Spallation Physics and the ADS Target Design

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This paper reviews the physics of the spallation which is a nuclear reaction in which a particle (e.g. proton) interacts with a nucleus. Given to the high energy of the incident proton, in a first stage it interacts with the individual nucleons in an intranuclear cascade which leads to the emission of secondary particles (neutrons, protons, mesons, etc.). In a secondary stage the nucleus is left in an excited state and can de-excite by evaporation and/or fission. Given to the high number of secondary neutrons produced (∼30 n/p for proton energy of 1 GeV), this reaction can be used as a source of neutrons, for example for ADS systems as external source to drive the sub critical reactor. The main codes used in the ADS target design and an example on the utilization of one of these codes (the LAHET code) for typical ADS target are given.

I. INTRODUCTION

The Accelerator Driven System (ADS), is an innovative reactor which is being developed as a dedicated burner in a Double Strata Fuel Cycle to incinerate nuclear waste [1]. The ADS system consists of a sub-critical assembly driven by accelerator delivering a proton beam on a target to produce neutrons by a spallation reaction. The spallation target constitutes the physical and functional interface between the accelerator and the sub-critical reactor. For this reason it is probably the most innovative component of the ADS. The target design is a key issue to investigate in designing an ADS and its performances are characterized by the number of neutrons emitted for incident proton, the mean energy deposited in the target for neutron produced, the neutron spectrum and the spallation product distribution.

II. THE SPALLATION REACTION PHYSICS

Spallation is a nuclear reaction in which a relativistic light particle like a proton or a neutron hits a heavy nucleus. The energy of the incoming particle usually varies between a few hundred of MeV and a few GeV per nucleon. In a first approximation this interaction process can be grossly divided in two steps.

In the first stage, usually known as intranuclear cascade, the incoming nucleon makes a few, mainly incoherent scattering with nucleons of the target, depositing in this way some fraction of its energy. The incoming nucleon sees the substructure of the nucleus, i. e. a bundle of nucleons, due to the reduced wavelength. This fast stage of nucleon-nucleon scattering interaction leads to the ejection of some of the nucleons and to the excitation of the residual nucleus which will cool itself afterwards (in the second stage).

The de-excitation of the residual nucleus can proceed in two main ways: evaporation and fission. The evaporation is the dedicated de-excitation channel and the excited nucleus emits nucleons or light nuclei such as D, T, He, α, Li, Be. The second important de-excitation mode is fission. In the fission process the nucleus is ultimately "cut" into two fragments of different masses. Generally the fate of the nucleus is its fragmentation.

The nucleus emits particles until its excitation energy goes below the binding energy of the last nucleon. At this state about 8 MeV are remaining and will be emitted by γ radiation. The de-excitation process does not end with the ending of the γ emission. In fact the nucleus resulting after γ decay is often radioactive which will decay until the corresponding stable nucleus is reached. Gaining a better knowledge on the neutron economy may have important consequences on the design of a high-intensity neutron facility. Indeed, if we assume that the neutron economy remains rather stable over a broad range of incident energies, then for a given neutron production the beam intensity could be reduced if higher energies are employed. Let's now have a look to a general description of proton-induced spallation reactions [2–7]. If the average number of nucleon-nucleon collisions,$\langle n\rangle$, is denoted by T, i.e.,

$$T=\langle n\rangle\,, \tag{1}$$

let's consider an incident proton at impact parameter b(fm), a target nucleus and the z-axis as the beam direction. The average number of nucleon-nucleon collisions taking place between the incident proton and the nucleons of the target is a function of b and can be expressed through the following expression:

$$T(b)=\bar{\sigma}_{NN}\rho(b)=\bar{\sigma}_{NN}\int_{-\infty}^{+\infty}\rho(r)dz\,, \tag{2}$$

where $\rho(r)$ is the target nuclear matter density and $\bar{\sigma}_{NN}$ is the isospin averaged value of the free nucleon-nucleon cross section at the beam energy considered. The probability density of having exactly n nucleon-nucleon collisions can be described by a Poisson distribution around the average value $T=\langle n\rangle$:

$$P_n=\frac{T^n e^{-T}}{n!}\,. \tag{3}$$

The cross section σ_n for having n primary collisions at impact parameter b can be calculated as:

$$\sigma_n=2\pi\int_0^{\infty}P_n b db\,. \tag{4}$$

Adopting this simple model, the mass ejected from the target is proportional to the excitation energy and thus, to the incident proton energy:

$$\langle dm_l \rangle = C(E^*)dT\,, \tag{5}$$

where the slope C is a function of the excitation energy E^* and m_l is the mass lost from the target (A-A_F where A_F is the mass fragment).

The above equation takes into account promptly emitted nucleons (knock-out) since the number of such particles is expected to be proportional to the number of primary nucleon-nucleon collisions. The rather complex kinematics and geometrical situation which governs the emission or retention of struck nucleons in the target and, in addition, the sequential evaporation process which may involve the emission of both nucleons and complex particles, made that the actual mass emitted when an incident proton traverses a target may be subject to considerable fluctuation around the mean. Again is useful to assume a Poisson distribution to describe these fluctuations:

$$P_{m_l}(T) = \frac{(CT)^{m_l} e^{-CT}}{m_l!}\,. \tag{6}$$

As previously done, this procedure allow to easily write the expression for the cross section σ_{m_l}:

$$\sigma_{m_l} = \int_0^\infty 2\pi b db\,. \tag{7}$$

The analysis carried on until now represent a simple model for proton induced spallation reactions in which a great emphasis has been placed on the necessity of a rather accurate parameterization of nuclear density which permits the calculation of the number of primary nucleon-nucleon collisions. This parameter permits the calculation of the mass evacuated from the target, which follow the energy deposition of the incident proton in the target, and thus an expression for the spallation product cross section.

III. SIMULATION CODES

Two widely used transport codes used to simulate the spallation reaction are LCS (LAHET Code System) and FLUKA. The LCS [8] code, developed at Los Alamos National Laboratory is a Monte Carlo code for treating the transport and interactions of nucleons, pions, muons, light ions and antinucleons in complex geometry. LAHET includes both the Bertini and the ISABEL intranuclear cascade model as user options. An evaporation model for the break-up of light nuclei is also included. An optional multistage pre-equilibrium model has been implemented as an intermediate stage between the intranuclear cascade and the evaporation phase of a nuclear reaction. Alternative level density parameterizations are also included. The MCNPX [10] code is another option based on the fully integration of the LAHET code in the MCNP [11] code environment, it only needs of one input file for both codes, avoiding the transfer of large data files.

The FLUKA (FLUctuating KAscade simulation program) [9] code, developed at CERN, is a Monte Carlo code able to simulate transport and interaction of electromagnetic and hadronic particles in any target material over a wide range of energies. FLUKA use the PEANUT (Pre-Equilibrium Approach to Nuclear Thermalization) model to describe an elastic nuclear interaction. This model consists of intranuclear cascade (INC), pre-equilibrium, evaporation and de-excitation. The current version of the code can simulate neutron interaction and transport down to thermal energies (multigroup below 20 MeV) and hadron-hadron and hadron-nucleus interactions up to 100 TeV. The validity of the physical models implemented in FLUKA has been benchmarked against a variety of experimental data over a wide energy range, from accelerator data to cosmic rays data. The FLUKA code has been used for spallation reaction simulation in the Energy Amplifier (EA) project.

Recently a Brazilian research group (IFUSP and CBPF) developed the MCMC/MCEF (MultiCollisional Monte Carlo plus Monte Carlo for Evaporation-Fission calculation) model to study nuclear reaction such as spallation. The MCMC and the MCEF model utilize the Monte Carlo approach to describe the intranuclear cascade and the evaporation/fission processes respectively. Their coupling originates the CRISP (Colaboração RIo-São Paulo) package [12]. The code takes into account the possibility of neutron, proton and alpha particle evaporation and gives information about neutron and proton multiplicity, angular distribution and energy spectra. Some preliminary results where obtained calculating neutron multiplicities in ^{208}Pb for 200-1200 MeV protons. The CRISP results where compared with results obtained with the LAHET code using both the Bertini and the ISABEL model and with experimental data. A very good accordance with experimental data was registered. The qualification of the CRISP package for ADS calculation is being performed [13, 14].

IV. RESULTS

In an ADS, a high energy proton beam irradiates a heavy metal target to produce spallation neutrons that initiate transmutation of long lived transuranic (TRU) and fission products keeping the reactor sub-critical. Therefore the spallation target is one of the most important components of an ADS. Since a large amount of neutrons is produced by spallation reaction, the important conditions in selecting the target material are the neutron production rate, heat removal, radiation damage stability.

Lead-bismuth eutectic (LBE) is preferred as target material due to its high production rate of neutrons, effective heat removal and a very small amount of radiation damage properties. In this work two types of LBE spallation targets are considered: the window and the windowless target. The LAHET code system package is used to calculate the mean number of neutrons produced in each target and the total energy deposited by the incident beam.

In the window type target the key issue is the design of an

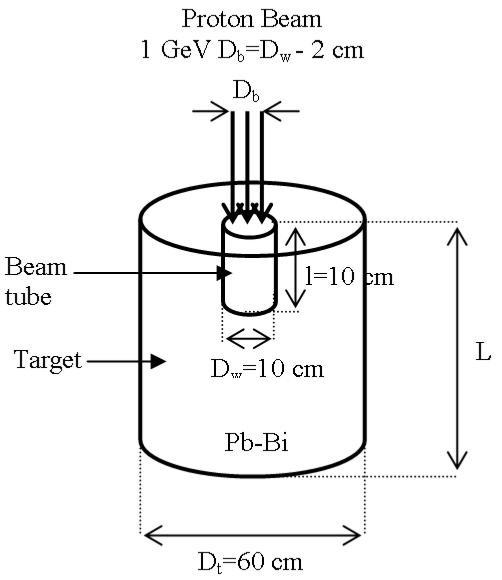

FIG. 1: The basic window target system.

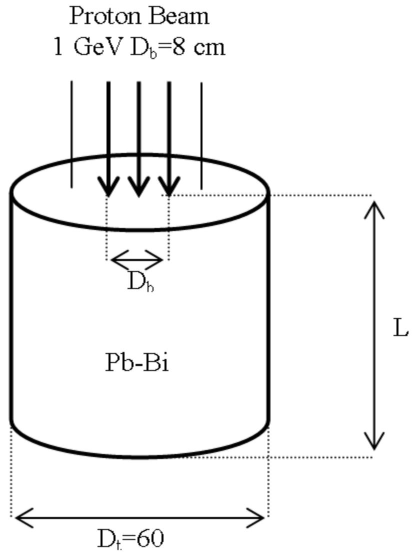

FIG. 2: The basic windowless target system.

appropriate beam window and LBE flow so that the system can sustain thermal and mechanical loads as well as radiation damage. In fact for an ADS of practical size (about 1000 MWth power) high power spallation targets are required (at least tenth of MW). A great part of the beam power is deposited as heat in the window and a small volume on the target system. In that case an optimum design of the beam window thickness, diameter and material has to be developed since the window itself has to face high thermal stresses. In Figure 1 is represented the basic window target system used in the LCS simulation. In this first approximated study energy deposition in the window is not considered. The total heat produced by each colliding proton, calculated with the LCS package is 632,73 MeV/p.

It is due to such difficulties of designing high power window target that targets designs without beam window are also considered. That is the case of the XADS (eXperimental ADS) developed in the frame of the fifth and sixth Framework Programme of EU and of the MYRRHA project [15, 16].

In the windowless configuration a tiny proton beam spot directly impinges on the target LBE free surface, Figure 2, avoiding the necessity of developing high proton and neutron flux resistant materials. As no mechanical component is directly exposed to the beam, widening the beam aperture for reducing power intensity is not required. Nevertheless, highly concentrated power beams may produce LBE evaporation. The total energy deposited by each colliding proton in the case of the windowless configuration is 621,32 MeV/p, as shown in Table 1.

TABLE I: Neutron Multiplicity (n/p) and Energy deposited in the target per incident proton calculated by LAHET for the windowless configuration.

L (cm)	*(n/p)*	*MeV/p*
10	9.08	232.518
20	16.087	399.341
30	20.859	501.573
40	23.480	557.927
50	24.954	591.848
60	25.769	615.576
70	26.028	617.512
80	26.238	619.738
90	26.322	620.455
100	26.417	621.317

V. CONCLUSIONS

The spallation target is the key component of any ADS concept since it constitutes the physical and functional interface between the accelerator and the sub-critical reactor. The development and design of the target implies a detailed assessment of different aspects mutually interacting, from the physics of spallation reaction including neutron generation and distribution, spallation product yields and damage rates to technological issues, such as choice of the most suitable material, power density distribution, heat removal, thermo-mechanics and fabricability.

In particular, accurate and rigorous assessment of nuclear parameters under different physical conditions is the prerequisite for an optimal design of the target and its interaction with the sub-critical core.

All these parameters, characterizing the spallation module, are extremely important since they will have several impacts on the design of the whole ADS. For example:

- The neutron angular and energetic distribution will determine the transmutation potential of the system,
- Target with high neutron source strength will drive an ADS with lower multiplication factor, thus improving safety conditions,

- Costs saving can be achieved by using a target with high proton to neutron conversion factor. In this way fewer particles current is required.

The spallation module design should then be based on a balanced optimization between neutronic efficiency, material properties and thermo-hydraulic performances

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