PHOTONEUTRON SOURCE BY HIGH ENERGY ELECTRONS ON HIGH Z TARGET: COMPARISON BETWEEN MONTE CARLO CODES AND EXPERIMENTAL DATA

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A photoneutron source has been designed and realized at the Beam Test Facility (BTF) of the electron/positron collider DaΦne, in the National Laboratory of Frascati, near Rome (Italy). Neutrons are produced sending high energy electrons to impinge on an optimized Tungsten target. This source could be suitably used for calibration of neutron detectors as well as for material and nuclear science investigations. Moreover photoneutron processes are encountered in many physics domains: from accelerator to reactor physics, mainly related to neutron shielding issues in high Z materials, used for gamma shielding.

This work presents the Monte Carlo simulations performed with different codes (FLUKA and MCNPX) to estimate the neutron rate and energy spectrum, obtained when 510 MeV electrons are sent against the designed target. Finally, the comparison of the Monte Carlo predictions of neutron and photon fluences around the target with the experimental values is discussed.

I. PHOTONEUTRON SOURCES: SCIENTIFIC MOTIVATION

The interest of the scientific community toward the research with neutrons spans over a wide range of applications: from fundamental physics to material science, from nuclear data measurements for supporting advanced fuel cycle in new generation reactors to neutron diffraction data routinely used for structural models of crystals, from biotechnology to drug discovery and so and so forth (Ref. 1). This explains the increasing number of neutron facilities worldwide.

Beside reactors, the most powerful neutron sources are accelerators: neutrons can be produced by spallation or by photoproduction. Spallation sources are very effective in producing neutrons but are large and expensive, on the contrary electron driven neutron sources, even if are less effective in neutron production, are rather cheap and compact machines that may also bring advantages in terms of reliability.

Several studies (Ref. 2) have shown that, when neutron fluxes higher than 1E+16 n/s are required for applications, spallation sources are preferred, while for lower neutron fluxes the photonuclear process will be more convenient in term of investment costs.

In addition to the need of new cost effective neutron sources, also the new Emerging Nuclear Systems have shown interest in photonuclear processes for the important implications they have on many fields, some of which are briefly listed below:

- Transmutation of nuclear waste either directly by photons or by neutrons produced by photonuclear reactions (ADS)
- Design of Lead Cooled Fast reactors
- Design of electron beam-dumps in intense electron beam accelerators
- Design of medical accelerators that use neutrons for boron capture therapy (BNCT)

and many others applications.

In this frame it is important to be able to satisfactorily describe the photonuclear physics in order to provide realistic and accurate estimations of neutron rates produced by electron and gamma interactions with matter.

II. IMPLEMENTATION OF PHOTONUCLEAR PHYSICS IN MONTE CARLO CODES

For a long while photonuclear processes were neglected due to the lack of complete evaluated data for applications. The computational issues of implementing photonuclear physics in particle transport and interaction codes are essentially derived from the difficulty of collecting and providing complete evaluated data for applications. In fact, photonuclear data are isotopic so that cross sections can have irregular dependency on the atomic number of the elements. Thus while photoatomic data are readily tabulated by element, photonuclear data are tabulated for each isotope of an element.

All this explains the reason for which a relatively complete photonuclear data file in ENDF format (for 164 isotopes) has been made available only after 2000 (ENDF-6 formatted files containing complete interaction description, as double differential cross sections, etc).

II.A. Photonuclear Physics in FLUKA code

FLUKA (Ref. 3) is a general purpose Monte Carlo code, that can generate and transport about 60 different particles over an energy range of more than 14 decades of magnitude. It deals with photonuclear reaction on the whole energy range since 1994, opening the way toward a more accurate electron shielding design.

For modeling purpose 4 regions are distinguishable on the base on the primary photon energy:

1. Giant Dipole Resonance (GDR): $E_\Upsilon < 30$ MeV
2. Quasi Deuteron Resonance (QD): $30 < E_\Upsilon < 200$ MeV
3. Delta Resonance: $E_\Upsilon > 140$ MeV
4. High energy range: $E_\Upsilon > 720$ MeV

Among these models, the first two are those describing the main mechanisms by which photoneutrons are produced.

Another important reason for which the FLUKA code has been chosen as reference code to design the optimized target is the availability, after the code upgrade of 2005, of a rich experimental data library for the total photoneutron cross sections. In fact, in addition to the IAEA photonuclear data library, it took advantages from evaluated data from various Laboratories (ORNL, LANL, CNDC, JAERI, KAERI, MSU) and many experimental data made available via the EXFOR database, so that, at present, in FLUKA the experimental values of the photoneutron total cross sections for 190 nuclides are available (Ref. 4).

For those nuclides for which experimental cross sections are not available some parameterization are used (i.e., Lorentz fit of the existing data).

The FLUKA version used for the design of the BTF photoneutron source is 2008.3b.0.

II.B. Photonuclear Physics in MCNPX code

MCNPX (Ref. 5) is a general-purpose radiation transport code that includes 3-D geometry, continuous-energy transport up to 1TeV, transport of 34 different particle types. The photonuclear physics in MCNPX was implemented late in 1999, in traditional Monte Carlo style, i.e a purely statistical based process.

The photonuclear data are used as an extension of the photon collision routines: the total photon cross section (photoatomic + photonucear) is used to determine the distance to the next photon collision. The type of collision is then sampled as photoatomic or photonuclear.

MCNPX had an important upgrade (Ref. 6), similarly to FLUKA, in 2005, when a new photonuclear physics package "CEM2K" for photons with energy from 5 MeV to 2 GeV has been added. This package includes two models, the Giant Dipole Resonance and the Quasi Deuteron one, that allow to complement the existing photonuclear data. These models can be used also for extending evaluation above 150 MeV, that represents the present upper energy boundary of the tabular data.

The MCNPX version used for the calculations is MCNPX 2.5.0.

III. THE DAFNE BEAM TEST FACILITY

The photoneutron source has been realized at the Beam Test Facility of the DaΦne collider, that is located at the National Laboratory of the I.N.F.N, in Frascati. The main aim of DaΦne is to make head-on collisions between high energy electron (matter) and positron (anti-matter) beams, in order to contribute to the study and solution of fundamental physics problems (i.e, study of CP violation, looking at the decay of Kaons, produced in the collisions of electrons and positrons of 510 MeV).

The electron and positron beams are accelerated by a 60 m long Linac, that can deliver a maximum current of 500 mA for electrons and 200 mA for positrons.

The beam at the end of the Linac can be, also, diverted from the nominal path toward the experimental hall of the Beam Test facility (BTF), where users coming from all over Europe can carry on their tests and experiments, for detector calibration, detector efficiency study, beam diagnostic device tests, etc. Particles can be provided in 1 or 10 ns pulses, with an injection frequency spanning from 1 to 50 Hz, in a wide energy range (25-750 MeV for e-) and intensity (from 1 up to 10^{10} particles/pulse).

A pulsed dipole magnet at the end of the Linac allows to provide alternatively beam to the DaΦne damping rings and to the test beam area, so that, when beams are injected into the collider, the BTF can still receive beam, even if with a lower repetition rate.

The continuous feeding of the BTF line, during the time sharing with the DaΦne collider, is technically possible because not all the Linac bunches are needed for filling the accumulator rings. Obviously, in this operation scheme the pulse length and the primary beam energy are the same of the DaΦne collider.

In Table I the main characteristics of the electron and positron beams that can be delivered in BTF are summarized.

TABLE I. BTF e-/e+ beam main characteristics

Energy range	25-750 MeV (e-) 25-510 MeV (e+)
Transverse emittance @ 510MeV (on both planes)	1 mm mrad (e-) 10 mm mrad (e+)
Energy Spread @ 510 MeV	1% (e-) 2 % (e+)
Repetition Rate	1-50 Hz
Number of particles per pulse	$1\text{-}10^{10}$
Macro Bunch duration	1 or10 ns
Spot size at the exit of the transfer line	2mm (single particle) 2cm (high multiplicity)

III.A. Neutrons at the Beam Test Facility: physics overview

Neutrons are produced in BTF, sending high energy electrons to impinge on an optimized high Z target, placed in the experimental hall, just in front of one of the two exits of the beam transfer line.

Electrons loose energy in the target mainly by bremsstrahlung, producing a photon cascade shower with a continuous energy spectrum, whose end point is equal to the maximum electron energy.

The produced photons can be absorbed by the nuclei of the target, exciting them. Afterwards, the excited nuclei decay in the fundamental state by boiling off neutrons, mainly according the mechanisms of the Dipole Giant Resonance, even if also neutrons of higher energy are expected due to the Quasi Deuteron mechanism.

The emission of protons is also possible but in case of heavy nuclei, this decay channel is strongly repressed due to the strong Colombian barrier.

The photoneutron reaction is a threshold reaction, since a nucleon can be made free only if the photon energy is greater than the binding energy of nucleons inside the nucleus.

Heavy nuclei exhibit a lower threshold and much higher photoneutron cross sections respect to light nuclei, so that they are more suitable for neutron photoproduction.

Anyway, in order to choose accurately the material and geometry that could maximize the neutron yield, taking properly into account the characteristics of the BTF electron beam, several Monte Carlo optimization calculations have been performed.

The rate of neutrons produced by photoproduction depends mainly on two factors: the beam power deposited in the target and the atomic number, Z, of the target nuclei. The maximum beam power that, at present, can be delivered on the target, according to the prescriptions of the Radioprotection Service, is limited to about 40-50 W.

Nevertheless, the authorization to transport and use all the Linac beam power (few tens of kW) for neutron production has been already requested and should be soon obtained.

IV. DESIGN OF THE NEUTRON SOURCE AND FINAL APPARATUS

The design of the experimental set-up for the BTF photoneutron source has been done using Monte Carlo codes. The main tasks to accomplish have been the definition of the target geometry and the choice of the material among high Z materials. FLUKA has been taken as the reference code, while MCNPX has been used for benchmarking purpose.

The first mandatory step, in the Monte Carlo model assessment, was the validation of the FLUKA model, testing its ability in predicting correctly the neutron source term. This has been done comparing the FLUKA predictions with respect to experimental or semi-empirical data provided by Swanson (Ref. 7) for several simple test cases. Swanson operated at SLAC at the end of 1970s, producing an important literature that still today constitutes the main reference for the design guidelines of shields around electron accelerators (Ref. 8).

The test cases used for validation are thick targets (thickness about 10 radiation lengths) of different material (Tungsten, Tantalum and Lead respectively) against which electrons of 500 MeV impinge. In Table II the predicted values by FLUKA code are compared with the Swanson's values.

TABLE II. Comparison between predicted and empirical neutron yields for different heavy materials

Material	FLUKA [n/kW/s]·E+12	Swanson [n/kW/s]·E+12
Tantalum	2.37	2.13
Tungsten	2.67	2.42
Lead	2.06	1.98

The estimated FLUKA rates have been derived from the "n/pr" values (neutron produced per primary electron), directly accessible in the output and by the following relation:

$$Rate[n/P[W]/s] = \frac{\frac{n}{pr} \cdot N_{pr}}{P_{dep}} \qquad (1)$$

where N_{pr} is the rate of primary electrons per second (#e-/s) and $P_{dep} = N_{pr} E_{dep}$ is the deposited power in the target. In case of thick targets, E_{dep} (the energy deposited by the single primary electron) coincides with the primary electron energy (500 MeV in the specific case).

Table II shows that there is a very good agreement (with difference less than 10%) between the predicted neutron yields by FLUKA and the Swanson's data. This makes us confident in the goodness of neutron source estimation by FLUKA calculations.

In addition to validation, important indications on the most effective material for neutron production can also be extracted: as Table II shows, Tungsten and Tantalum offer a greater neutron yield respect to Lead. In all the examined cases the neutron spectrum is pretty well a Maxwellian curve, peaked around 1 MeV, with little differences, according to which the maximum for Lead is a little bit shifted toward the higher energies, as it is shown in figure 1:

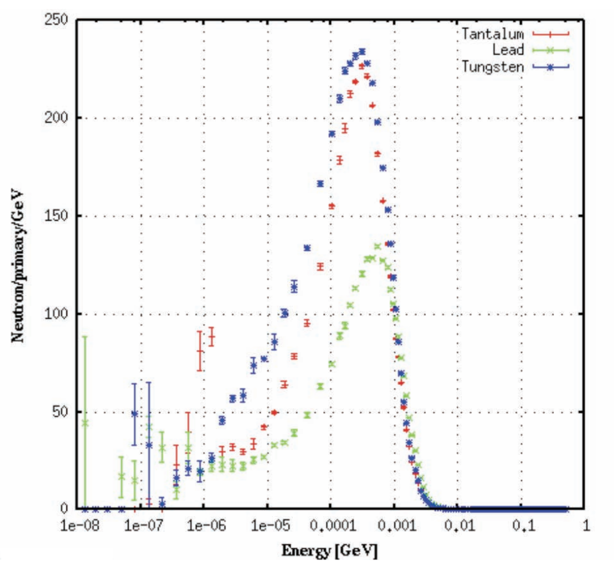

Fig. 1. Neutron Energy Spectra from a thick target in case of 3 different materials.

IV. A. Optimization of the target

Since the neutron yield for Tungsten is only slightly higher than Tantalum, the final choice between these two materials has been done on the base of the thermophysical properties: Tungsten offers a more effective heat transfer by conduction, having a thermal diffusivity almost 3 times larger than Tantalum.

For the optimization of the geometry, all the characteristics of the electron beam (energy spread, spot size and energy distribution, etc) have been properly inserted in the simulations.

A cylindrical configuration has been chosen for the target: the linear dimensions (both length and radius) have been determined as a result of an optimized procedure to maximize the neutron yield. The procedure has foreseen to estimate, for each configuration (that means fixed length and radius), the neutron fluence leaving the target and the neutron-to-photon fluence ratio in different locations and directions respect to the incident primary beam, mapping accurately all the solid angle around the target. As an optimization criterion, in a recursive process based on increasing the linear dimensions, we identified the best solution to be the one for which, a new step would have affected only marginally the photoneutron yield (an effective gain of only few percent). Increasing the cylinder length of 5 X_0 (where X_0 is the radiation length of the electromagnetic cascade) from 10 to 15 X_0, would have lead a corresponding enhancement in neutron yield of about 10%, while going from 15 to 20 X_0, the gain would have been less than 3%. So that a final cylinder length of 17 X_0 has been chosen (which identifies the beginning of the plateau in the neutron yield curve vs the cylinder lenght for a fixed deposited energy). At the same time, a fine tuning of the final radius has been also performed, so that, using the same optimization process, the optimum value for the radius has been determined to be ~ 10 X_0 (35 mm).

In the end, the optimized target designed and used as neutron source in BTF is a cylindrical bulk of radius 35 mm and length 60 mm.

The geometrical dimensions of the target and the accuracy by which the transversal electron beam size and position can be set (better than few mm) assure that all the primary electron energy will be deposited in the target[1] and since the photoneutron yield depends mainly on the value of the deposited energy, the estimated neutron yield sensitivity with respect to the primary beam geometrical parameters (beam spot size and radial location of the beam center) is actually negligible (less than 3%) .

The maximum neutron yield of neutron leaving the optimized Tungsten target has been estimated to be 0.212 neutrons per primary, integrated on all the energy spectrum and all the solid angle. The actual yield of neutrons produced per primary has been estimated to be 0.2189, showing that less than 3% of the produced neutrons are absorbed in the target.

Concerning the spatial distribution of the emitted neutrons, the information of the direction of the incident photon is lost, either in the GDR mechanism or in the QD

[1] The predicted deposited energy by a 510 MeV electron in the optimized target is 493 MeV ± 3%

one, so that the photoneutrons are quite well isotropically distributed around the target.

Table III summarizes the FLUKA estimations of the photon and neutron fluences around the target: going from a polar angle of 0, with respect to the electron impinging direction, to $\pi/2$, the photon fluence is reduced by two orders of magnitude, whereas the neutron fluence remains almost unchanged. Moreover, the Monte Carlo simulations show that the harder component of photon fluence is collimated in forward direction, along the electron beam. The Monte Carlo predictions of the spatial neutron and photon distribution around the target have determined important constraints in the design of the experimental set-up of the photoneutron source.

TABLE III. Neutron and Photon Fluences around the target. Polar angle is respect to the electron impinging direction

Polar Angle [deg]	**Photon Fluence [ph/cm^2 /pr]**	**Neutron Fluence [n/cm^2 /pr]**
0	1.166E-02 +/- 1.2 %	5.782E-06 +/- 0.6%
-30	3.187E-04 +/- 2.1 %	7.325E-06 +/- 1.4 %
30	2.001E-03 +/- 0.7%	6.987E-06 +/- 0.2 %
-45	2.556E-04 +/- 1.5 %	6.731E-06 +/- 1.5 %
45	9.855E-04 +/- 0.7 %	6.373E-06 +/- 0.8 %
-60	1.801E-04 +/- 3.3 %	5.841E-06 +/- 1.1 %
60	4.766E-04 +/- 1.8 %	5.353E-06 +/- 1.5%
90	9.619E-05 +/- 4.2 %	4.379E-06 +/- 1.1 %

IV.B. Final Experimental set-up

The photoneutron source is located in the BTF experimental hall, and as a consequence, the produced neutrons cannot be scattered everywhere, but have to be shielded all around the target, with the exception of well defined extraction lines, along which it should be possible to properly collect neutrons for measurements.

Taking into account the estimated photon and neutron maps reported in Table III, the final shield around the target has been completely defined: a multi-layered lead-polyethylene-lead shield covers almost all the solid angle around the target, leaving only three free paths: the middle square window for the primary electron inlet, and two cylindrical holes for the neutron extraction at 0° and 90°, in a plane perpendicular to the primary electron beam direction (see figure 2).

In Table IV the values of the neutron fluences, as predicted by the FLUKA code, in several locations of the experimental set-up are reported (refer to figure 3 for identifying the points).

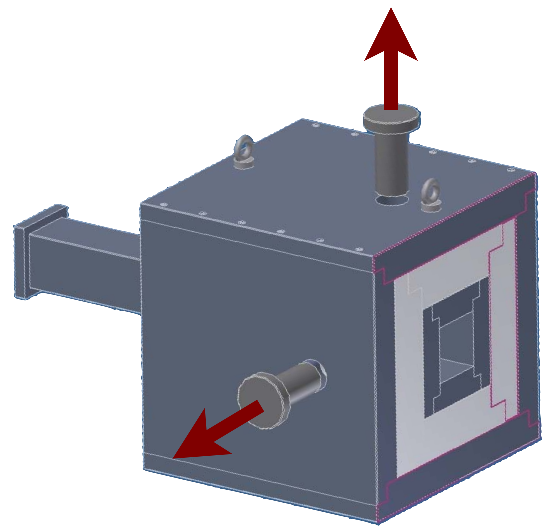

Fig. 2. Target Shield: the 2 neutron extraction lines in the plane perpendicular to the primary electron directions are put in evidence (exploded end caps are also shown)

TABLE IV. Expected neutron fluences per primary (first column) and estimated neutron rates, for 40 W of primary beam deposited on the target (510 MeV electrons) (second column)

Location	**Fluence [n/cm^2/pr] (on all the spectrum)**	**FLUX [n/cm^2/s] (on all the spectrum)**
exiting the target (A)	1.8E-03 ±4%	8.80E+08
entering the shield (B)	4.1E-04 ±4%	2.30E+08
leaving the shield (C)	4.9E-05 ±4%	2.50E+07
1.49 m from target (D)	8.1E-07 ±4%	3.90E+05

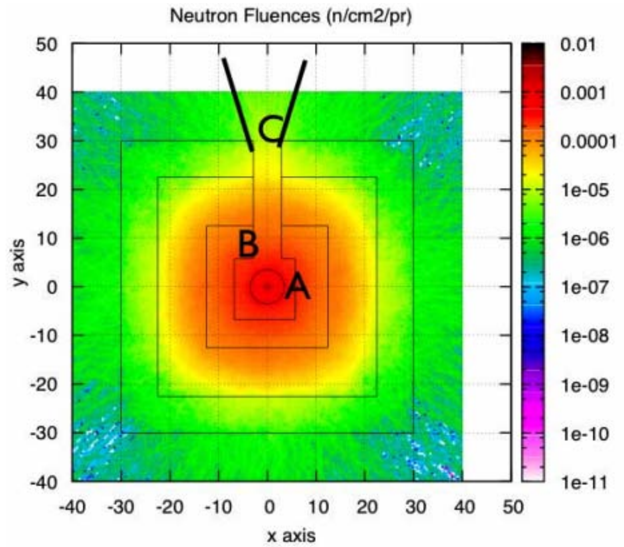

Fig. 3. Neutron fluence in the experimental apparatus (A indicates a point close to the target external surface, B is the inlet in the shield hole, C is the outlet of the shield hole)

One of the main drawbacks of this kind of source is the inevitable high photon background in which neutrons are immersed. In fact at 1.49 m from the target, along one of the two extraction lines, the photon fluence arriving on a spherical virtual detector of 10 cm has been estimated to be 1.4E-5 ph/cm^2/pr and this value has to be compared with a value for the neutron fluence of 8.1E-7 n/cm^2/pr, collected on the same detector.

For this reason several solutions have been investigated in order to enhance the neutron to photon ratio along the extractions lines. The results of FLUKA simulations show that, using caps of suitable material and thickness, it is possible to reduce significantly the photon contribution without affecting so much the neutron one. For example, a cap, of 25 cm length and made of Lead, enhances of more than an order of magnitude the neutron to signal ratio, leaving almost unmodified the neutron spectrum.

Studies of other materials for the extraction lines and of a possible beryllium inner reflector are currently under development and should provide useful indications about the increasing factor of the neutron fluence escaping from the shield.

V. EXPERIMENTAL MEASUREMENTS: THE FEASIBILITY TEST

The experimental set-up has been completely mounted in April 2010 and the first experimental neutron measurements have been performed at the end of May 2010. The experimental configuration of the feasibility test is shown in figure 4.

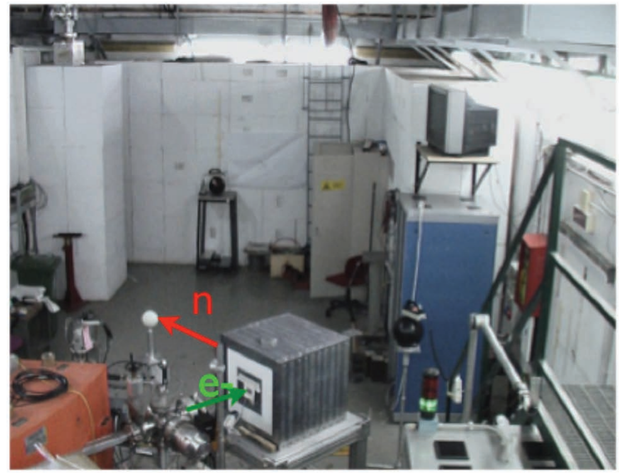

Fig. 4. Experimental set-up. One of the 7 Bonner Spheres is located in the reference point. (the white sphere). The other two black spheres in the picture are environmental detectors (they are used to check the repeatability of the irradiation condition within ±1.5 %)

Measurements have been done by using a Bonner sphere spectrometer, composed of 7 polyethylene spheres with radius 2", 3", 5" 7", 8", 10", 12", respectively. Each sphere can host in its center Dysprosium activation foils.

These spheres have been sequentially exposed in the reference point of the feasibility test (1.49 cm from the target center along one of the 2 extraction lines, at 1.24 cm from the floor), for an irradiation time of about 0.5 h for each sphere. The foils were counted in a portable beta counter and their specific activity has been corrected by: 1) the discrete activation function, 2) the decay from the exposure, 3) the counting, 4) the decay during counting, and finally normalized to the number of 510 MeV electrons delivered to the target. These values were unfolded using the FRUIT code (Ref. 9) and by the response functions of each sphere, previously calculated by MCNPX (Ref. 10) and reported in figure 4.

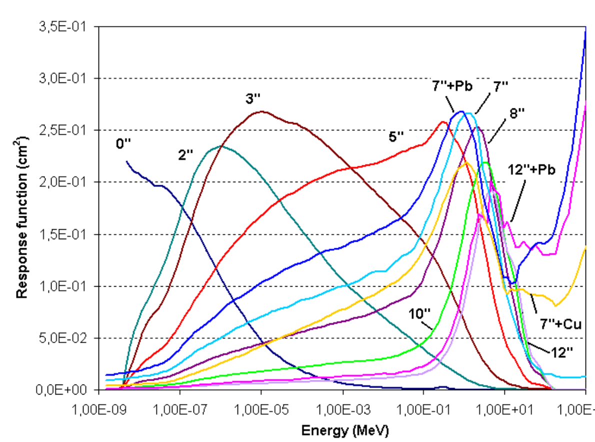

Fig. 5. Bonner spheres response functions.

VI. COMPARISON BETWEEN MONTE CARLO PREDICTIONS AND MEASUREMENTS

The comparison between the predicted neutron spectra, at reference point, estimated by FLUKA and MCNPX respectively, with the measured one is reported, in isolethargic[2] representation, in figure 6.

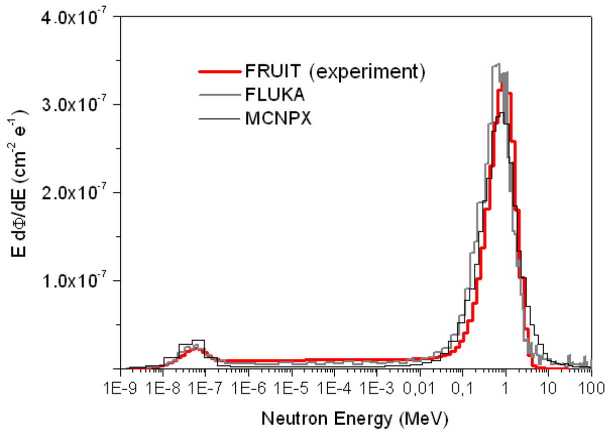

Fig. 6. Experimental and Monte Carlo predicted neutron spectra at the reference point

Figure 6 shows that there is a very good agreement between measurements and simulations, concerning the shape and the position of the Giant Dipole Resonance, as well as of the little thermal peak.

As predicted for, the majority of produced neutrons belong to the energy range from 10 KeV to 20 MeV: the calculated neutron spectrum has a Maxwellian shape with average around 0.7 MeV.

Statistical tests have been performed in order to quantify properly the accordance of Monte Carlo predictions with experimental values. In particular we used the $\chi 2$ Goodness of Fit test[3] in order to asses quantitatively the Monte Carlo accuracy around the Giant Dipole Resonance. The p-values that we found, respectively for MCNPX and FLUKA, are 0.996 and 0.967. This allows to conclude that MCNPX and FLUKA provide an accurate reconstruction of the experimental resonance, both in energy position and amplitude.

The experimental and calculated total neutron fluences, collected over a sphere of 10 cm, at the reference point are reported in Table V, confirming again the good agreement between experimental and predicted values.

[2] In an isolethargic plot the value of the energy spectrum, in each energy bin, is multiplied by the mean energy of the bin itself : <E>dΦ/dE

[3] $\chi 2 = (MC^2 - Exp^2)/(\sigma^2_{MC} + \sigma^2_{Exp})$, n= number of Exp point. Σ= Sum(χ2) over n. p_value= CHIDST(Σ,n)

TABLE V. Total neutron fluence per primary: comparison between experimental measurements and predictions.

Measurements [BSS] $1/[cm^2/pr]$	**MCNPX $1/[cm^2/pr]$**	**Fluka $1/[cm^2/pr]$**
8.04E-7±3%.	8.06E-7± 4%	8.12E-7±5%

On the base of these results, it is possible to conclude that, at present, since we are authorized to deposit only a small fraction of the total Linac power (40-50 W), we are able to have, at about 1.49 m from the target, a maximum neutron rate of about 4E+5 n/cm^2/s, that is mainly composed (≥80%) of neutrons with energy around 0.7 MeV, as correctly predicted by Monte Carlo simulations.

Finally, in figure 7, the estimated photon energy spectrum at the reference point as obtained by FLUKA and MCNPX, has been reported.

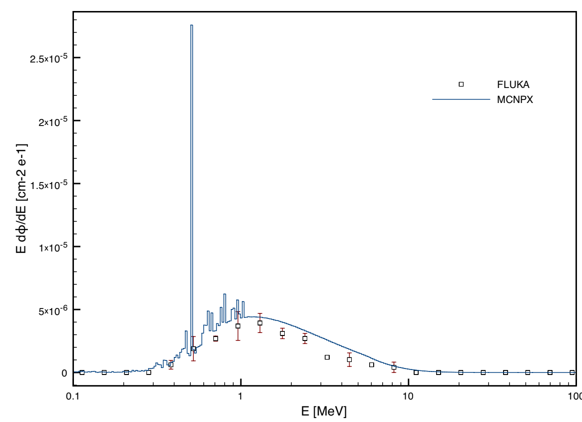

Fig. 7. Isolethargic plot of photon spectrum: FLUKA vs MCNPX.

MCNPX and FLUKA agree within few percent in the estimation of the total photon fluence at the reference point: 1.2E-5 ph/cm^2/pr ± 5%.

Measurements of the photon fluence at the reference point have been recently performed, by using a crystal inorganic scintillator (YAP: Ce). Raw data are still under processing, but preliminary analysis shows that the measured photon fluence is about an order of magnitude larger than the Monte Carlo estimations (about 1.E-4 ph/cm^2/pr) **.**

This discrepancy is, actually, easily explainable by the fact that in the performed Monte Carlo simulations, the BTF experimental hall has not be completely represented, so that backscattering phenomenon and radiation interactions with walls and instrumentations cannot be taken into account in the present simulations.

V. CONCLUSION

A photoneutron source has been successfully realized at the DaΦne BTF: the feasibility test was successfully carried out in May 2010, demonstrating definitively the BTF ability of providing not only electrons, positrons and tagged photons (Ref. 11), but also neutron beams.

The measured neutron rate and spectrum, at the reference point for the feasibility test, are in good agreement with the simulations. Anyway, further measurements of both neutron and photon fields, in several points of the BTF experimental hall, have to be done, in order to properly characterize the facility: a new measurement campaign has been already scheduled in short time and results will be soon available.

Other investigations are underway for a suitable design of the extraction lines (both in terms of material allocation and geometric configurations), in order to enhance the neutron to photon ratio.

From the computational point of view, an important task to fulfill concerns the use of another important Monte Carlo code, GEANT4, in order to investigate if the differences in photonuclear physics implementation can affect the simulation results. A detailed comparison of the three Monte Carlo codes is foreseen.

The BTF neutron source will be soon made available to the whole international scientific community for its main scopes.

ACKNOWLEDGMENTS

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