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Abstract :

Good knowledge of spallation reactions is necessary to design accelerator-based transmutation systems. An extensive program has begun at Saturne to measure energy and angular distributions of neutrons produced by incident protons or deuterons of up to 2 GeV on several thin targets. Our measurements will extend the available data to higher energies than the present limit of 800 MeV enabling improvements to the codes which are sometimes in poor agreement with the data.

1. Introduction :

Spallation reactions are often used to produce intense neutrons fluxes. Of the many applications which are being studied, hybrid spallation-reactor systems are useful for producing energy or incinerating wastes. In these systems, a spallation source is provided by the interaction of protons or deuterons of about 1 GeV with a heavy target. The neutrons produced interact with a sub-critical blanket assembly in which nuclear wastes are burned and/or energy is produced with a reduced production of radioactive wastes.

To conceive such projects, especially to design the spallation target and to predict the radiation damage in structural materials, good knowledge of spallation processes is needed. Fundamental nuclear data such as the number of neutrons produced for each incident particle and their energy and angular distribution are necessary to achieve such accelerator-based transmutation applications.

Such data are also essential for validating and improving the codes which simulate spallation processes. Some comparisons between these codes have shown their poor agreement. Moreover, we must emphasize that there are no data for spallation reactions above 800 MeV[1] and, even below this energy, there are discrepancies between different measurements[2].

Therefore, in order to produce more extensive and reliable data, a new program has begun at Saturne to measure the double differential cross-sections for neutrons produced by protons or deuterons with energies between 800 MeV and 2 GeV on various thin targets. The first data were taken at the end of 1994 and this program will continue until 1997.

2. Experimental arrangement :

The present experimental arrangement was designed to study the energy distributions of neutrons produced by thin targets at 0°. Future measurements will extend these data to the angular distributions up to 160°. Neutron energy is normally measured using pulsed beams and time of flight techniques. The synchrotron of the Laboratory National Saturne does not allow such measurements because the beam structure is essentially dc and long flight paths are not available. We therefore use two different techniques to measure neutron spectra. The experimental set-up is shown in figure 1.

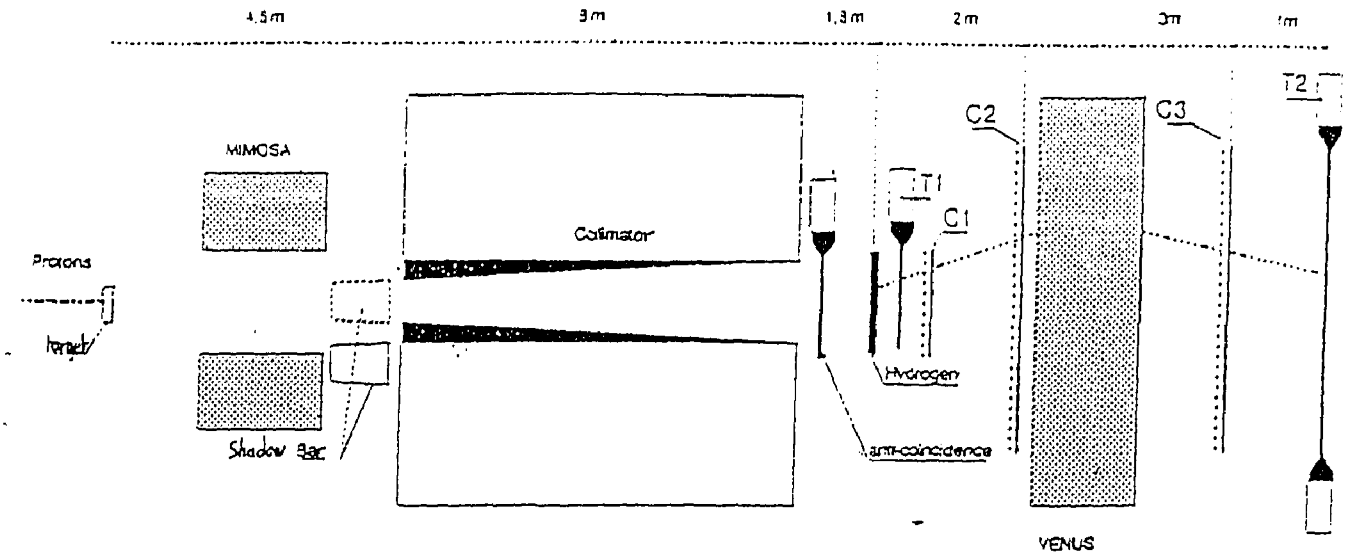
For the high energy measurements, neutrons produced by the spallation target are collimated and then pass through a liquid hydrogen convertor located 15 meters downstream. The momentum of protons produced by back-angle elastic scattering of the neutrons is measured by a magnetic spectrometer with an angular acceptance of 15 degrees and low energy cutoff of about 100 MeV. Their trajectory is reconstructed from information provided by three double-plane wire chambers. The trigger is provided by a coincidence between the front-end scintillator (T1) and a plastic scintillator hodoscope behind the spectrometer (T2). The beam intensity, about 10^{10} particles per second, is measured using two triple-element scintillator telescopes viewing a 50 μm mylar target placed upstream in the beam. Absolute calibration of these telescopes is obtained by irradiating a disk of carbon and counting the β decay rate from ^{11}C, for which the production cross-section is known.

For the measurements of the lower energy neutrons, the beam intensity is reduced to 10^6 particles per second so that individual beam particles can be counted by a thin scintillator placed just in front of the production target. The diameter of this counter was made slightly smaller than the target to ensure that all the beam particles counted by the scintillator also traverse the target. Neutrons produced within a solid angle of 0.07 msr about zero degrees are detected by an NE213 scintillator placed 13.5 meters downstream and time of flight is measured relative to the tagged proton. Time resolution measured from the prompt gamma-ray pulses is about 1.5 ns. In the analysis, the gamma-rays are removed from the time of flight spectra using pulse shape discrimination. These low energy measurements extend from about 4 to 200 MeV. The energy resolution at 200 MeV is about 10 MeV so a good comparison can be made with the high energy spectrum.

In both cases, protons which did not interact in the target or other charged particles emitted in the forward direction, are deflected by a magnetic field into a concrete beam stop, before the collimator. But it is necessary to ensure that all the charged particles which could appear to be neutrons in the spectrometer or the NE213 scintillator are eliminated. So in addition to the sweeping magnet we placed a thin scintillator after the collimator to tag and reject all the stray charged particles. Moreover, a shadow bar is used to measure the background created by the interaction of neutrons with the collimator and air in the flight path.

The lengths of the targets are a compromise between the counting rate, the number of unwanted secondary reactions in the target and the energy loss.

An essential aspect of these measurements is the determination of detection efficiency. A useful feature of Saturne is that it is easy to switch to deuteron beams. By using their break-up on a Be target, we can produce quasi-monoenergetic neutron beams that are used to calibrate the detection system.



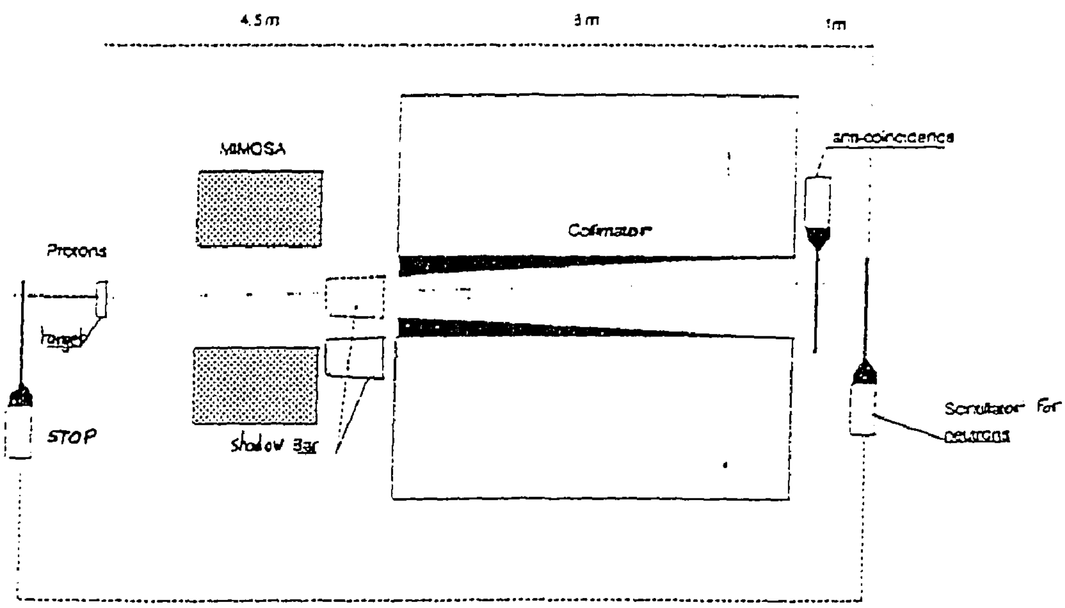


Fig. 1 : Experimental arrangement : Above: measurement of neutron energy from 100 MeV to the beam energy. Below: measurement of neutron energy from 2 to 200 MeV.

3. Analysis and results :

This experimental set-up was installed during the first month of 1994 and tested in June. The first measurements, made during November 94, determined the efficiency of the detectors for neutrons varying from 50 MeV to 1.15 GeV. We also measured the neutron spectra at 0° produced by 800 MeV protons on a lead target and by 1.2 GeV protons on both lead and iron targets.

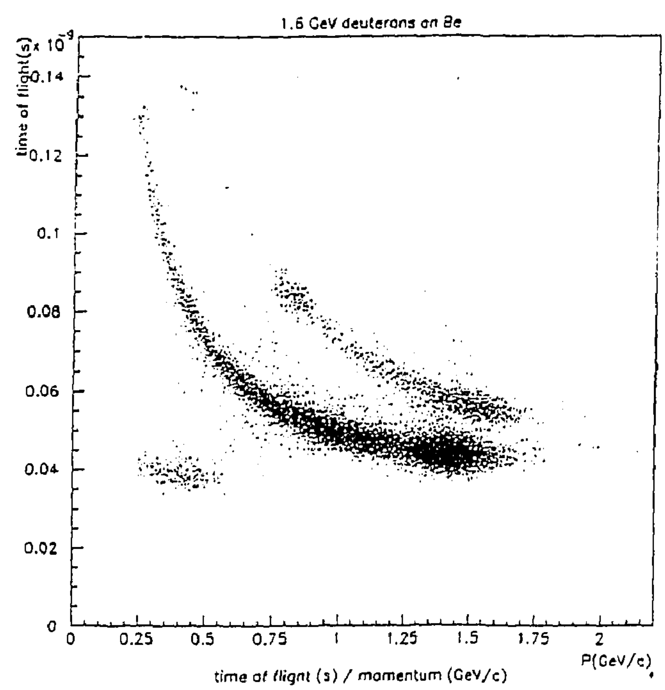


Fig. 2 : Mass discrimination spectrum measured with 1.6 GeV deuterons on a 7.5 cm Beryllium target.

For high energy neutrons, trajectory reconstruction provides proton momentum by the relation between the particle path in a magnetic field and its velocity. Combined with a time of flight measurement between T1 and the scintillator hodoscope of the spectrometer, we can discriminate protons from other charged particles. A typical mass spectrum is shown in figure 2. The mass resolution is adequate to provide unambiguous identification of protons, allowing us to separate them from the deuterons and pions which are also detected.

Assuming that the recoil protons are produced by elastic scattering (inelastic processes are discussed below), the momentum measured by the spectrometer determines the incident neutron energy.

Software cuts on the trajectory reconstruction were used to eliminate protons which did not originate in the liquid hydrogen convertor. In order to reduce these events (50 % of the data), structural materials surrounding the target have been disminuished for the next experiments. To estimate the background created by the environment of the neutron production target, data were taken without the target. A total background of about 20 % was then subtracted.

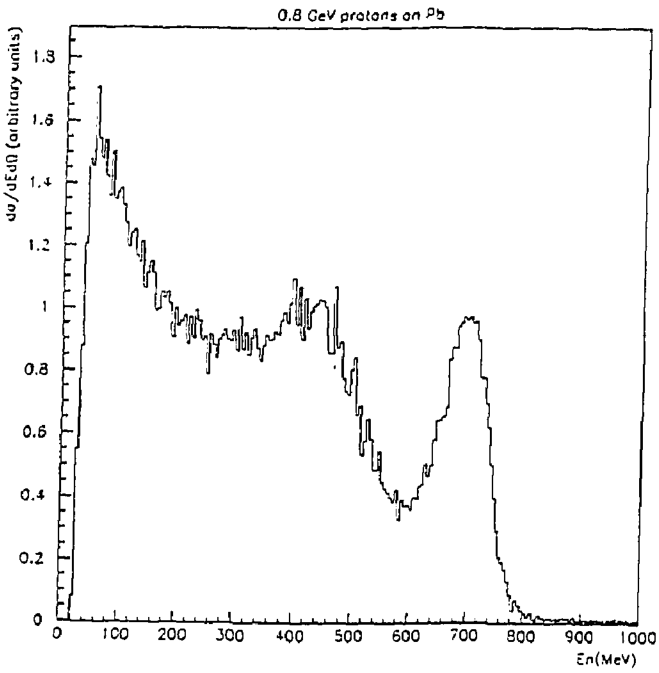


Fig. 3 : Preliminary neutron spectrum measured with the spectrometer using 800 MeV protons on a 2.5 cm lead target.

An example of the spectra obtained at 0° with 800 MeV protons on a lead target is shown in figure 3. This spectrum is characterized by a peak at an energy near than that of the proton beam which is due to quasielastic charge exchange in the lead nucleus. There is also a broader peak, 300 MeV below, which is produced by reactions involving quasifree pion production. This spectrum has not been corrected for the spectrometer detection efficiency. This correction will be made using the measured responses of the spectrometer to quasi-monoenergetic neutrons from 200 MeV to 800 MeV : for each energy, we can deduce the neutron flux produced by the deuteron break-up using the cross-sections of either the elastic scattering[1), 2), 3)] or the $np \rightarrow d\pi^0$ reaction[4)] in the hydrogen convertor.

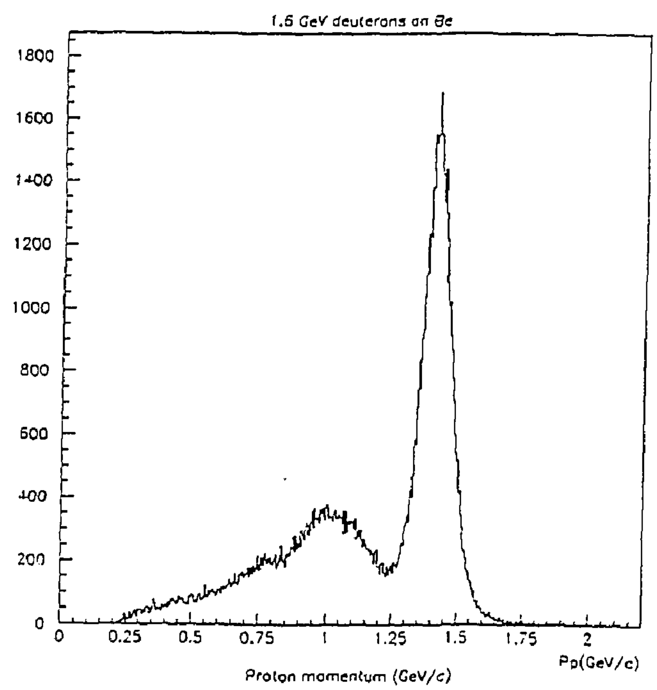


Fig. 4 : Proton spectrum measured with a quasi-monoenergetic neutron beam produced by 1.6 GeV deuterons on a 7.5 cm Beryllium target.

Figure 4 shows an example of the response of the spectrometer to quasi-monoenergetic neutrons. The width of the elastic peak is mainly due to the momentum wavefunction of the break-up deuterons. This proton spectrum is dominated by elastic scattering. The contribution from inelastic reactions, at lower energies, involve pion production such as $np \rightarrow pn\pi^0$ or $np \rightarrow pp\pi^-$.

In measuring spallation neutron spectra, however, we can not distinguish the kind of reaction that produced each proton detected in the spectrometer. For the moment, we have assumed only elastic scattering, so the neutron spectra still need to be corrected for the contribution due to inelastic processes. This deconvolution will use the spectrometer responses obtained for each quasi-monoenergetic neutron beam.

For the low energy spectra, the neutron energy is measured by the time of flight technique. A pulse given by the neutron detector is used as a start for the time of flight measurement. Stop pulses, measured by the proton detector are delayed by one microsecond and sent to the TDC, used in common start mode. This delay represents the maximum time required for a 1 MeV neutron to travel along the 13.5 m flight path. During this time several stop pulses can be registered. To be sure of measuring the proton correlated with the neutron production, the train of stop pulses is routed through a pulse separator. The separator accepts a series of pulses and routes each one in turn to separate outputs. This series of pulses is then sent to eight TDC's. By adding the eight TDC spectra, we can reconstruct the real time of flight spectrum at the cost of an additional random background. An identical TDC-separator system is used to record this uncorrelated background using a non-delayed stop pulse. This background to be subtracted constitutes typically 60 % of the events after elimination of gamma rays.

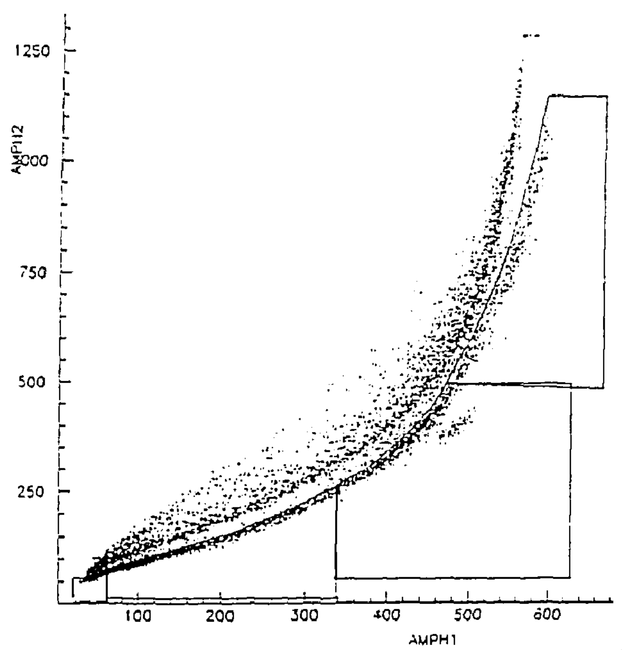


Fig. 5 : Neutron discrimination spectrum measured with 200 MeV deuterons on a Beryllium target. The curves are the cuts used to eliminate gamma rays.

The pulse shape difference between signals due to neutrons and those due to gamma rays is used to remove those gamma rays which are detected despite the thick lead cylinder surrounding the NE213 scintillator. This pulse shape discrimination consists of storing two different components of the signal given by the neutron counter (the full integrated pulse and the decay tail) and plotting them in a two dimensional spectrum, as in figure 5.
The software cuts removes most of the gamma rays from the time of flight measurement. More or less 80 % of the total events were due to gamma ray detection.

After these corrections, we obtain a net time of flight spectrum. The results obtained with 800 MeV incident protons on a lead target are shown in figure 6. This spectrum has not been corrected for the detector efficiency which was measured with monoenergetic neutron beams at Saturne. The neutron flux for these measurements was calculated from the known cross-sections for the break-up of deuterons on Be[5)]. For the lower energies from 2 to 16 MeV, the efficiency was measured with the Van de Graaff accelerator at Bruyères-le-Châtel, using the $^3H(p,n)^3He$ and the $^3H(d,n)^4He$ reactions. For each measurement our scintillator and another smaller neutron counter with a well known efficiency were placed symmetrically at +/- 20° to the beam direction. Thus, a comparision of the counting rates provided the detector efficiency. The results obtained for these efficiency measurements are shown in figure 7.

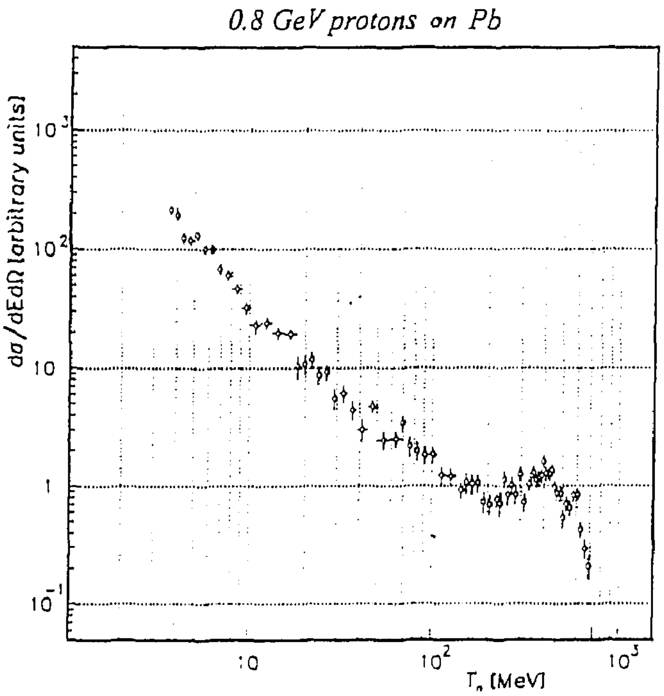


Fig. 6 : Preliminary neutron spectrum measured by the time of flight technique, with protons of 800 MeV on a lead target.

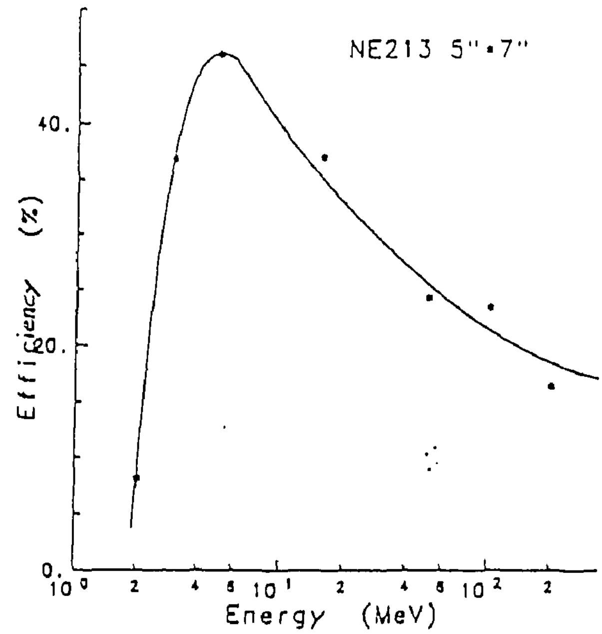


Fig. 7 : Efficiency curve of the neutron counter with measurements made at Bruyères-Le-Châtel (2 to 16 MeV) and with quasi-monoenergetic neutron beams at Saturne (50 to 200 MeV)

4. Future :

Measurements will be extended this year to higher energy protons (1.6 GeV and above) and to incident deuterons. The targets will be a range of different elements such as Al, Fe, Zr, W and Pb. These elements are chosen either as likely structural materials to be used in hybrid systems or as good spallation targets. Due to time constraints , only two targets (Pb and Fe) will be studied at all energies and incident particles, however measurements will be made at least at one energy on all the targets.

The design of accelerator-based transmutation systems and the improvement of applicable codes, requires a good knowledge of the angular distribution of spallation neutrons. For example, it is crucial to know how many neutrons are likely to be emitted through the window which will separate the accelerator beam from the target used for transmutation.

The extension of our measurements to the angular distribution of the neutrons necessitates a change of our experimental set-up in order to detect neutrons emitted at several angles simultaneously. Therefore, the future experiment will be mounted in a larger hall. Concrete shielding will surround the target and protect the detectors from the background created by the beam stop. Several collimators will pierce this wall at the angles we want to study. The spectrometer will run from 0° to 90°, since high energy neutrons are not expected above 90°, and six scintillators will be used for time of flight measurement of the low energy neutron distributions.

This new set-up will also be used to measure the energy spectrum of neutrons emitted by thick targets. In this case, only the scintillators will be used as only low energy neutrons are expected to escape from the target. We will study the neutrons emitted from several points of the target with different incident particles, energies, sizes and composition of targets. These measurements will be useful for testing the codes under a variety of conditions. These experiments will be a collaboration between the LNS (Saclay), PTN (Bruyères-le-Châtel), the DAPNIA/SphN (Saclay), the Demon group and Uppsala University with the additional participation of the IPN (Orsay) for the measurements with thick targets. The experimental set-up will be installed in 1995 and the first measurements will be made in the middle of 1996.

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