Spallation Neutron Production On Thick Target At Saturne

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Abstract: In view of the new spallation neutron source projects, we discuss the characteristics of the neutron spectra on thick targets measured at SATURNE. Some comparisons to spallation models, and especially INCL4/ABLA implemented in the LAHET code, are done.

I. Introduction

A renewed interest for spallation neutron sources has appeared for several years with new or foreseen facilities dedicated to material irradiation (SNS[1)]-SINQ[2)]-NSP[3)]) and with ADS projects (Trade[4)]-Myrrha[5)]). The most common materials used in such facilities are lead, tungsten, bismuth, iron or aluminium as target, coolant, window or structure material. In order to optimise the future neutron sources and for safety reasons (ex: damages), the behaviour of these materials under proton (beam) and neutron irradiation has to be known. Since it is impossible to build a data library, because of the large energy range at work, the use of calculation models is necessary. However these models have to be tested on experimental data. With the neutron spectra measured at SATURNE on thick targets[6),7)] (Pb, Fe, W, Al), spallation models, known to give good results on thin targets, can be tested now in more realistic conditions. We describe the experimental set up and experiments at SATURNE in section II, compare SATURNE data to KEK data in section III, and to the spallation model INCL4[8)]/ABLA[9)] implemented in the LAHET[10)] code in section IV. We conclude in section V.

II. Experimental set up and experiments

The experimental set-up (fig.1) was the same as the one used for the thin target measurements except that, because very few neutrons are expected to have energies higher than 400 MeV, only the time-of-flight method was used [11)]. Measurements with various lengths and diameters of cylindrical targets were conducted on the different targets. The collimators and the possibility to longitudinally translate the target allowed the selection of neutrons coming from different emission zones, thus enabling to test the propagation of the cascade along the target. Measurements were performed at 0° and every 15° from 10 to 160°. The detail (diameter, length and measurement position for each target) of the different measurements is given in the table 1.

Because of the collimators, the target area seen, totally (full exposition zone) or partially (penumbra zone), by a detector depends on the angle of the collimator and on the target diameter and longitudinal position. Therefore, on each figure and for each angle a diagram showing the full exposition and penumbra zone has been added. All data presented here are number of neutrons per incident proton,

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MeV and cm^2 of detector. The systematic errors on the data are the same as for thin target measurements, as discussed in details in [12], and are always less than 12%.

Target	Energy (GeV)	Diameter (cm)	Length (cm)	Position (cm)	Config.
Lead	0.8	10	40	30	2
		20	40	10	2
			65	10 30 50	1
	1.2	10	65	10 30 50	1
		20	65	10 30 50	1
					2
			105	50 70	1
	1.6	10	105	10 30 50	2
		20	105	10 50	1
				50	2
Iron	0.8	10	40	10 30	2
		20	40	10 30	2
	1.2	10	65	10 30 50	1
		20	65	10 30 50	1
	1.6	10	105	10 30	2
		20	105	10 30	2
Tungsten	0.8	15	59	10	2
	1.6	15	59	10 30	2
Aluminium	1.6	20	105	10 30	2

Table 1: experiments done at SATURNE on thick targets

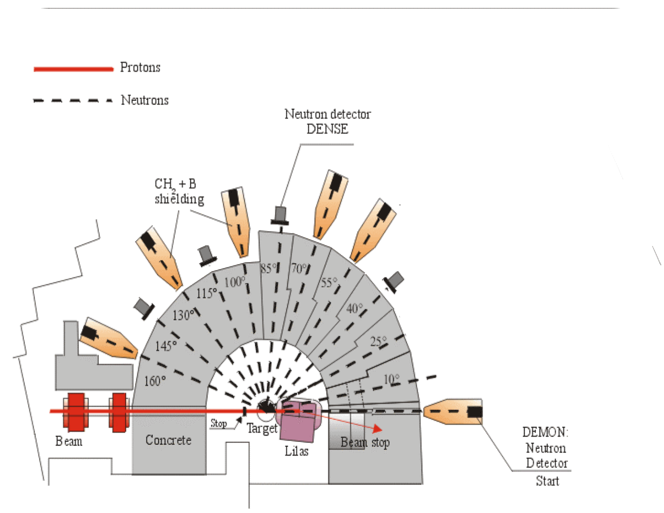

Figure 1: experimental set up

III. Comparison with KEK data

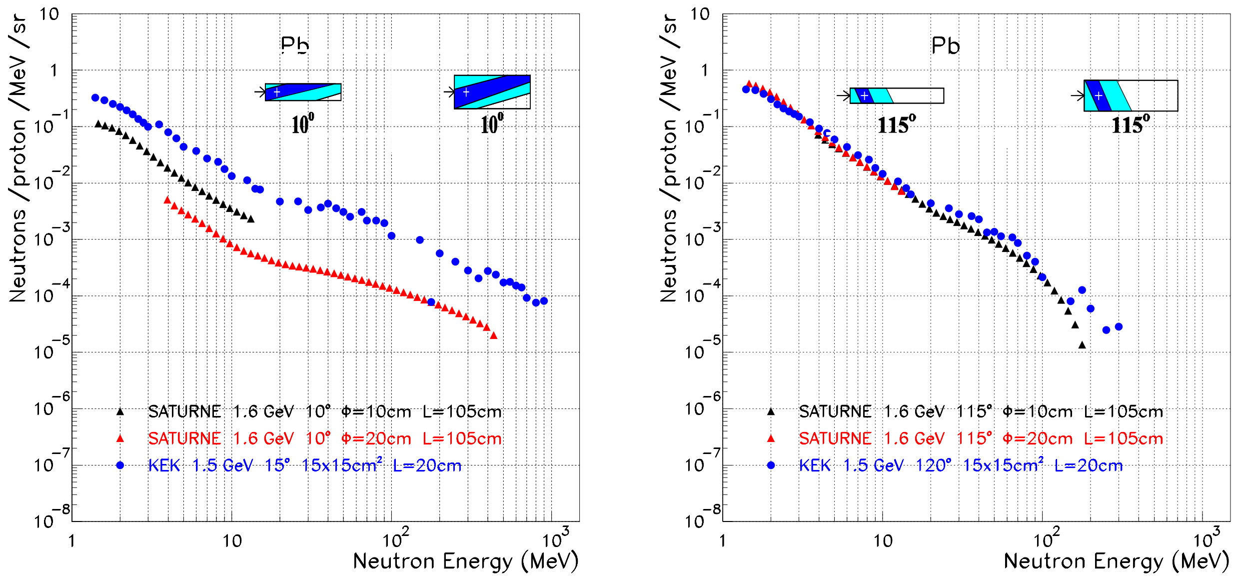

Figure 2: Neutron spectra from a cylindrical lead target measured at SATURNE at 1.6 GeV (black points: Φ=10cm; red points: Φ=20cm) and parallelepiped target at KEK at 1.5 GeV (blue points) at 10° or 15° (left side) and 115° or 120° (right side). The enclosed schemes show the region of the target seen by the detectors at SATURNE in the case of the 10 cm and 20 cm diameter targets respectively.

A similar experiment has been carried out at KEK[13)]. The experimental set up used at KEK to measure neutron spectra produced from a thick lead target bombarded with 1.5 GeV protons is approximately the same one used at SATURNE. The main differences between the experiments are the target geometry (a 15*15*20 cm^3 parallelepiped) and the positions of the detectors. Nevertheless, we can compare the behaviour of the spectra. This is done on fig.2 where the results obtained at KEK (at 15° and 120°) are shown together with the ones from SATURNE for the cylindrical targets L=105cm, Φ=10 and 20cm at angles 10° (left) and 115° (right) respectively. The enclosed schemes show the region of the target seen by the detectors at SATURNE in the case of the 10 cm and 20 cm diameter. For the forward angle, a much larger number of neutrons is found in the case of the KEK experiment. This can be understood from the difference between the lengths of the two targets and transport through the target. Actually, in such targets most of the protons interact in the first 20 cm leading to the emission of high-energy, forward-peaked neutrons. In a long target, as in SATURNE, the transport, i.e. secondary reactions, tends to scatter and consequently decrease the neutron flux for forward angles, while at KEK a large part of the primary neutrons are detected.

On the contrary, at 115-120°, the primary neutrons pass through too little matter to be affected by secondary reactions and, therefore, the number of emitted neutrons does not depend on the target diameter or shape. That is why both experiments give practically the same results.

IV. Comparisons with models

The spallation process can be split in two mechanisms. First the nucleus is excited by the projectile and emits particles with high energies (Intra-Nuclear Cascade), and afterwards it deexcites via evaporation of light particles with lower energies, and/or fission for the heavy nuclei.
The model combination INCL4/ABLA is known to give rather good results with thin targets[8)], especially for neutron spectra. So these data from SATURNE are interesting to test this combination on thick targets. This work can be done now since INCL4 and ABLA have been implemented in the high energy transport code LAHET. Other models like Bertini[14)] and ISABEL[15)] for the INC, and Dresner[16)] for the deexcitation phase are available in LAHET.
LAHET is used to describe the spallation reactions and transport of high energy particles. When neutrons in the target are below 20 MeV the transport is then done by MCNP. In order to minimise the computer time, only the target geometry is taken into account in LAHET and MCNP. The neutrons created and ready to leave the target are stored in libraries and another code is called to transport these neutrons from the target surface to the detectors.

We will focus on the combination INCL4/ABLA. Nevertheless we will compare it not only with the data, but also to another combination, Bertini(+preequilibrium)/Dresner, which is the most common combination used, up to now, for thick target calculation or simulations. Since it is impossible to plot here all results, we will show on figures 3-5 some comparisons which summarize the quality of INCL4/ABLA according to the data and to the Bertini/Dresner model.
In general, INCL4/ABLA well reproduces the SATURNE data whatever the material, geometry and angle, with a few discrepancies. The energy dependence of the model seems rather good since the quality of the agreement is the same at the three energies.

Results obtained with different target diameters or length are well understood with the simulations. For instance, the behaviour observed in fig.3 concerning the comparison of two different diameters is perfectly reproduced by the calculations. It is found that a smaller diameter (10 compared to 20 cm) has little effect on the sideward emitted neutrons while it leads to an important increase (about a factor 2) of the neutrons emitted in the direction of the beam. This could be a problem for shielding considerations. The models allow to predict the total amount of neutrons below and above 20 MeV, which are 29.7 (resp. 23.5) n/p for the 20 (resp. 10) cm diameter target.

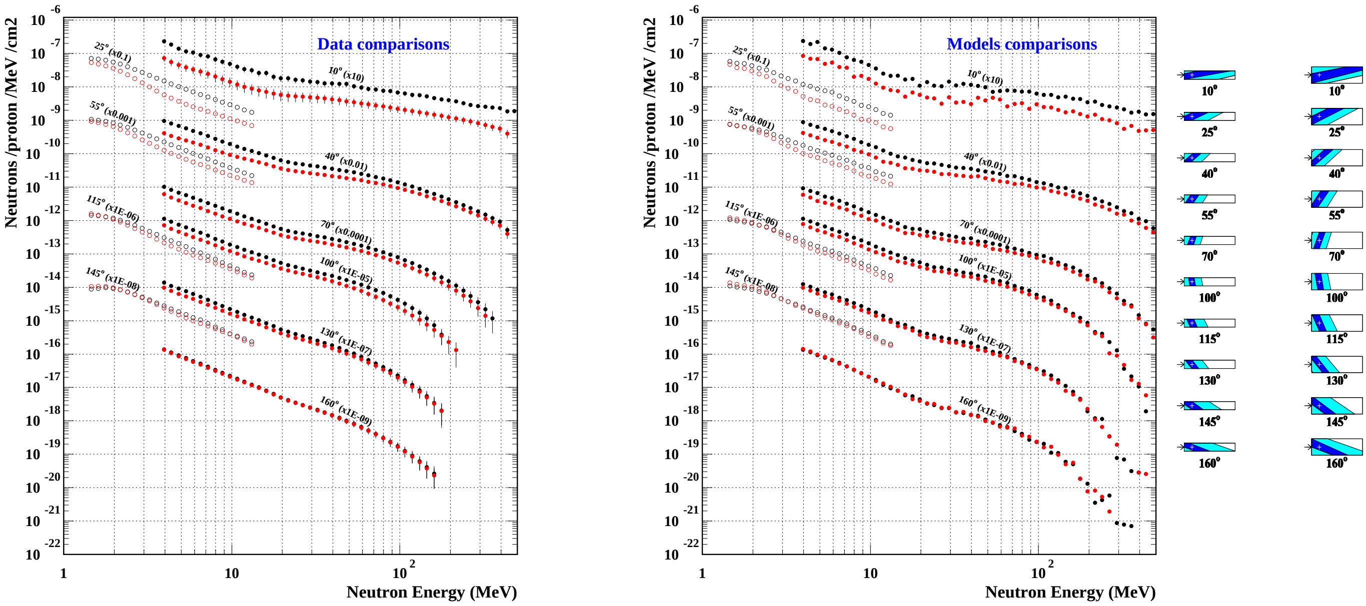

Figure 3: Neutron spectra on 10 cm (black points) and 20 cm (red points) diameter lead targets at 1.2 GeV. Data from SATURNE (left side) and results of INCL4/ABLA model combination (right side).

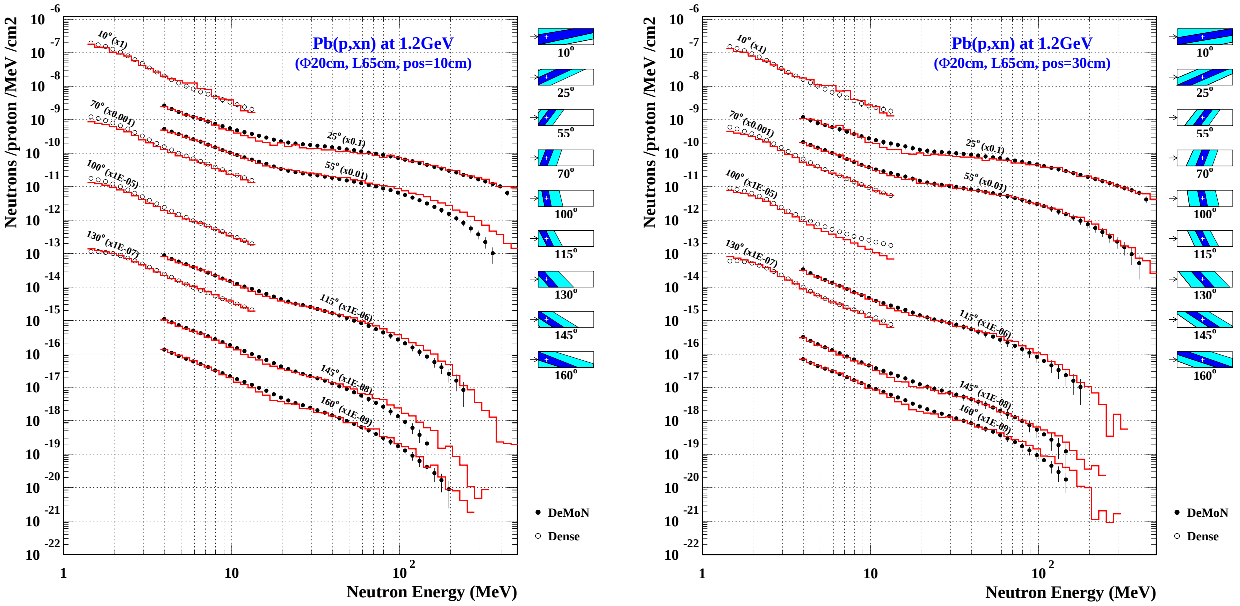

Figure 4: Neutron spectra measured at SATURNE on a 20 cm diameter lead target at 1.2 GeV (black points) compared with calculations made with the LAHET3/MCNP code using the INCL4/ABLA model combination (red line). The two figures correspond to two different longitudinal positions of the target with respect to the collimators.

In fig.4 examples of the obtained results are shown for a 20 cm diameter lead target at 1.2 GeV for two different longitudinal positions of the region aimed at by the collimators. The agreement is very good, except for the position 10 cm, where the neutrons from the cascade (above 70-80 MeV) are overestimated at some angles. This behaviour is consistent with what has been observed for thin targets[8)]. If we move the same target to the position 30 or 50 (not shown) cm these discrepancies disappear. An explanation could be that the neutrons detected in this case come from an interaction occurring further in the target (see the schemes on the right of the figures), consequently at a lower energy and that the model predicts more correctly the spectra at lower energies.

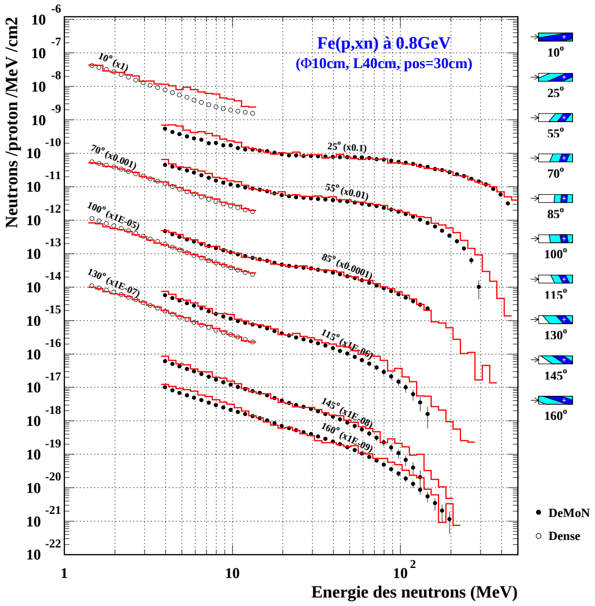

Figure 5: Neutron spectra measured at SATURNE on a 10 cm diameter iron target at 0.8 GeV (black points) compared with calculations made with the LAHET3/MCNP code using the INCL4/ABLA model combination (red line).

For iron target the results, on fig.5, are also good, and here the discrepancy is for the very forward and backward angles (10° and 160°) and for the energies between 3 and 15 MeV. The neutrons amount is overestimated. At these energies the neutrons come mainly from evaporation process, even if some neutrons emitted during the cascade can have slowed down. Nevertheless the reason is not obvious.

In fig.6, data at 1.6 GeV for a lead and an iron target are compared with INCL4/ABLA (red curve) and also to the Bertini(+preequilibrium)/Dresner combination (blue curve). Actually, whatever the material, diameter or length of the target, or beam energy, the agreement obtained with the two combinations is of similar quality. In general, small discrepancies are observed which corresponds to the ones already pointed out with thin targets: Bertini/Dresner is less good in the intermediate energy region (around 100 MeV) especially for iron while INCL4/ABLA tends to overestimate the high energy neutrons at angles close to 90°.

The difficulty with thick targets is that several effects are combined. For instance, the neutrons detected have been produced by different spallation reactions at different energies, and covered different distances through the target. So, it is often difficult to understand the reason of a given effect or discrepancy

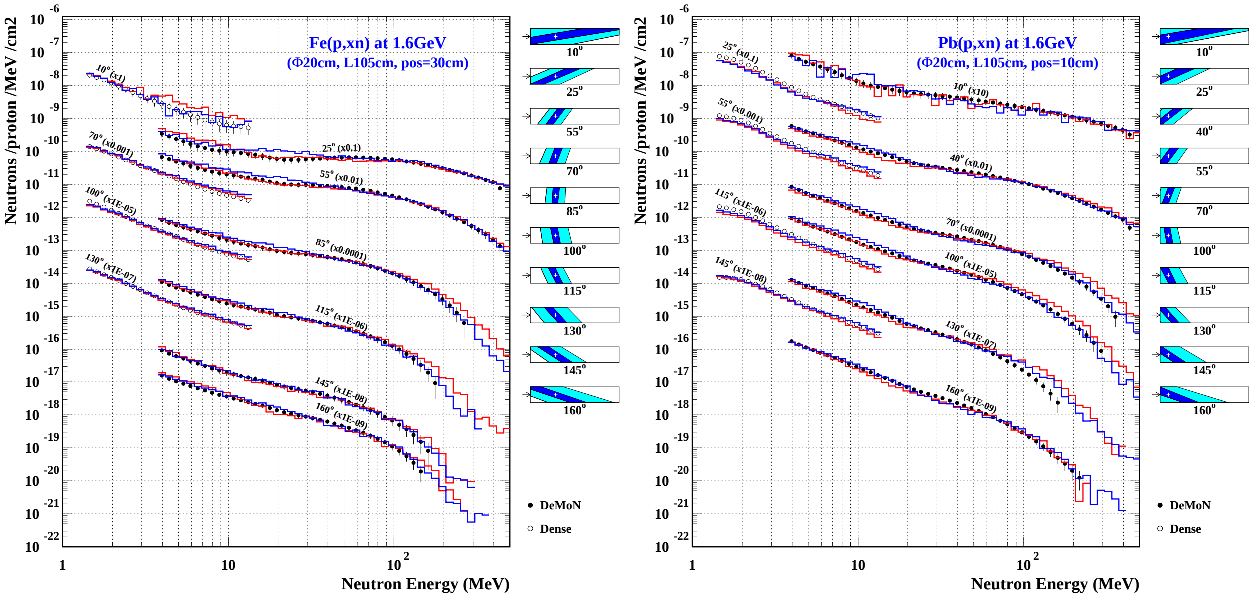

Figure 6: Neutron spectra comparisons between SATURNE data (black points), INCL4/ABLA model (red line) and Bertini/Dresner model (blue line) for a lead and an iron target at 1.6 GeV.

V. Conclusion

These accurate neutron spectra on thick targets measured at SATURNE are very useful, of course, to know where (angle), how many (cross section) and which kind (energy) of neutrons are emitted from a thick target, but also to test and give sometimes the way to improve the spallation models. Thus, we know now that the spallation model INCL4/ABLA, which gave good results for thin target, is good as well for thick targets. We have seen some slight discrepancies with the data, but INCL4 and ABLA improvements are still in progress.

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