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Measurement of fast and thermal neutron flux from the d + D reaction using the activation method

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Abstract

The neutron flux originating from the d + D reaction has been measured at the GENEPI 2 neutron source at LPSC Grenoble. The activation method has been used. The foils activated by neutrons were located at angles ranging from 0^o to 90^o with respect to the deuteron beam direction, allowing to obtain fast and thermal neutron yields within those angles.

0.1 Introduction

Fast, about 2.5 MeV, and thermal neutron yields from d + D reaction have been measured at the GENEPI 2 neutron source [1] at LPSC Grenoble. The experiment originated from an idea to measure yields of fission products by detection of $\gamma - \gamma$ coincidences at GENEPI. The proof of feasibility was first demonstrated by test at LPSC using spontaneous fission of ^{252}Cf, after which an experiment has been performed at Jyväskylä with a continuous neutron spectrum produced by 40 MeV d on carbon. Ultimately, at GENEPI the yields should be studied with 14 MeV neutrons from the d + T reaction. Before performing such measurement one needs to be sure that Ge-detectors do not receive a lethal doses (about 10^9 per cm^2) during the experiment. With tritium the neutron yield shall be two orders of magnitude higher than we have measured now. A decrease of flux according to distance law means that the reduction from the target to the detectors will be of about $10^{\,3}$. A shielding wall against fast and thermal neutrons has presumably to be built and tested before the γ-γ coincidences run can proceed.

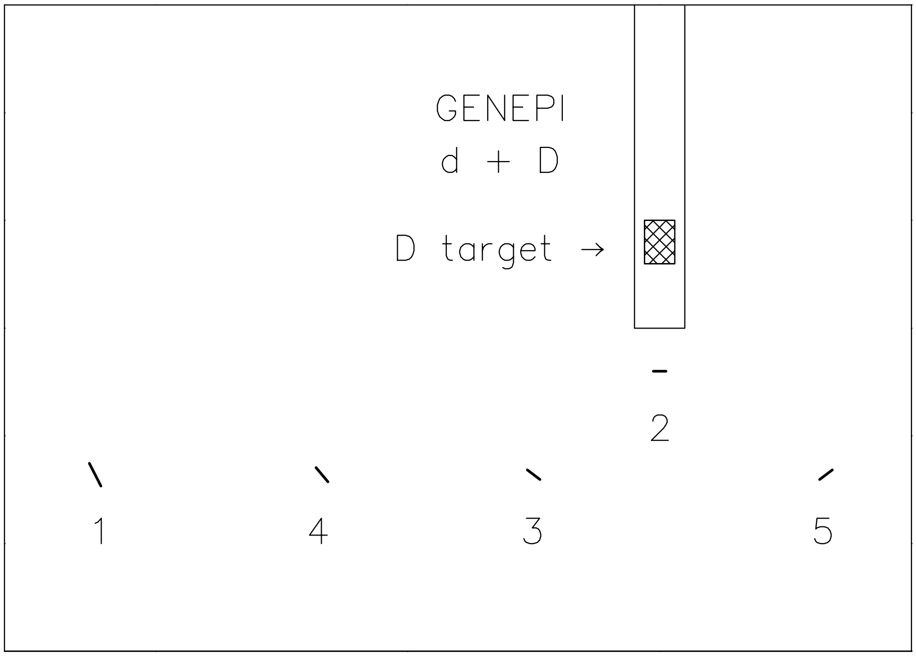

Figure 1: Positions of activation foils with respect to the GENEPI beam line. There is no nickel foil at position 5. Foil 1 is at 112 cm from the beam axis.

0.2 Experimental apparatus

Activation foils, i.e. 5 indium foils (0.5 mm thick) and 4 Ni foils (1 mm thick), all as squares of 2.5 by 2.5 cm, were placed as shown in Fig. 1 and reported in Table 1. A foil was placed 42.5 mm from the deuterium target, at zero degree to the deuteron beam axis to assess the flux on the uranium target in the actual experiment. Other foils were placed to monitor the neutron flux at the positions planned for transport tape system and Ge-detectors. The angular energy dependence of neutrons generated at the GENEPI neutron source can be found in [2]. Thermal neutrons originate from the multiple collisions fast neutrons undergo in material present in the GANEPI cave, e.g. concrete.

0.3 Measurement

During the first run on 5.05.2010, the GENEPI beam was on during 6.75 hours with an average current of 25 μA (220 keV d^+ beam, peak current of 40 mA and 1 kHz repetition rate). After that, the neutron-irradiated foils were taken to the LPSC student's lab where they have been counted during the following evening for indium short-lived activities and later for cobalt

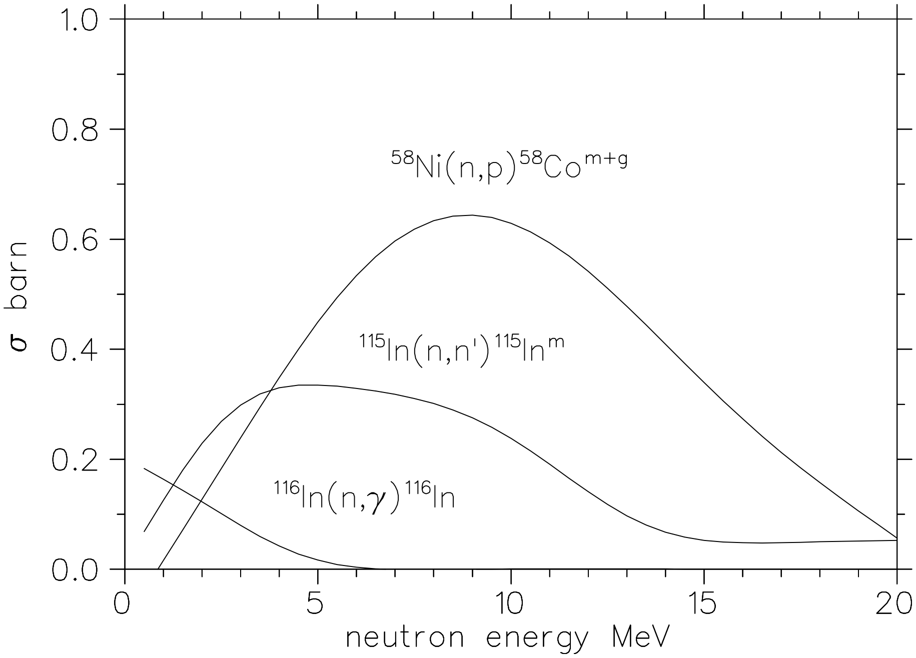

Figure 2: Activation cross sections usable for deuterons on D and T targets at GENEPI, taken from EXFOR on NNDC. The production of ^{116}In is dominated by the thermal neutron flux. For a deuteron beam of 220 keV the neutron energy decreases from 3.08 MeV at 0^o to 2.50 MeV at 90^o, which causes a small change in σ.

activities. The half-lives are 4.49 h for ^{115}In(n,n')^{115}In that counts neutrons above 400 keV and 54.3 m for ^{115}I(n,γ)^{116}In that counts thermal neutrons if one neglects a low tail extending to few MeV, since σ_{th}= $\simeq$ 200 b. Cross sections are shown in Figure 2. The nickel foil has to be counted longer because of the ^{58}Co half-life of 70.9 days. Moreover, it has an 9.15 hour isomer that has first to decay before one can start counting. After a few days the cross section to be used is the sum of those for ground state and isomer. These are available separately in the EXFOR data base at NNDC. Unfortunately, the neutron flux calculated from ^{115}In and ^{58}Co activities are presently in slight disagreement. The fact that ^{58}Co results deviate from ^{115}In is due to the limited duration of the run. It was too short to approach saturation of the 9.15 h isomer (this is the condition to be fulfilled for applying the sum g+m instead of decomposition of the activity curve).

Table 1: Results on neutron flux ($/\mathrm{cm}^2/\mathrm{s}$) with 90 μA of 220 keV deuterons on deuterium target. Errors are estimated to 5% to which statistical errors must be added. The latter can be neglected for the foil at d=0, but can reach 30% for the weak 1097 and 1294 keV peaks in the last counting series. Indicated are the distances from axis, angle to axis, fast-neutron energies and series numbers of separated countings.

foil	from axis cm	θ deg.	E_{fast} MeV	series	^{115}In fast	^{116}In thermal	
					γ 336.2	γ 1097.3	γ 1293.6
2	0	0	3.09	1	$2.68\,10^5$	121	138
				2	$2.68\,10^5$	139	130
				3	$2.65\,10^5$	106	107
				4	$2.72\,10^5$		
5	-33	68	2.66	1	$1.37\,10^3$	23	25
				2	$9.17\,10^2$	26	23
3	25	73	2.71	1	$2.98\,10^3$	22	13
4	67	81	2.59	1		20	17
				2		17	16
1	112	85	2.55	1		22	18
				2		17	21

0.4 Results and conclusions

Table 1 presents the results. The method to obtain the neutron flux using the activation method is discussed in the appendix. One sees the good consistencies of series of countings, together with the rather expected fact that the fast-neutron flux decreases roughly as $1/\mathrm{d}^2$. In contrast, thermal neutrons are present everywhere with a quite constant flux. These data are now being compared with the number of neutrons calculated using the protons counted in the silicium detector.

0.5 Appendix

The method to obtain the neutron fluxes is as follows. The number of counts in a peak in a certain spectrum N is the product of reaction rate R, a time factor T_f and a spectroscopy factor S_f.

$$N_\gamma = R(n, \sigma, \phi)\, T_f(\lambda, t_i, t_w, t_c)\, S_f(\gamma)$$

The time factor T_f is essentially free of errors. If the GENEPI beam is constant, it is just made of the irradiation time t_i, the waiting time after end of irradiation t_w, the counting time t_c and the radioactive decay constant of the nucleus λ.

$$T_f = (1 - e^{-\lambda\, t_i})\, e^{-\lambda\, t_w}\, \frac{1 - e^{-\lambda\, t_c}}{\lambda} \frac{t_{active}}{t_c}$$

The spectroscopy factor is the product of detector efficiency and decay branchings, depending on the γ-ray but constant in all countings of the same activity.

$$S_f = \varepsilon(E_\gamma)\, b(E_\gamma)$$

While the branching is given e.g. in NNDC and is well known, the efficiency we used is a bit approximative. For simplicity, we started with an efficiency curve supplied by B. Clement recorded with ^{152}Eu at large distance to obtain the energy dependence. The curve was then rescaled at the measurement distance using the dependence on distance that we have measured with a ^{137}Cs source. The small change of energy dependence due to the fact that the γ beam is less parallel when the source is closer to the detector is neglected. We counted the indium and nickel foils seprately. No correction for the foil thickness, changing the average distance, nor for self-absorption has been done yet. It remains small anyway as shown below. The derivative of efficiency with distance is 2.6% per mm for detector 1 at the measurement distance. The average plane of the indium foil is at 0.25 mm from the bottom, which consequently causes a 0.8% decrease of efficiency.
Considering the foils are activated uniformly over their volume, the attenuation due to self-absorption is easy to calculate if the Ge-detector is far enough to consider the γ beam to be parallel. The transmitted fraction of produced activity is

$$T = \frac{1 - e^{-\mu\, x}}{\mu\, x}.$$

We observe 97% of the 336 keV γ-rays produced in the 0.5 mm indium foil. We should consequently increase the calculated flux for the 336 keV γ-ray by 3-4 % to be more accurate. Corrections for other foils and reactions are even smaller since γ energies are higher and Z of the foil is lower. The reported values are without this correction.

The standard reaction rate is the product of number of target nuclei per cm^2, cross section σ and neutron flux per second ϕ on the target. The target is assumed to be thin. This condition applies here because projectiles are neutrons. Moving the foil area term, the formula can be read as the product of number of nuclei in the foil, σ and flux per cm^2.

$$R = n\,\sigma\,\phi$$

The expression for n is then

$$n = \frac{a\,\rho\,V\,N_A}{A}$$

a is the abundance of the isotope of interest in the foil (e.g. 0.957 for ^{115}In). The product ρV, with V the volume can be calculated (e.g. ρ(In)= 7.31 g/cm^3) or obtained by weighting the foil. N_A is the Avogadro number $6.022\,10^{23}$ and A is the atomic weight of the foil element (e.g. 114.82 for indium).

The value of σ depends on the energy of the neutron, see Fig. 2, which in turn depends on the angle with respect to the beam. The later is taken from Atomic Data and Nuclear Data Tables (Vol.11, No.7, (1973), p. 569-619). For thermal neutrons the value σ= 200 b of ^{115}In(n,γ)^{116}In is used (EXFOR). The small contribution from faster neutrons is neglected.

Then the last variable ϕ is the searched neutron flux per cm^2 and seconds.

0.6 Reference

[1] G. Kessedjian et al., ^{7}Li elastic scattering cross section measurement using slowing-down spectrometer, Proceeding of Measurements and Models of Nuclear Reactions (EFNUDAT), Paris, France (2010).
[2] N. Thiolliére, Neutron elastic scattering cross-section measurement on carbon and fluorine in epithermal energy range using PEREN platform, PhD thesis, Universit Joseph Fourier, Grenoble, France, 2005, in French. The angular energy dependence of neutrons generated at the GENEPI is shown in Fig. 3.7.