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Neutron Emission Spectra from Inelastic Scattering on $^{58,60}\text{Ni}$ with a White Neutron Source at FIGARO

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Abstract. Neutron emission spectra from inelastic neutron scattering on natural nickel at the FIGARO facility have been measured by a double time-of-flight technique. The incident neutrons are produced from the spallation source of the Weapons Neutron Research facility, and their energies are determined by time of flight. The emitted neutrons and gamma rays are detected by 16 liquid scintillators and one high-resolution germanium or one barium-fluoride detector, respectively. The results for incident neutron energies from 2 to 10 MeV are compared with predictions of nuclear model calculations performed with the code EMPIRE-II. Finally, the level density parameters “a” and “ ΔE ” are extracted.

INTRODUCTION

Neutron inelastic scattering, which contributes substantially to radiation damage and neutron energy conversion, is of great importance for applications. It can also be used in studies of nuclear structure and reaction mechanisms. Because nickel is a component of many structural materials, an adequate knowledge of the neutron inelastic scattering reactions is required on this element, and, for most applications these data are needed over a large range of incident neutron energies. Experimental data on these reactions can also be used as a test of parameters for nuclear models. In this goal, the FIGARO (Fast Neutron-Induced Gamma-Ray Observer) facility [1] with the white neutron source of the Weapons Neutron Research facility is used. This paper describes the measurements of $^{58}\text{Ni}(n,n')^{58}\text{Ni}$ and $^{60}\text{Ni}(n,n')^{60}\text{Ni}$, presents the results, and compares them with calculations performed with the nuclear reaction-model code

EMPIRE-II [2]. The extraction of the level density parameters for ^{58}Ni and ^{60}Ni , a subject of continuing interest, *e.g.* Ref. [3], is then described.

DESCRIPTION OF THE EXPERIMENT

At the FIGARO facility, a well-collimated pulsed neutron beam is available from the Target-4 spallation neutron source by the interaction of a pulsed beam of 800-MeV protons from the Los Alamos Neutron Science Center (LANSCE) accelerator with a tungsten target [4]. The neutron production is monitored by a ^{235}U and ^{238}U fission chamber placed at 16 meters from the neutron production target [5]. The proton beam current is usually around 5 μA . The resulting neutron spectrum ranges in energy from a few keV to approximately the proton beam energy of 800-MeV, with most of the flux concentrated between 1 and 300

MeV. The energies of the incident neutrons are determined by a time-of-flight (TOF) method.

Fig. 1 shows the layout of the experiment. To determine the incident neutron energy, the start of the TOF is given by the proton beam on the Target-4 and the TOF stop is obtained by the detection of a gamma-ray from the neutron reaction on the target. The collimated-neutron beam hits the Ni sample (cylinder 3 cm long and 1.2 cm in diameter) at 21 m from the neutron source. The excited nuclei decay by the emission of gamma-rays and neutrons, which are then detected.

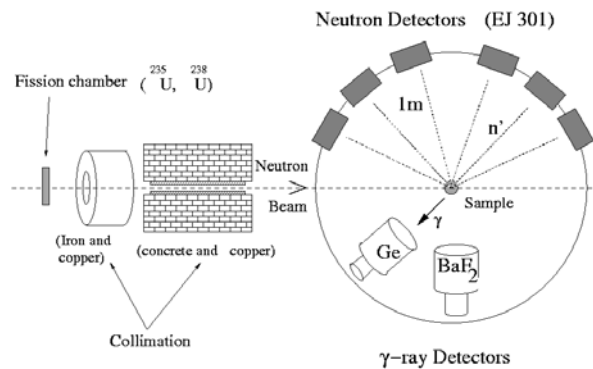


FIGURE 1. Experimental setup for neutron-induced scattering, with typical locations for 6 of the 16 neutron detectors are shown

Outgoing neutrons are measured with 16 liquid scintillators EJ301 (5 cm thick, and 12.5 cm in diameter of active scintillator) [6]. These scintillators exhibit excellent pulse-shape discrimination properties, particularly for fast neutron counting and spectrometry in the presence of gamma radiation. The liquid scintillators are positioned about 1 m from the sample so that a second TOF can be used to determine the energy of the outgoing neutrons. By using a pulse-shape discrimination technique with two integrated gates (long and short) on the pulses from the liquid scintillator signals, it is possible to separate the gamma-ray pulses from the neutron pulses.

Gamma rays, emitted from the decay of the nucleus are detected by one high-resolution germanium or one barium-fluoride detector. The germanium detector provides a energy resolution but a poor timing and efficiency, whereas the barium-fluoride detector has a high gamma-ray efficiency and present a low neutron-capture cross-section, but has a low energy resolution. An energy window can be applied on the gamma-ray energy in order to select the transition between two levels in the residual nucleus.

MEASUREMENT PROCEDURE

For inelastic reactions, the residual nucleus is in a highly excited state, which subsequently decays via a gamma-ray cascade to the ground state. Because there is sufficient angular momentum in the system to populate a rather wide range of residual states, few of these states decay directly to the ground state and, in an even Z and even N residual nucleus, nearly all decay through the first excited state. In ^{58}Ni , a coincidence measurement between the gamma decay from the first excited state (at 1.45 MeV) and the outgoing neutron emission provides information on the excited levels of ^{58}Ni . The same situation applies for the even-even ^{60}Ni nucleus, with a first excited state at 1.33 MeV. As the first excited levels for ^{58}Ni and ^{60}Ni are close (1.45 MeV and 1.33 MeV, respectively), it is not possible to disentangle the two gamma lines with the barium-fluoride detector. As more than 98 % of the detected gamma rays are from the barium-fluoride detector, the separation between the two Ni isotopes was not possible in the present experiment. The measurements are then realized for both ^{58}Ni and ^{60}Ni at the same time.

Neutron Detector Efficiency

The neutron-detector efficiency was measured with two methods. The first one, mainly for low neutron energies, used the fission neutrons from a spontaneous fission source of ^{252}Cf . The measured fission spectrum was then compared to the ^{252}Cf neutron emission spectrum reference from the Nuclear Energy Agency (NEA) [7] and the efficiency ($^{252}\text{Cf}_{\text{measured}}/^{252}\text{Cf}_{\text{NEA}}$) is calculated. The second method, providing larger statistics for higher neutron energies, was based on MCNPX simulations [8]. A brick of pure lead was placed in the neutron beam to reduce beam intensity and the transmitted neutrons were then detected by a liquid scintillator in the beam at the sample position. For the MCNPX simulations, the transmitted flux after the lead brick, at the sample position was calculated with, as the neutron source, the neutron flux extracted from the uranium fission chamber. The measured neutron flux was compared to the neutron flux calculated with MCNPX and the efficiency was extracted. By combining these two efficiencies at low and high neutron energies, the measured neutron spectra from the Ni sample were corrected for the neutron detector efficiency.

Data Reduction

In order to sum the data from all neutron detectors, we present the data as a plot of the excitation energy E_x of the residual nucleus as a function of the incident neutron energy E_n . E_x is evaluated by subtracting the ground-state mass from the invariant mass of the residual nucleus of the $\text{Ni}(n,n')\text{Ni}$ reaction. The background, measured with beam and without sample is subtracted to the sample measurements. By subtracting the ground-state energy from the total energy, the excitation energy E_x as a function of E_n is available, see Fig. 2.

In order to extract data proportional to cross-section from the E_x - E_n matrix, one-dimensional energy spectra were generated by summing TOF bins corresponding to a “slice” in incident neutron energy, and projecting onto the excitation energy axis. Then, the excitation energy distribution for a given incident neutron energy was compared with the EMPIRE-II calculations

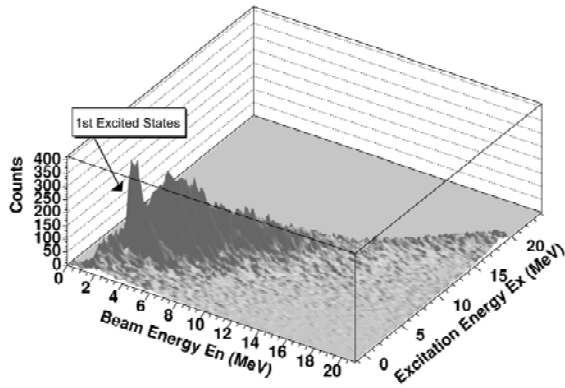


FIGURE 2. Excitation energy of the residual nuclei $^{58,60}\text{Ni}$ as a function of the incident neutron energy.

RESULTS AND COMPARISONS WITH EMPIRE-II

The neutron inelastic scattering on natural Ni from 2 to 10 MeV is presented. In natural Ni, the two main isotopes, ^{58}Ni and ^{60}Ni , have abundances of 68 % and 26 %, respectively. As explained earlier, it is not possible experimentally to separate these two isotopes. The measured emitted neutron spectra presented in the following include the contribution of both isotopes. Furthermore, the spectroscopy of excited states of ^{58}Ni and ^{60}Ni has been studied so that we know that, for the $^{58}\text{Ni}(n,n')^{58}\text{Ni}$ and $^{60}\text{Ni}(n,n')^{60}\text{Ni}$ reactions, almost all of the excited states decay through the first excited states of ^{58}Ni and ^{60}Ni [9,10].

For incident neutron energies lower than the effective threshold for the (n,np) reactions (≈ 11 MeV and ≈ 13.5 MeV for ^{58}Ni and ^{60}Ni , respectively), the measurement of the neutron emission n' of $\text{Ni}(n,n')\text{Ni}$ in coincidence with the 1.45 and 1.33 MeV transition from the first excited states of ^{58}Ni and ^{60}Ni to the ground state is approximately equal to the measurement of the neutron emission in $\text{Ni}(n,n')\text{Ni}$.

The comparison of these measurements with nuclear model calculations, like EMPIRE-II, will test the different parameters of the model. The least well-known parameter for the nickel isotopes is the nuclear level density [3]. EMPIRE-II does not provide exclusive spectra, therefore the calculated and measured spectra can be compared as long as the (n,n') channel is the only open channel. Finally, before comparisons with experimental results, the calculations are broadened by the experimental energy resolution. Results are presented in Fig. 3 and 4 for different incident neutron energies.

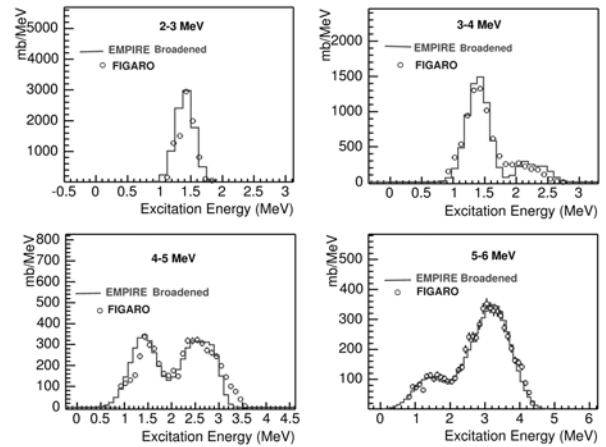


FIGURE 3. Angle integrated neutron inelastic scattering spectra for neutron energies from 2 to 6 MeV, normalized to the mean area (cross-section) of the calculations. The solid line depicts the results of EMPIRE-II calculations.

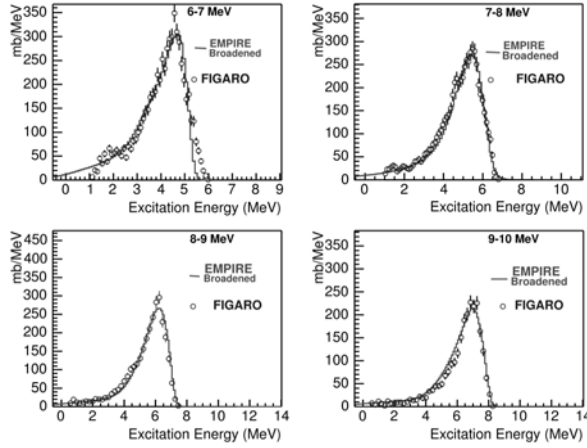


FIGURE 4. Angle integrated neutron inelastic scattering spectra for neutron energies from 6 to 10 MeV, normalized to the mean area (cross-section) of the calculations. The solid line depicts the results of EMPIRE-II calculations.

The good agreement between the measurements and the calculations is obtained by taking the Ignatyuk systematics for the level densities description [11] with the Nix-Moller corrections [12] in the EMPIRE-II calculations.

These calculations allow the extraction of the level density parameters from the Gilbert and Cameron description [13]:

$$\rho \propto \frac{1}{(E - \Delta)^2} \exp\{2[a(E - \Delta)]^{1/2}\}$$

with E the energy, Δ the pairing energy correction and a the Fermi-gas parameter. In this description, a and Δ are equal to:

$$\begin{cases} a_{58} = 8.1 \text{ MeV}^{-1} & \Delta_{58} = 3.15 \text{ MeV} \\ a_{60} = 8.4 \text{ MeV}^{-1} & \Delta_{60} = 3.10 \text{ MeV} \end{cases}$$

CONCLUSION

With the experimental apparatus FIGARO and methods for the measurement of neutron inelastic

scattering in the MeV region, information on the neutron emission spectra for the reaction $\text{Ni}(n,n')\text{Ni}$ in coincidence with the first excited to the ground-state transitions in ^{58}Ni and ^{60}Ni are obtained. A comparison with calculations performed with EMPIRE-II allows an evaluation of the level density parameters. In the near future, a similar study will be performed for Mo and Pb, and other reaction-model codes like GNASH [14] will be used for evaluating the level density parameters.

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