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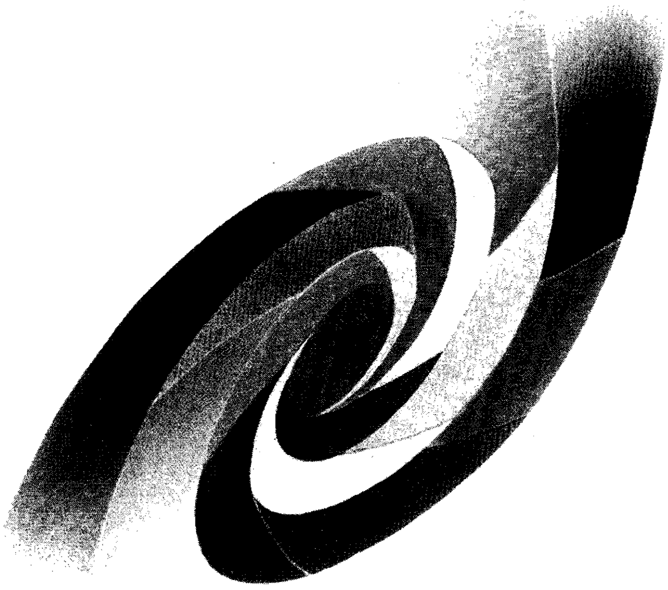

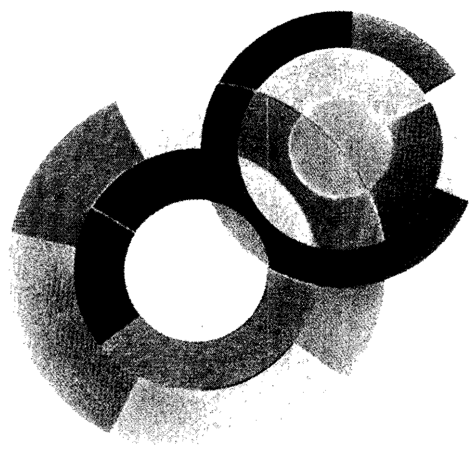

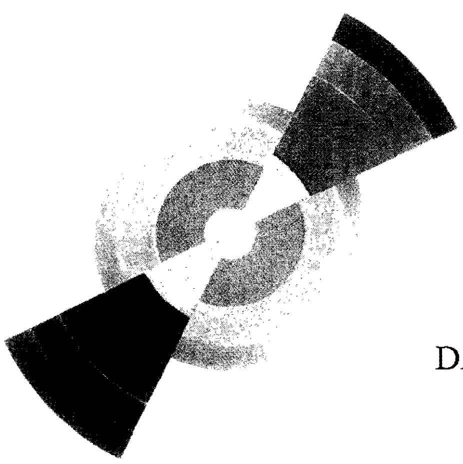

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Delayed Neutrons in Liquid Metal Spallation Targets

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Abstract. The next generation spallation neutron sources, neutrino factories or RIB production facilities currently being designed and constructed around the world will increase the average proton beam power on target by a few orders of magnitude. Increased proton beam power results in target thermal hydraulic issues leading to new target designs, very often based on liquid metal targets such as Hg, Pb, PbBi. Radioactive nuclides produced in liquid metal targets are transported into hot cells, into pumps or close to electronics with radiation sensitive components. Besides the considerable amount of photon activity in the irradiated liquid metal, a significant amount of the Delayed Neutron (DN) precursor activity can be accumulated in the target fluid. The transit time from the front of a liquid metal target into areas, where DNs may be important, can be as short as a few seconds, i.e. well within one half-life of many DN precursors. Therefore, it is necessary to evaluate the DN flux as a function of position and determine if DNs may contribute significantly to the activation and dose rate.

The multi-particle transport code MCNPX combined with the material evolution program CINDER'90 is used to predict the DN precursors and construct the DN tables. These DN tables are employed within the generalized geometrical model of the MegaPie spallation target at PSI (Switzerland). We show that the contribution of DNs and prompt spallation neutrons to the neutron flux is comparable at the very top of the liquid PbBi loop. We also demonstrate that these estimates of DNs within MCNPX are very much model-dependent. No experimental data are available for DN yields and time spectra from high energy fission-spallation reactions. An experiment to perform these measurements is proposed.

Introduction

Liquid PbBi metal loop in the case of the MegaPie spallation target, as in most of the high power spallation targets based on liquid metal technologies (e.g., [1]), extends much further compared to the primary proton – heavy metal interaction zone (~27 cm defined by the 575 MeV proton stopping range). As it is presented in Fig. 1 (on the right), the activated PbBi reaches as high as 400 cm arriving in the heat exchanger, from where it returns to the initial position. It takes ~20 s for the entire ~82 liters of PbBi make a "round trip" at a flow rate ~ 4 liters/s. It is clear that a big part of the DN precursors, created in the interaction region via high energy fission-spallation, will not have enough time to decay completely even at the very top location of the liquid metal. The main goal of this work is to provide quantitative estimates of the neutron fluxes due to DNs at the top position of the heat exchanger (see Fig. 1) and compare it with the prompt neutron flux at the same location.

Calculation procedure

Similarly as in [1] we employ the multi-particle transport code MCNPX [2] combined with the material evolution program CINDER'90 [3]. The DN data (emission probabilities and decay constants) were based on the ENDF/B-VI evaluations [4]. For the MegaPie project we used 575 MeV (1.75 mA; 1 MW) proton beam interacting with the liquid PbBi target. We modeled the 3-D geometry of the target in detail by taking into account all materials used in the design [5].

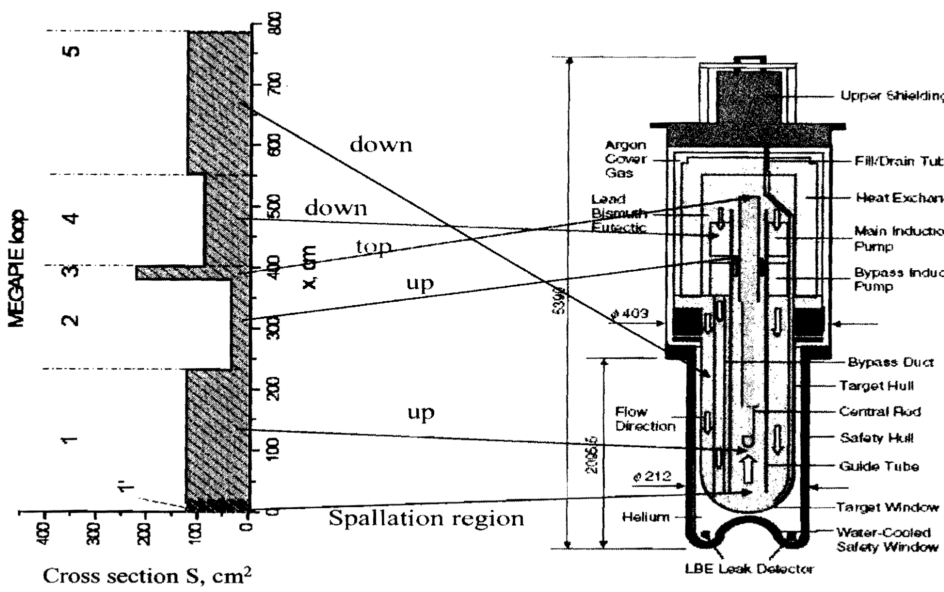

Figure 1. On the right: a schematic view of the MegaPie target with dimensions given in (mm). PbBi flow directions are indicated by arrows. On the left: cross section of the liquid PbBi loop as a function of the PbBi geometrical position – trajectory *x (cm)*.

The following procedure was applied to estimate the DN parameters for MegaPie:

1) calculation of independent fission fragment distributions with MCNPX;
2) calculation of cumulative fission fragment yields with CINDER'90;
3) identification of DN precursors and construction of the 6-group DN tables.

After having built the DN table we developed a generalized geometrical model to estimate the DN activity densities at any position x of the MegaPie target loop (see Fig 1.). Within this model the DN activity at position x can be expressed as

$$a(x)=\sum_{i=1}^{n}a_i(x)=\sum_{i=1}^{n}a_i^a\frac{1-\exp(-\lambda_i\tau_a)}{1-\exp(-\lambda_i T)}\exp(-\lambda_i\tau_d(x))$$

with τ_a *,s* - activation time (PbBi under irradiation); T*, s* - total circulation period of PbBi; τ_d*, s* - transit (decay) time to reach the point x; λ_i, s^{-1} - decay constant of the DN precursor *i*; a_i, *n/(s cm*^{3}*)* - density of DNs due to the precursor *i*.

Results

By the use of the above equation and Table 1 we found that at the very top position of the MegaPie PbBi loop (400 cm level above the target window) the DN activity is of the order of 2×10^5 n/(s cm^3) if the INCL4 model is used (see Fig 2 and Table 1). This intermediate result permitted us to estimate the neutron flux level in the MegaPie heat exchanger. For this purpose again using MCNPX we modeled in detail the heat exchanger geometry and recalculated neutron flux now inserting the volumetric DN source as a function of *x*. We found that the neutron flux at this position due to DN and prompt spallation neutrons is of the same order of magnitude, both equal to a few 10^6 n/(s cm^2). This preliminary result shows that activation and dose rates due to DN should not be neglected.

Model dependence of DN estimates

Unfortunately there is no experimental data available for DN yields from high energy fission-spallation reactions to test our predictions. In addition, the best available data for isotopic fission fragment distributions [6] contain only one delayed neutron precursor for each Z, being the last measured isotope on the neutron rich-side (e.g.

^{87}Br and ^{92}Rb in Fig. 3). Furthermore, in the case of a thick spallation target one would need data for all energies to take into account the proton transport phenomena. Therefore, a number of different intra-nuclear cascade models within MCNPX [2] were tried in order to evaluate possible uncertainties in our results.

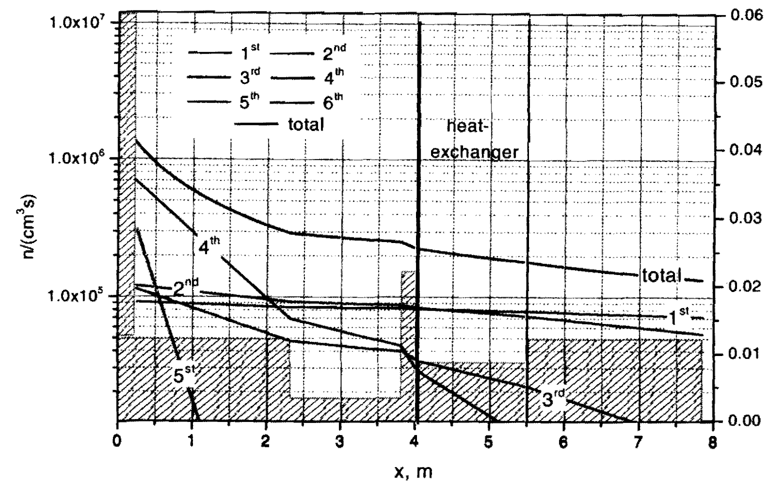

Figure 2. DN activity as a function of the PbBi geometrical position *x* (see Fig. 1). Contributions due to the individual DN groups (from 1 to 6) are also presented.

Table 1. DN parameters (6-group representation) in the case of the MegaPie target. Note that DN yields are normalized for 10^6 incident protons.

	INCL4 model		**CEM2k model**	
Group	$T_{1/2}$, s	a_i, n/p times 10^6	$T_{1/2}$, s	a_i, n/p times 10^6
1	55.489	0.87	55.600	6.78
2	16.290	0.89	16.346	15.25
3	4.985	0.44	4.658	23.58
4	1.900	1.19	1.629	174.24
5	0.519	0.21	0.451	129.95
6	0.197	0.00	0.108	233.52
Total (averaged)	**(18.703)**	**3.59**	**(1.903)**	**583.35**

Fig. 3 presents fission fragment distributions for the p(1 GeV) + Pb reaction in the case of Br and Rb isotopes: both theoretical and experimental values [6] are presented. After examination of these and other isotopic distributions with the precursors of DNs we choose only two physics models to construct the delayed neutron tables, namely INCL4 and CEM2k. The INCL4 predictions are the closest to the experimental data, while CEM2k results in systematic overestimation of neutron rich nuclei. In other words, the DN estimates based on these two models would give limiting values of possible DN fluxes within MCNPX.

In Table 1 we provide the 6-group DN parameters based on different physics models, namely INCL4 and CEM2k as discussed above. In brief, both the yields and time spectra of DNs are model-dependent nearly by two orders of magnitude. This analysis shows that DN yields and time spectra from high energy fission-spallation reactions should be measured since no data of this type are available. This data would certainly constrain the physics models within the MCNPX code, and the fission fragment distributions on the neutron rich-side in particular.

In this context we propose to perform DN measurements using 1 GeV protons interacting with massive Pb target at PNPI Gatchina, St Petersburg, Russia. DNs will be detected with optimized He-3 counters following specific irradiation intervals, namely with long (~300 s), short (~10 s) and very short (~50 ms) irradiation periods in order to enhance the contribution of different periods of DN precursors. With available proton beam intensity of ~10-100 nA we expect to produce up to ~10^5-10^6 n/s of DNs over 4π. Estimated counting rate with a single He-3 detector is of the order of ~50 n/s at t = 0. Not only the total yield of the DNs but also their decay curves will be measured in order to extract the corresponding decay constants and single group weighting factors within the 6-group DN model.

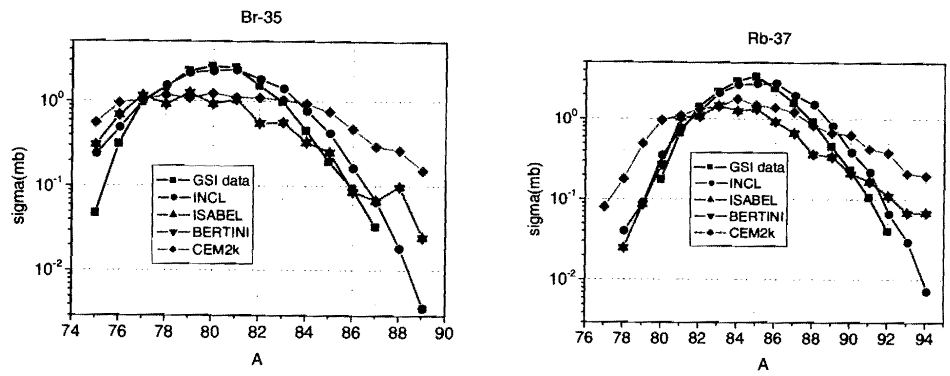

Figure 3. Fission fragment distributions form the p(1 GeV) + Pb reaction for Br and Rb isotopes. Both theoretical model calculations and experimental data [6] are presented.

Summary

The DN flux and corresponding time spectra were estimated in the case of the MegaPie spallation target at PSI (Switzerland). For this purpose a generalized geometrical model was built, and could be used for other liquid metal targets. The DN tables within 6-group model were constructed for the first time for high energy fission-spallation reactions.

We showed that the neutron fluxes at the very top position of the MegaPie due to DNs and due to prompt spallation neutrons were of the same order of magnitude, i.e. both equal to a few 10^6 n/(s cm^2). This result warns that DNs can result in operational issues, which must be taken into account in detailed design studies of high power spallation targets based on liquid metal technologies.

We also demonstrated that the final estimates of DNs were very much model-dependent within the MCNPX code. No experimental data are available for DN yields from high energy fission-spallation reactions. The experiment to perform these measurements is proposed and will be carried out in 2005.

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