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Cross Sections for γ-Ray Production in the ^{191}Ir$(n, xn\gamma)$ Reactions

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Abstract. Discrete γ-ray spectra have been measured for nuclei populated in ^{191}Ir$(n,xn\gamma)$ reactions, with $x \leq 11$, as a function of incident neutron energy using neutrons from the "white" neutron source at the Los Alamos Neutron Science Center's WNR facility. The energy of the neutrons was determined using the time-of-flight technique. The data were taken using the GEANIE spectrometer. The cross sections for emission of 202 γ rays of $^{181-191}$Ir were determined for neutron energies 0.2 MeV $< E_n <$ 300 MeV. Comparison with model calculations, using the GNASH reaction model, and with GEANIE results from the similar $^{193}Ir(n,xn\gamma)$ reactions is made.

INTRODUCTION

Cross sections of (n,xn) reactions are necessary in applications, e.g., activation detectors (also known as radiochemical detectors) used to probe energy components of a neutron fluence. The ^{191,193}Ir isotopes constitute a set of such detectors. The few-MeV region can be probed by the (n,n') production of the $11/2^-$, τ=10.5 d isomer [1] of ^{193}Ir, while the higher-energy part of the spectrum can be assessed through higher-order (n,xn) reactions on both ^{191,193}Ir. For instance, the ^{191}Ir$(n,2n)^{190g}$Ir channel can be used to cover the energy range from 8 to 20 MeV, since the ground state of ^{190}Ir has a half-life of τ=11.8 d. Some data on these reactions exist at neutron energies of 14 MeV and below. The existing data, calculations, and evaluations can be verified, improved, and extended above $E_n = 14$ MeV through a technique that combines measured neutron-induced partial γ-ray cross sections with detailed theoretical modeling [2].

The combination of a high-energy-resolution germanium-detector array (GErmanium Array for Neutron Induced Excitations - GEANIE) with the "white"-neutron source at the Los Alamos Neutron Science Center (LANSCE) Weapons Neutron Research (WNR) facility enables the detection of γ rays in neutron-induced reactions over a wide range of incident neutron energies and the determination of the partial cross sections for production of these γ rays. In the present work we report on preliminary results for the production of γ rays in many exit channels in the bombardment of ^{191}Ir with fast neutrons.

EXPERIMENTS

Discrete γ rays have been measured for Ir isotopes populated in ^{191}Ir$(n,xn\gamma)$ reactions as a function of incident neutron energy using the spallation neutron source at the LANSCE/WNR facility [3] and the Ge γ-ray spectrometer GEANIE [4] located 20.34 m from the neutron source. GEANIE was comprised of 26 Ge detectors (11 planars and 15 coaxials) with Compton suppression available for 20 of these detectors.

The neutrons are produced in a ^{nat}W spallation target driven by an 800-MeV proton beam with an average current of ~ 2 μA. The beam-time structure was as follows: 100 Hz of "macropulses," 625 μs long, each macropulse containing approximately 170 "micropulses," spaced every 3.6 μs. The energy of the neutrons was determined using the time-of-flight technique. The neutron flux on the target was measured with a fission chamber, consisting of ^{235}U and ^{238}U foils [5], located 18.48 m from the center of the spallation target.

The target consisted of one thin-walled polystyrene capsule, 2.3 cm in diameter, containing 2.0 grams of Ir metal powder, 98.2% enriched in ^{191}Ir. Two natural Fe foils of 2.3 cm diameter, 82 mg/cm^2 thick in total, were placed in front of the ^{191}Ir capsule during part of the experiment. The Fe foils were included so that the known cross section at $E_n = 14.5$ MeV [6] of the strong 846.8-keV, $2^+ \rightarrow 0^+$ transition of ^{56}Fe, produced in natural Fe from inelastic scattering, could be used to normalize the cross sections obtained in the present experiment. Relative detector efficiencies were determined using a variety of calibrated γ-ray sources and corrections for the finite beam-spot size and γ-ray attenuation in the samples (both Ir and Fe) were modeled using the MCNP Monte Carlo radiation transport code [7]. A total of $\sim 8.5 \times 10^8$ γ singles and higher-fold data were recorded (190 million planar and 650 million coaxial). More details about the experiment and the analysis of the data will be given elsewhere [8].

RESULTS AND DISCUSSION

The cross sections for emission of a total of 202 γ rays of $^{181-191}$Ir isotopes were determined. A detailed description of the results for all 202 transitions will be reported elsewhere [8]. Below, we give examples of these preliminary results and compare with GEANIE results from the $^{193}Ir(n,xn\gamma)$ reactions [9]. A comparison with model calculations using the GNASH [10] reaction model is made.

Approximately one third of the 202 transitions belong to the ^{191}Ir(n,n') channel. In this channel ten previously unknown transitions were observed [8]. The cross sections for the production of fifteen additional transitions belonging to Os isotopes from the reaction channels that involve emission of one proton were also determined. An example of a level scheme showing several of the 202 transitions is shown in Fig. 1. This figure includes the 42 transitions of ^{189}Ir [the $(n,3n)$ channel] for which we were able to determine cross sections.

The nuclear structure of the ^{189,191,193}Ir isotopes is similar at low-excitation energies [11], the lowest negative-parity state being the $11/2^-$ isomer originating from the odd proton occupying the $h_{11/2}$ orbital. The sequence of negative-parity states above the isomers (see, for example, the level scheme in Fig. 1) is also similar and originates from the proton decoupled band built on this orbital. As can be seen in Fig. 1 the four strongest transitions observed to directly populate the $11/2^-$ isomer of ^{189}Ir are the $7/2^- \rightarrow 11/2^-$, $(9/2, 11/2^-) \rightarrow 11/2^-$, $13/2^- \rightarrow 11/2^-$, and $15/2^- \rightarrow 11/2^-$ transitions. Exactly the same structure exists in ^{191}Ir and ^{193}Ir. The sum of the cross sections obtained for these transitions in each channel is expected to represent a big portion of the total cross section that populates the corresponding isomers. The nuclear structure changes abruptly in ^{187}Ir [11], where the lowest negative-parity state is the $9/2^-$ state [1] originating from the intruder $h_{9/2}$ orbital; hence, this comparison cannot be extended to the $(n,5n)$ reaction channel.

A comparison of the sum of cross sections obtained for the four stronger transitions directly populating the $11/2^-$ isomers [1] of ^{189,191,193}Ir [as (n,n') and $(n,3n)$ channels] in the present experiment and in a similar ^{193}Ir$(n,xn\gamma)$ experiment [9] is shown in Fig. 2 together with the population observed feeding the corresponding ground states. These sums represent only a percentage of the total population of the channels and need to be corrected for the strength of weak or unknown transitions that are not observed in order to deduce the total population. Prior to the present work there were no experimental measurements of the ^{191}Ir$(n,n')^{191m}$Ir isomer population. From Fig. 2 it can be seen that the population of the $11/2^-$ isomer and the ground state is very similar in the (n,n') channels. In both cases the population of the isomer is very weak at low neutron energies, as one would expect, since the isomer is a high-spin state and the states feeding it are also high-spin states. As the neutron energy increases, more higher-spin states are populated and, hence, the population of the isomer increases compared to the population of the ground state. This behavior continues up to ~ 8 MeV neutron energy, where the $(n,2n)$ reaction channel opens. Nuclear-reaction modeling can be used to calculate the same quantities, i.e., the sum of the cross sections for the four individual γ rays, along with the total isomer population cross section. The ratio of these quantities can then be used to correct the experimental data by accounting for the missing contributions. Such a procedure, already applied successfully in the results of the ^{193}Ir experiment [9], will be used in the present analysis in the future. Currently, calculations based on the GNASH reaction model [10] are in progress toward this end.

An example of the cross sections obtained for nine of the 202 γ rays is shown in Fig. 3. One γ ray for each channel from (n,n') to $(n,9n)$ has been selected. The expected shift of the excitation functions to higher neutron energies with an increasing number of emitted neutrons and increasing induced neutron energy can be clearly observed. The results are compared with preliminary predictions from the GNASH reaction model [10] in the first three channels (the theoretical calculation currently is limited to $E_n < 30$ MeV).

SUMMARY

In conclusion, partial ^{191}Ir$(n,xn\gamma)^{191-x}$Ir, $x \leq 11$, cross sections for 202 transitions have been measured for neutron energies in the range 0.2 MeV $< E_n <$ 300 MeV. A comparison of the population of the $11/2^-$ isomers of ^{189,191,193}Ir [as (n,n') and $(n,3n)$ channels] in the present experiment and in the ^{193}Ir$(n,xn\gamma)$ experiment was made. These data provide new information for partial γ-ray cross sections over a wide neutron energy range and valuable feedback for calculations on the same or similar reactions. ^{191}Ir$(n,xn\gamma)$ calculations using the GNASH reaction model are in progress.

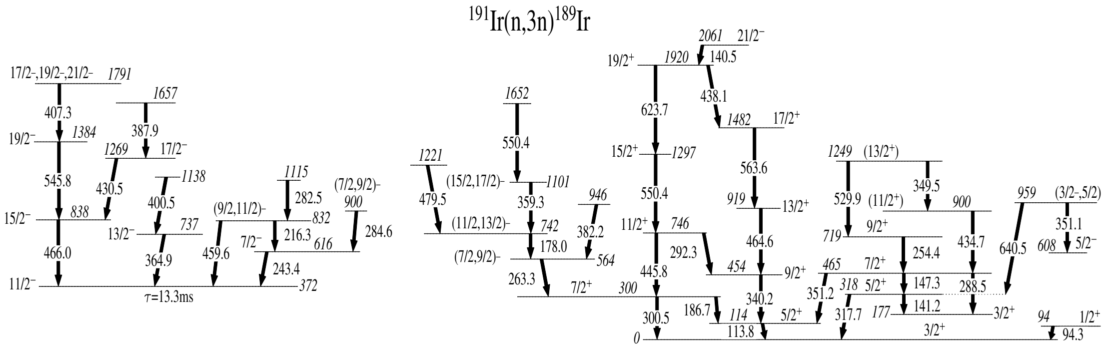

FIGURE 1. Previously known [1] partial level scheme of ^{189}Ir including all transitions for which we were able to determine cross sections in the present work. Transition and excitation energies are given in keV.

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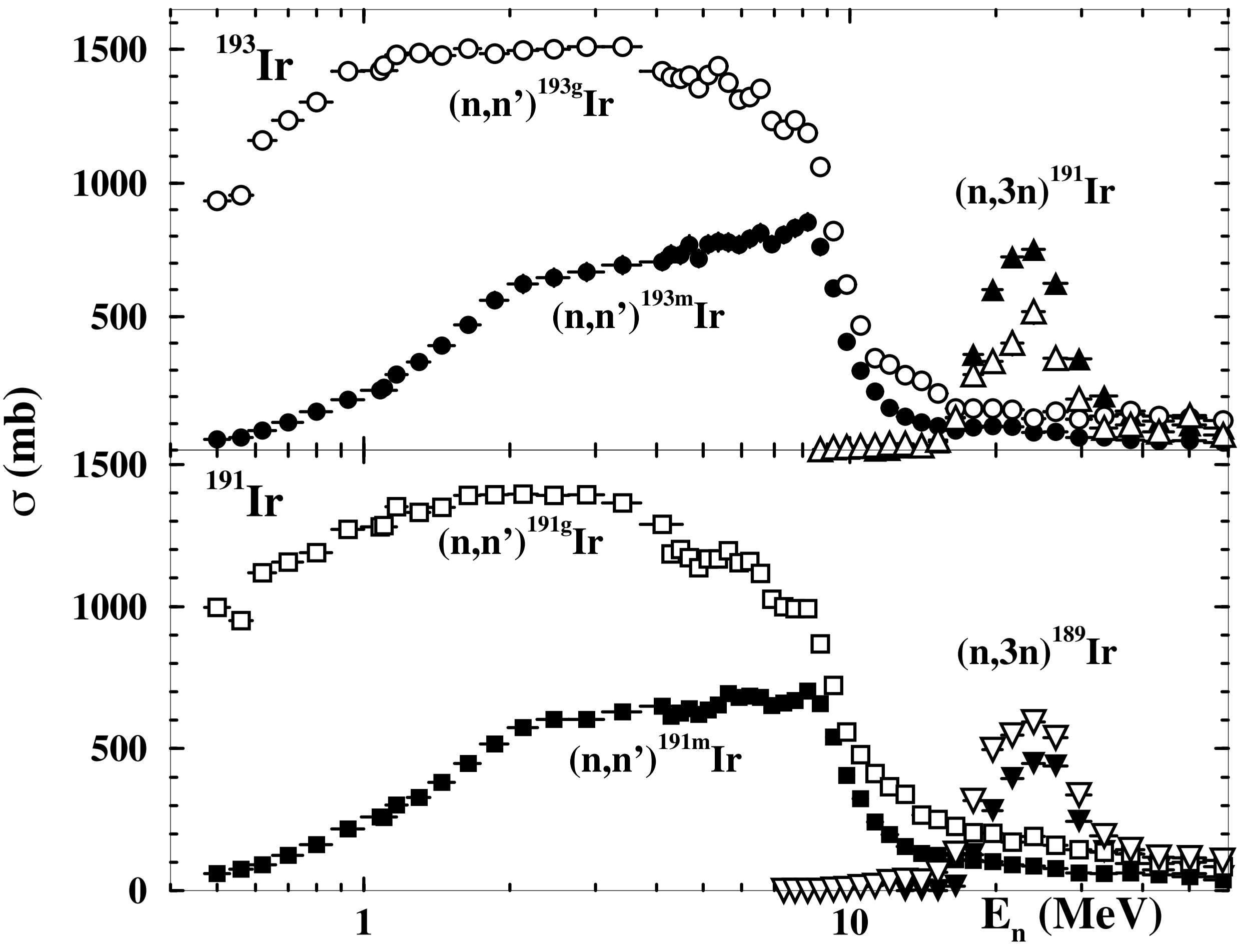

FIGURE 2. Sums of cross sections obtained for four transitions feeding directly the $11/2^-$ isomer and the ground state as a function of incident neutron energy (0.5 MeV $< E_n <$ 300 MeV) for the (n,n') and $(n,3n)$ channels in the present experiment and in the ^{193}Ir$(n,xn\gamma)$ experiment [9]. Specifically, these previously known [1] transitions are the $7/2^- \to 11/2^-$, $9/2^- \to 11/2^-$, $13/2^- \to 11/2^-$, and $15/2^- \to 11/2^-$ transitions feeding the $11/2^-$ isomer in ^{193}Ir (219.2-, 483.2-, 389.1-, and 398.8-keV transitions, respectively; solid circles), in ^{191}Ir (219.7-, 482.5-, 385.5-, and 420.1-keV transitions, respectively; solid squares in (n,n') and solid triangles in $(n,3n)$), and in ^{189}Ir (243.4-, 459.6-, 364.9-, and 466.0-keV transitions, respectively - see Fig. 1; solid reversed triangles), while the transitions feeding the ground states are 94.3-, 113.8-, 300.5-, and 317.7-keV in ^{189}Ir (see Fig. 1; open reversed triangles), 82.4-, 129.4-, 178.9-, 343.5-, 351.2-, 588.0-, 624.1-, and 686.4-keV in ^{191}Ir as the (n,n') channel (open squares), 82.4-, 129.4-, 343.5-, and 351.2-keV in ^{191}Ir as the $(n,3n)$ channel (open triangles), and finally in ^{193}Ir (open circles) the 138.9-, 180.1-, 357.8-, 361.9-, 460.5-, 557.4-, 559.3-keV, plus the 107.0-, 288.9-, and 387.5-keV transitions (the latter three feed the 73-keV level and replace the strength of the unobserved 73.0-keV transition, which lies below the Ir x-rays).

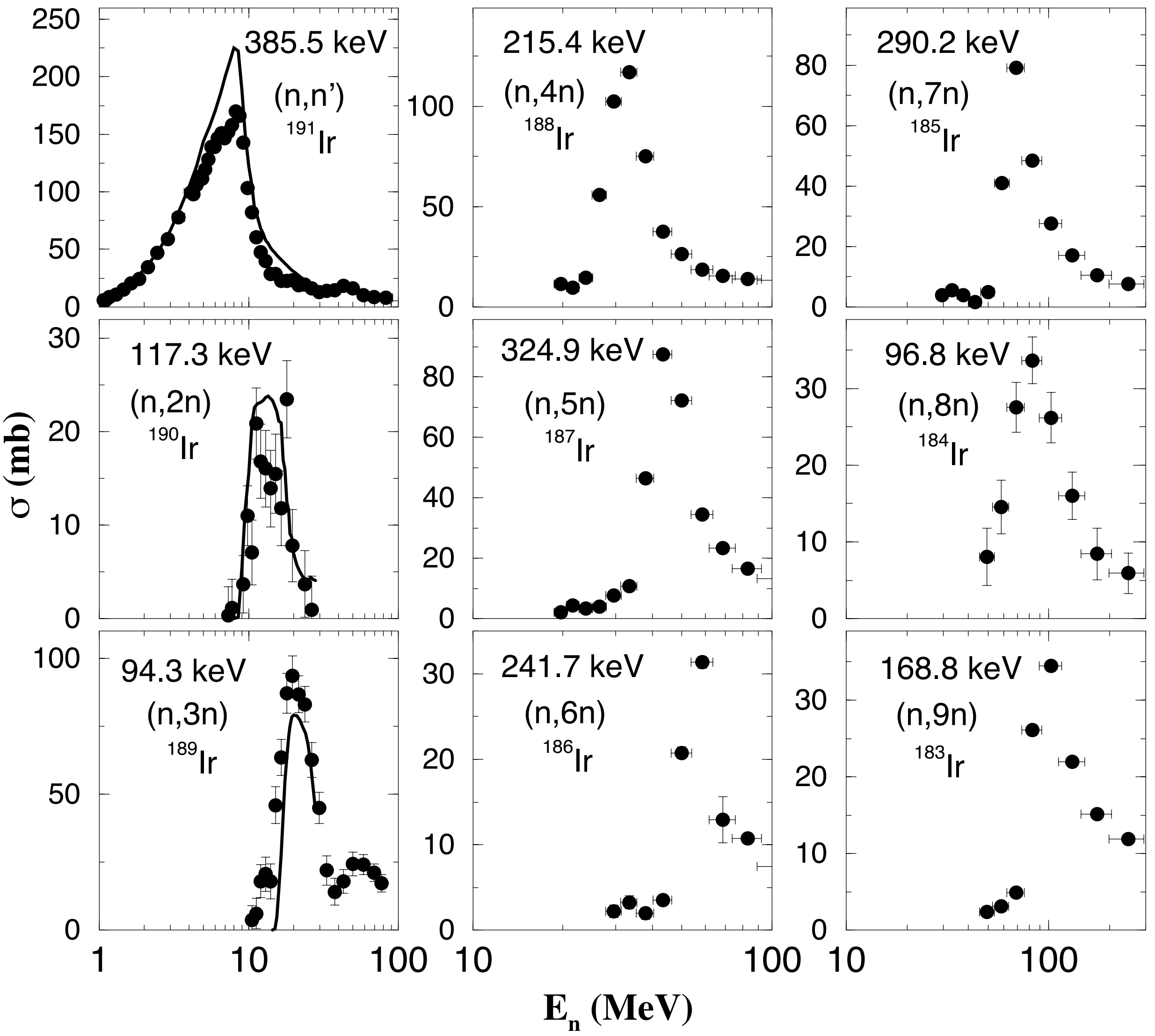

FIGURE 3. Cross sections as a function of incident neutron energy (1 MeV $< E_n < 300$ MeV) for one transition in each of the (n,n') to $(n,9n)$ channels. Specifically, these previously known [1] transitions are: 385.5 keV, $(13/2^-) \to 11/2^-$, from 557-keV level of ^{191}Ir; 117.3 keV, $(6^+) \to (5^+)$, from 288-keV level of ^{190}Ir; 94.3 keV, $1/2^+ \to 3/2^+$, from 94-keV level of ^{189}Ir (see Fig. 1); 215.4 keV, (8 To $11^-) \to (8^-,9^-)$, from 924-keV level of ^{188}Ir; 324.9 keV, $17/2^- \to 13/2^-$, from 675-keV level of ^{187}Ir; 241.7 keV, $9^+ \to 7^+$, from 359-keV level of ^{186}Ir; 290.2 keV, $(17/2^-) \to (13/2)^-$, from 449-keV level of ^{185}Ir; 96.8 keV, $(8)^- \to (7)^-$, from 208-keV level of ^{184}Ir; and 168.8 keV, $13/2^- \to 9/2^-$, from 185-keV level of ^{183}Ir. The solid lines represent predictions by the GNASH reaction model [10].