LA-UR- 00-4591

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Submitted to: Proceedings of the 16th International Conference on Applications of Accelerators in Research and Industry

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Study of reactions of fast neutrons with nuclei with FIGARO at LANSCE

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Abstract. We discuss the new FIGARO experiment under construction at the Weapons Neutrons Research (WNR) facility at LANSCE, for the measurement of γ rays and neutrons from interactions of fast neutrons with nuclei. A first measurement was performed in 1999 with ^{59}Co, using a single germanium detector. Prompt γ rays from reactions with neutrons in the energy range from 2 to 200 MeV have been measured. Excitation functions have been obtained for transitions from (n,n'), $(n,2n)$, $(n,3n)$, (n,p), (n,np), $(n,2np)$ and (n,α) reactions. The results have been compared with existing data, and with calculations using the code GNASH. They indicate that with FIGARO high quality data can be obtained in the considered energy range.

INTRODUCTION

From the study of reactions of fast neutrons with nuclei in which γ rays are produced, it is possible to obtain information on the nuclear level densities (1). In the neutron energy range available at the WNR facility at LANSCE (1 to several hundreds MeV), neutrons produce reactions with nuclei, leaving the residual nucleus in an excited state, which may decay by γ emission. The energies of the emitted γ's are a signature of the residual nucleus, and therefore of the type of the reaction taking place. Information on the level density at high excitation energy can be obtained from the population of low-lying excited states. Further information can be obtained if one or more of the emitted neutrons are detected, since in this case an $n - \gamma$ coincidence measurement allows not only to identify the type of reaction but also to determine the excitation energy of the residual nucleus. Particularly interesting would be to investigate the level densities near the neutron separation energy. This kind of measurement would provide information on the angular momentum distribution of the level density.

In 1999 we have begun setting up the FIGARO (Fast neutron-Induced GAmma Ray Observer) experiment at the Weapons Neutrons Research facility at LANSCE, intended to study this type of reactions. Besides measurements of nuclear level densities for a broad range of excitation energies, FIGARO can be used for other types of applications, for instance, studies of transitions where the internal conversion coefficient is high, in order to extract
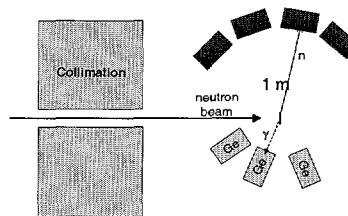
FIGURE 1. Schematic view of the FIGARO experimental setup.

information on nuclear structure by means of detection of conversion electrons, or measurements of interest for Waste Transmutation.

In its final configuration, the basic components of FIGARO will be (Fig. 1): *i*) an array of three-four high purity germanium detectors, for the detection of γ rays; *ii*) a similar number of neutron detectors, which will be NE213 liquid scintillators because of their capability to perform pulse shape discrimination and separate the γ-ray background; they will operate in coincidence with the germanium detector, in order to determine, by measuring the energy of the emitted neutron, the excitation energy of the nucleus; *iii*) according to the needs of a particular
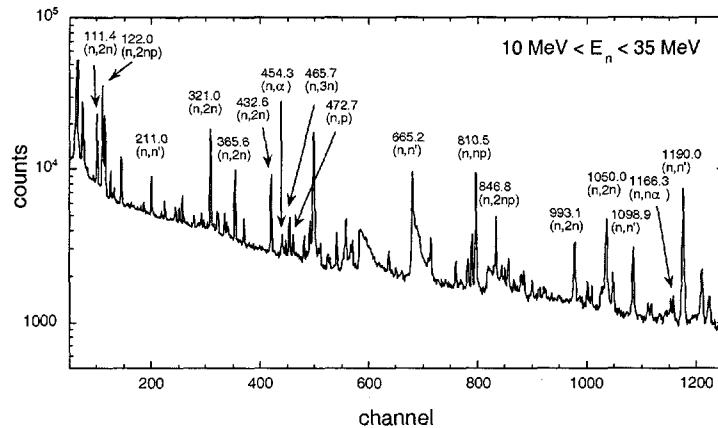
FIGURE 2. Spectrum of γ rays from interactions of neutrons in the energy range 10-35 MeV with ^{59}Co. Gamma-ray energies for different reactions are indicated in keV.

experiment, different types of detectors will be installed. An example of an alternative detector is constituted by the ICEBALL II array (2), from the University of Pittsburgh, for the measurement of conversion electrons (3).

MEASUREMENT WITH COBALT

Experimental Setup

We began to build the facility in 1999. The first goal was to evaluate the possibilities for this kind of measurement at the experimental station chosen for FIGARO. The experiment was prepared on the flight path at 30 degrees with respect to the incoming proton beam at a distance of about 22 meters from the neutron source.

Collimation of the neutron beam is very important for this type of experiment. High energy neutrons, above a few MeV, have great penetrating power and they induce reactions that make lower energy neutrons and γ rays. Present-day germanium detectors with large volumes are very sensitive to these background radiations. Because these detectors have no directional sensitivity (until tracking detectors are available), background radiations incident from all directions are indistinguishable from γ rays from neutron interactions in the sample under study. For these reasons, we concentrate on the design of beam collimators and of shielding to reduce radiations from the collimators from reaching the detectors.

The beam line consists of an adjustable shutter, pre-collimators at 9 and 15 meters from the source, a defining collimator at 19 meters followed by clean-up collimators. Shielding of iron or copper surrounds each of these collimators. Lead is used as the last of the clean-up collimators. The defining collimator for the experiments reported here had a diameter of 2.2 cm. Inserts are now available to reduce the beam diameter further. Care was taken to further shield the γ-ray detector from backgrounds produced at neighboring flight paths.

For this measurement we used one germanium detector, of about 25 % efficiency. The detector was placed at about 15 cm from the sample, at an angle of 130 degrees with respect to the beam line. A fission chamber (4) was placed in the beam at a farther distance, of about 26 m from the neutron source, for the measurement of the neutron flux.

Measurements were performed with ^{59}Co. This sample was chosen to support previous studies of $(n,x\alpha)$ reactions performed at WNR (5); moreover, we could compare with previous data from a similar measurement performed in Oak Ridge (6).

The sample consisted of monoisotopic ^{59}Co, cut in ten approximately square tiles of dimension 7.3 cm^2 each, 0.05 cm thickness and mass 3.2 g. They were arranged forming samples with one, two or five layers: by measuring with samples of different ticknesses we could evaluate the multiple scattering inside the sample (1), which can be important at high incident neutron energies.
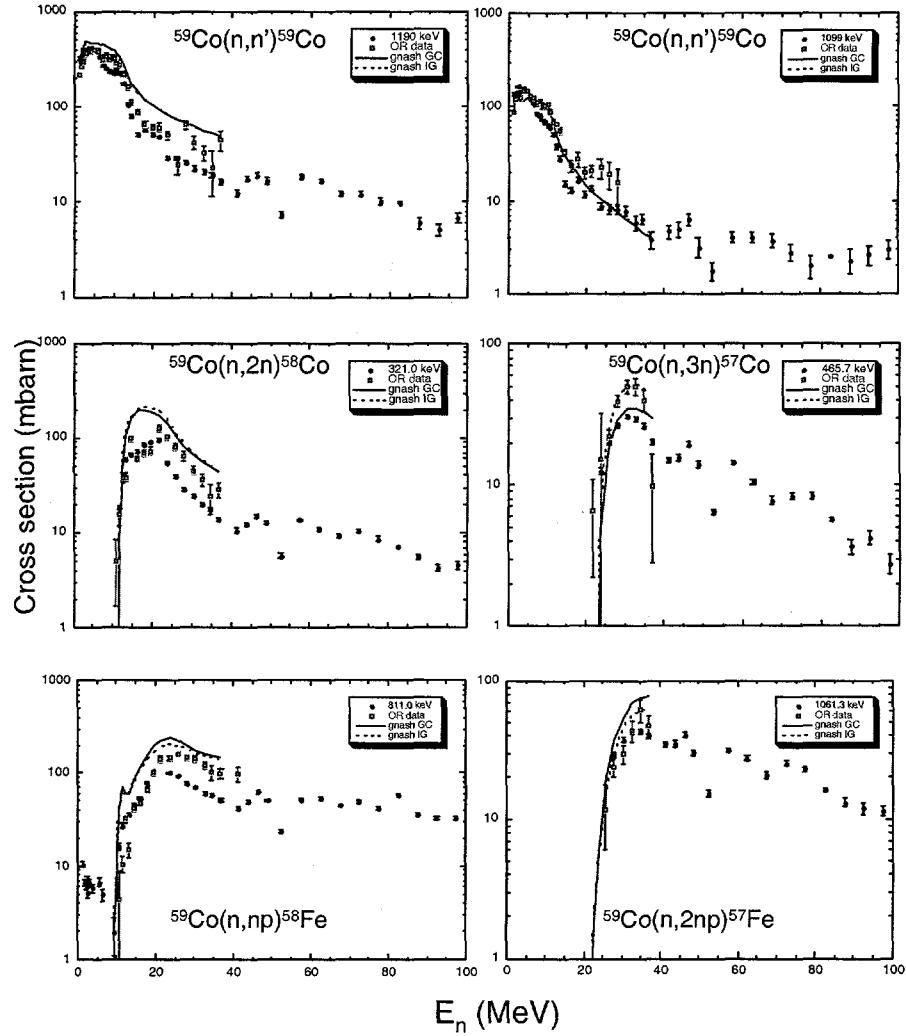
FIGURE 3. Excitation functions for γ rays of indicated energies, corresponding to different reactions ^{59}Co(n,xn γ), for incoming neutron energies from 1 to 100 MeV. Data from the present measurement are indicated with full dots; they are normalised to the data from Ref. (6), indicated with open squares. Statistical uncertainties only are drawn. Results from GNASH calculations are represented with full and dashed lines, using the Gilbert-Cameron and Ignatyuk level density models, respectively.

The accelerator was running at 120 Hz repetition frequency, with an average current of 6 μA. The proton beam had a time structure of macropulses, about 625 μs long, composed by micropulses spaced of 1.8 μs, each micropulse being about 1 ns long. In this configura-

tion, at the FIGARO flight station neutron energies above 1.5 MeV could be measured.

Data were taken with the cobalt samples in the different configurations. The data shown in this paper refer to a 24 hours measurement only. Measurements were also

taken with the sample out to measure the background. The electronics setup consisted of standard NIM and CAMAC modules. Data were collected using the VMS based data acquisition system XSYS (7). The standard fast/slow coincidence logic was applied to measure the time and amplitude of the signals from the germanium detector, as well as the fission chamber signals.

Data Analysis and Results

In Fig. 2 a γ-ray spectrum measured by the germanium detector, for neutron energies in the range from 10 to 35 MeV, is shown. Several lines corresponding to different reactions are observed; the stronger ones are indicated in the figure.

The data were sorted out in selected neutron energy bins from the two-dimensional spectra representing the pulse height spectrum versus the neutron time-of-flight. The widths of the neutron energy bins were different, increasing with the neutron energy, from 1.5 MeV to 200 MeV. The neutron energy was determined by time-of-flight, having as a starting time reference the time T_0 determined by the γ flash emitted in the spallation process inside the neutron source. A correction for the dependence of the T_0 on the TOF, which was due to a walk effect, was applied.

The obtained spectra were analyzed with the fitting program XGAM (8), which allowed to fit simultaneously the entire γ spectrum from 0.1 to 3 MeV.

The cross section for a specific γ for the incident neutron energy E_n was obtained from the formula

$$\sigma(E_n, E_\gamma) = \frac{\text{counts}_{\gamma, \Delta E_n}}{\varepsilon_{\text{det}} \times (\text{N. neutrons}_{\Delta E_n}) \times \left(\frac{\text{N. atoms}}{\text{cm}^2}\right)_{\text{sample}}}.$$
(1)

where ε_{det} is the detector full-peak efficiency. The number of neutrons in the energy range ΔE_n within the solid angle $\Delta\Omega$ is determined by the neutron flux, measured by the fission chamber. A correction for the dead time was also applied.

Given the uncertainty in the knowledge of the exact amount of ^{235}U deposit in the fission chamber at our disposal, and on the uniformity of its distribution, we normalized our cross section to the Oak Ridge data. For future measurements, absolute cross sections will be determined by using a well characterized flux monitor, and by comparing with standard cross sections.

We obtained the excitation functions for several γ rays. In Fig. 3 six excitation functions for different reactions are shown. Data from Ref. (6) are also shown. As can be seen, the statistical uncertainties for the present measurement are lower. The main contribution to the

systematic uncertainties comes from the uncertainty on the amount of ^{235}U in the fission chamber. At neutron energies above 30 MeV, the uncertainty in the ^{235}U fission cross section becomes significant.

We performed calculations of excitation functions using the reaction code GNASH (9). For the γ decay part, the $E1$ γ-ray strength function model of Kopecky-Uhl (10) was used. Lorentzian models for the $M1$ and $E2$ strength functions were also used. Two models of level densities were tested: the Gilbert-Cameron (11) and the model by Ignatyuk (12). The results of the calculations for the two level density models are shown in Fig. 3 for six transitions. There is a overall good agreement with the data, with perhaps some exceptions, like for the $(n, 2n)$ reaction. Since the calculated total $(n, 2n)$ cross section reproduces well the experimental value (13), the observed discrepancies may be due mainly to the incomplete knowledge of the level scheme. Below 50 MeV both models give satisfactory results.

The preliminary results presented in this paper clearly indicate that, thanks to the high neutron flux available in the neutron energy range of interest, measurements of γ-ray excitation functions with low statistical uncertainties, for the study of nuclear level densities, can be performed at WNR.

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