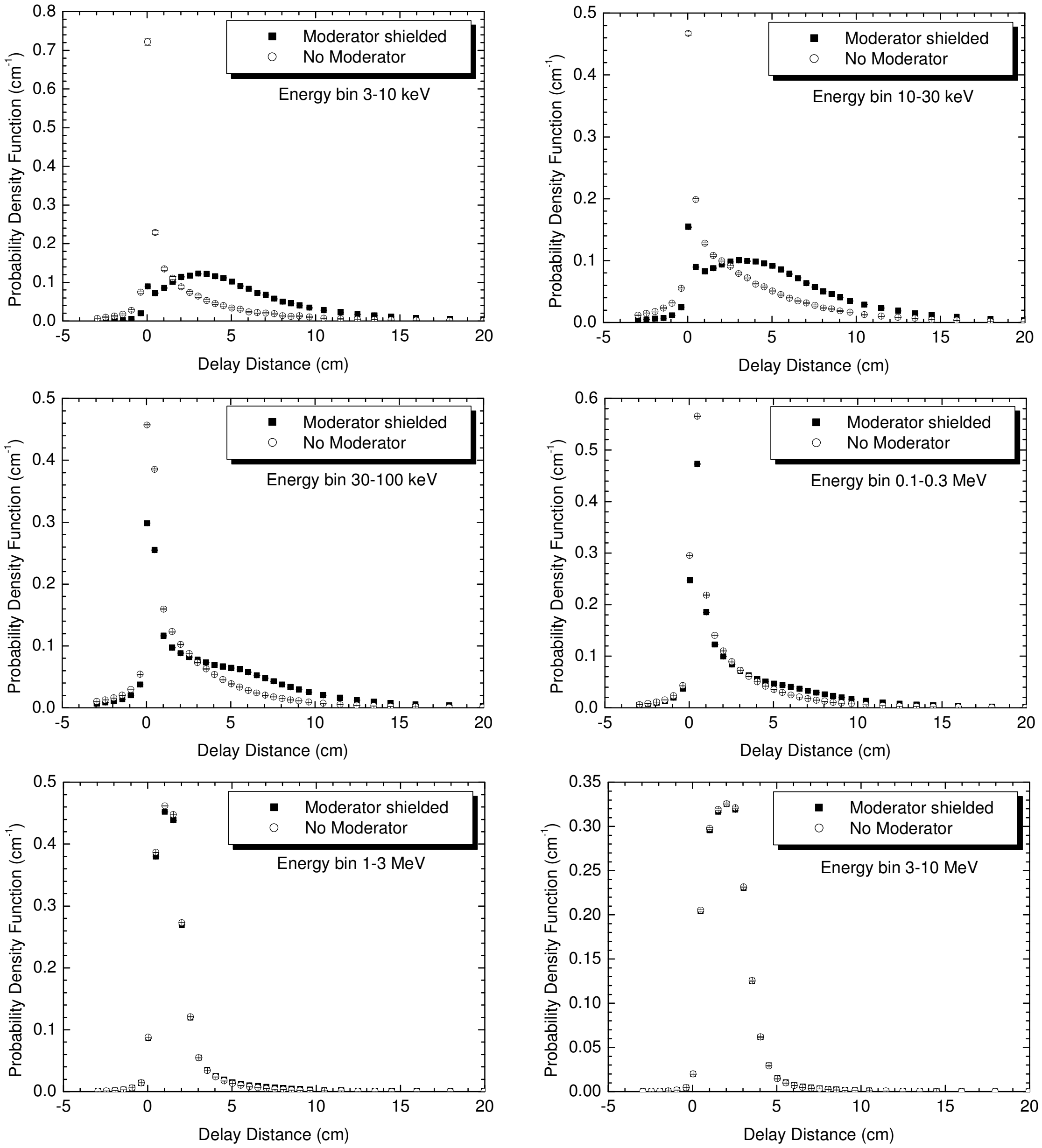

Fig.4 Resolution functions for the direct neutron spectrum at 90°

In Fig. 4 it can be observed that the moderator has a significant influence on the shape (FWHM) of the RF. This effect is evident for the neutron energies below 300 keV. Here the higher tail of the RF, if the moderator is present, is caused by neutrons, which are scattered back by the moderator after leaving the rotary target. These neutrons need to travel a larger distance to reach the detector, which is observable in the values of the delay distance.

5. Conclusions

Our results show that the MCNP4C3 code can be successfully used to simulate the current GELINA target and to design a new neutron target. We compared the Monte Carlo simulations of the absolute neutron fluxes with the measurements, in both cases a satisfactory agreement was achieved. Further, we made a comparison of the resolution functions for the moderated neutrons with previous dedicated calculations. Here an excellent agreement was achieved. Finally, the resolution functions for the direct neutron spectrum were simulated, where we demonstrated the influence of the moderator on the resolution function of the GELINA target. As far as the heat removal is concerned it should be stressed that the proper heat removal problem has to be solved in parallel with the neutronics problem as these phenomena are directly related. The heat transfer simulation tools will be implemented into the investigation as soon as a new target geometry is optimized from the neutronics point of view.

6. References

1. A. Benussan, J. M. Salome, “Gelina: a modern accelerator for high-resolution neutron time of flight experiments,” Nucl. Inst. Meth., **155**, 11 (1978).
2. D. Tronc, J.M. Salome, K. Böckhoff, “A new pulse compression system for intense relativistic electron beams,” Nucl. Inst. Meth., **228**, 217 (1985).
3. A. Brusegan, G. Noguere, F. Gunsing, “The resolution function in neutron time-of-flight measurements”, J. Nucl. Sci. and Techn., **Suppl. 2**, 685 (2002).
4. C. Coceva, A. Magnani, “Resolution Rotary Target”, Internal report GE/R/ND/06/96, EC-JRC-IRMM, Geel, Belgium (1996).
5. J. F. Briesmeister, ed., "MCNP - A General Monte Carlo N-Particle Transport Code, Version 4C," LA-13709-M, LANL, Los Alamos, USA (2000).
6. M. Flaska, D. Lathouwers, T.H.J.J. van der Hagen, H. van Dam, W. Mondelaers, A. Plompen, A. Borella, P. Schillebeeckx, P. Rullhusen, “Study of properties of the GELINA neutron target,” Proceedings of The Nucl. Mathematic. And Comput. Sciences, A Century In Review – A Century Anew, Gatlinburg, Tennessee, USA (2003).
7. IAEA-TECDOC-1178, “Handbook on photonuclear data for applications: Cross sections and spectra,” Vienna, Austria (2000).
8. M. C. White, “Release of the LA150U Photonuclear Data Library,” X-5:MCW-00-87(U), LANL, Los Alamos, USA (2000).
9. S. S. Dietrich, B. L. Berman, “Atlas of photoneutron cross sections obtained with monoenergetic photons,” Atomic Data and Nuclear Data Tables*,* **38**, 199 (1988).