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NEUTRON-INDUCED GAMMA-RAY PRODUCTION

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ABSTRACT

High resolution Ge detectors coupled with the WNR high-intensity, high-energy, pulsed neutron source at LAMPF recently have been used to measure a variety of reactions including (n,xn) for $1 \leq x \leq 11$, (n,nα), (n,np), etc. The reactions are identified by the known gamma-ray energies of prompt transitions between the low lying states in the final nuclei. With our spallation neutron source cross section data are obtained at all neutron energies from a few MeV to over 200 MeV. Applications of the data range from assisting the interpretation of the planned Mars Observer mission to map the elemental composition of the martian surface, to providing data for nuclear model verification and understanding reaction mechanisms. For example, a study of the Pb(n,xn) reactions for $2 \leq x \leq 11$ populating the first excited states of the even Pb isotopes is underway. These data will be used to test preequilibrium and other reaction models.

INTRODUCTION

Recently a program to perform measurements of (n,xγ) cross sections for individual gamma-ray lines in the incident neutron energy range from a few MeV up to a few hundred MeV has been implemented at the Weapons Neutron Research (WNR) target area of the Los Alamos Meson Physics Facility (LAMPF). Results of a feasibility study on a natural Fe sample were reported in 1989[1], and preliminary results of (n,xnγ) measurements on Pb isotopes have been presented this year[2]. A series of similar measurements on structural materials (e.g. Fe, Cr, Ni, etc.) was performed at the Oak Ridge Electron Linear Accelerator (ORELA) facility by Larson, et al[3]. The ORELA data were measured up to 40

MeV incident neutron energy. The WNR neutron source produces intense neutron fluxes from below 1 MeV to over 200 MeV. This energy range and the high intensity available make the WNR a unique facility for fast-neutron research.

The good energy resolution of Ge detectors allows identification of individual gamma rays from final state nuclei produced in neutron induced reactions. When used in conjunction with the WNR neutron source, Ge detectors can provide excitation function data for "exotic" reactions such as $(n,7n\gamma)$, which are difficult to measure by other means, as well as data for $(n,n'\gamma)$, (n,p), (n,α), (n,np) and other reactions.

The data obtained in these measurements complement an ongoing effort at Los Alamos National Laboratory to extend the capabilities of nuclear models for improved reliability of calculations in the 20-100 MeV incident nucleon energy range[4]. Initial calculations using the current implementation of the GNASH computer code[5] are presented along with the data in this paper.

Our measurements also have application to the Mars Observer mission to map the elemental composition of the surface of Mars using a gamma-ray spectrometer. In order to accurately interpret the Mars Observer data a good knowledge of neutron-induced nonelastic reaction cross sections is needed.

Following a brief description of the experiments and analysis, new results will be presented for ^{207}Pb and ^{56}Fe, and the applications of the data will be discussed.

EXPERIMENT

The WNR neutron source has been described in detail elsewhere[6]. The pulsed proton beam typically consists of 725 μs wide macropulses containing micropulses with widths on the order of 1/2 ns. The spacing between micropulses may be varied, but is usually 1.8 μs. The neutron production target is a tungsten cylinder 7.5 cm long and 3.0 cm in diameter. Extensive shielding and collimation produce a well-defined neutron beam of uniform intensity at the sample. The earlier experiments which will be described were performed on an 18 m flight path at 15° with respect to the incident proton beam. Currently the measurements are carried out on a 41 m flight path at 30° with respect to the incident proton beam. The neutron flux is monitored during experiments with a fission ionization chamber[7] containing separate foils of ^{235}U and ^{238}U. The fluence is determined from either the $^{235}U(n,f)$ or $^{238}U(n,f)$ cross sections, which are well known below 20 MeV. From 20 to 200 MeV the $^{235,238}U(n,f)$ cross sections have been measured relative to the H(n,p) reaction at our laboratory[8] with an accuracy of approximately 10%. The flux on the 18 m, 15° flight path is shown in fig. 1. Two Ge detectors positioned at 90° and 125° provide some limited angular distribution information. The efficiencies of the detectors (relative to a 7.6 cm diameter x 7.6 cm long NaI detector) are in the range from 12 to 30%. The

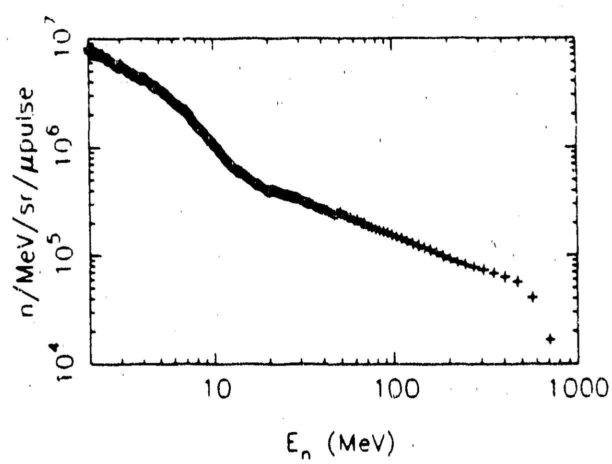

Fig. 1. The neutron flux measured by the $^{238}U(n,f)$ reaction on the 18 m, 15 degree flight path. The flux is in units of neutrons/MeV/steradian/micropulse. The beam solid angle is 33 μsr and typical beam conditions give an average of 16 k micropulses/s.

energy resolution obtained varied from 1.8 to 3.0 keV full width at half maximum at 864 keV. The absolute detector efficiencies were determined in position from calibrated sources.

To reduce the scattered neutron intensity at the detectors a ^{6}LiD absorber was mounted in front of the detectors. The Ge detectors were shielded and collimated with a 5 cm thick layer of tungsten powder sealed in an annulus constructed from an inner tube of plastic and an outer tube of 1 mm thick steel.

The data are stored in 2-dimensional (2D) arrays, typically with 4096 channels of pulse height (PH) versus 512 channels of time of flight (TOF). The data are also stored event by event on disk and then transferred to tape.

DATA ANALYSIS

The event by event data allow us to take advantage of the full resolution available from our data acquisition electronics by re-sorting the data into larger 2D arrays if necessary. Usually the 2D data acquired during the runs are sufficient.

The analysis is performed in four steps. First the data are binned into selected neutron energy bins depending upon the neutron energy resolution desired and on the statistics available. During the binning process we correct for any timing variation with pulse height and for the time dependent dead time of the time-to-digital converter. If desired the data may be binned in pulse height. Second, the yields of the peaks of interest are extracted by fitting an appropriate (usually linear) background to the region surrounding the peaks and obtaining the net sum in the peak. Third, the neutron fluence is determined from the fission yield in neutron energy bins identical to the Ge detector data. Finally, the fluence and data are combined to calculate the absolute cross section, with corrections being made at this point for multiple scattering and attenuation effects. To handle the large amounts of data obtained in these experiments the analysis procedure is automated as much as possible.

RESULTS AND DISCUSSION

Preliminary data on the ^{204,206,207,208}Pb(n,xγ) reactions were obtained in 1989 on the 18 m flight path. Reactions on ^{208}Pb were observed up to (n,11n) which has a threshold of almost 78 MeV. This year more extensive data were acquired on ^{207}Pb on the 41 m flight path. The major goal of this experiment is to determine the cross sections for the (n,xn) reactions, where $2 \leq x \leq 11$, populating the first excited states of the even Pb isotopes from ^{206}Pb to ^{198}Pb. These cross sections may serve as a benchmark for testing nuclear reaction models in the medium energy regime.

A spectrum taken on the 41 m flight path with a sample isotopically enriched to 92.78% in ^{207}Pb is shown in fig. 2. The reactions populating the first

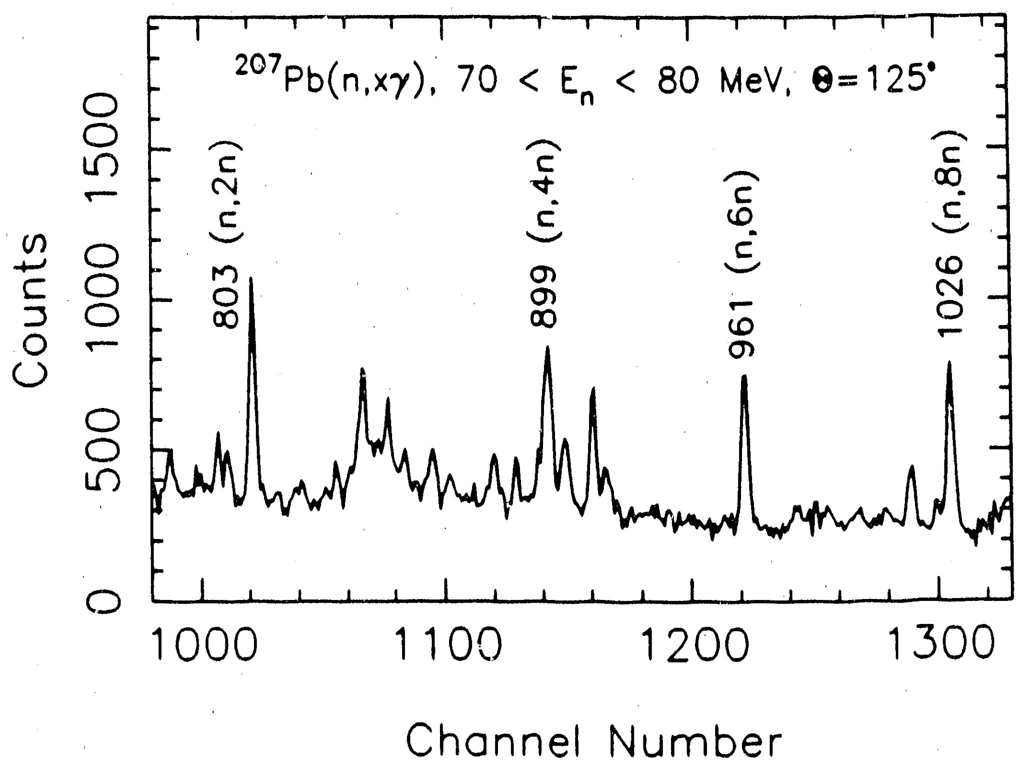

Fig. 2. A pulse height spectrum for ^{207}Pb(n,xγ). This spectrum is for incident neutron energies from 70 to 80 MeV. The gamma-ray energies and the associated reactions are listed above the peaks.

excited states of the even Pb isotopes and the gamma-ray energies are indicated on the figure. This spectrum was projected from our 2D array of TOF vs PH for incident neutrons in the energy range from 70 to 80 MeV. The data were acquired in 40 hours of running.

The total reaction cross section may be approximated by $4\pi\sigma(125°)$ because the P_2 term of the usual angular distribution expansion is zero for 125°, and the P_4 coefficient is often small. This "total" cross section for the $^{207}Pb(n,2n\gamma)$ reaction populating the first excited state of ^{206}Pb is shown as a function of energy from 3 to 200 MeV in fig. 3.

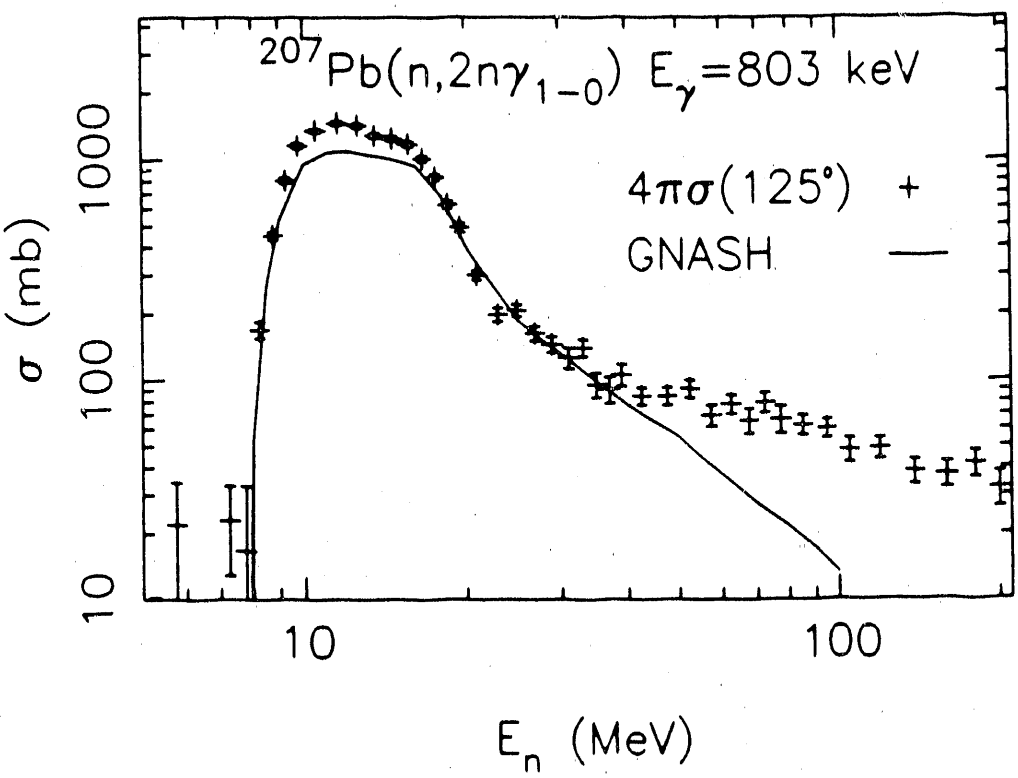

Fig. 3. The excitation function for $^{207}Pb(n,2n\gamma)$ and the GNASH model calculation. The contribution of the 2.200 MeV isomer has been subtracted (see text).

At an excitation energy of 2.200 MeV in ^{206}Pb there is an isomeric state with a lifetime of 126 μs. Because of its long lifetime the decay of this state appears as a background which is constant on the 1.8 μs time scale of our measurement. In order to make a comparison with the GNASH model calculation we have subtracted the calculated contribution from the decay of this state from the calculated total cross section. Correspondingly, a background constant in time has been subtracted from the data.

A detailed description of the initial GNASH model calculations for Pb and ^{56}Fe is given by Young[9]. These preliminary results indicate that the Pb data will provide a good test of the two different level density parameterizations now used in the code. In addition, the observation of individual gamma-ray transitions provides a more stringent test of the code because different levels (with different spins) contributing to a transition may be investigated.

The GNASH model calculation predicts the energy dependence well up to 40 MeV, although it somewhat underestimates the cross section in the 10 to 20 MeV range. The compound-nucleus spin population used in the code is most likely inadequate above 40 MeV where non-equilibrium reactions are occurring. We plan to modify GNASH to improve the high energy predictions.

The lighter even-mass Pb isotopes all possess isomeric states with lifetimes in the range from 40 to 500 ns, and thus require a more sophisticated correction procedure. In each case at least one of these isomeric states is strongly populated by the (n,xn) reaction.

Gamma-ray production data on Fe are of interest both for the Mars Observer mission and as input for radiation transport in applications where Fe is used as a structural material or as shielding. Data have been acquired on an isotopically enriched ^{56}Fe sample on both flight paths. Absolute cross sections calculated from data taken on the 18 m flight path are shown in fig. 4 for the $^{56}Fe(n,n'\gamma)$ reaction populating the first excited state of ^{56}Fe, and in fig. 5 for the $^{56}Fe(n,2n\gamma)$ reaction populating the second excited state of ^{55}Fe with the decay to the ground state. These data are in good agreement with the results of Larson[3], and extend the energy range from 40 to 200 MeV. The GNASH model calculations are in good agreement up to 25 MeV. As mentioned above we plan to enhance the model to improve its higher energy predictions.

One goal of the Mars Observer mission is to map the elemental composition of the surface of Mars using a gamma-ray spectrometer. The majority of the gamma-rays from the martian surface are expected to be produced by neutron-induced reactions. The neutrons are produced in much the same manner as in our source, by the spallation of cosmic-ray protons in the martian crust. Analysis of the Mars Observer data to obtain elemental abundances requires a knowledge of the incident cosmic-ray flux, both the energy spectrum and composition, the neutron spectrum produced at the planet's surface, and the cross sections for gamma-ray production as a function of neutron energy up to energies as high as a few hundred MeV. Samples which have been measured to determine cross sections for the stronger transitions include: C, B_4C, BN, SiO_2, Mg, Al, Si, S, Ca, Ti, Fe, Cr, Mn, and Ta.

Identification of the nuclear reactions which can contribute to the observed yield of individual lines, and improving the data base on gamma-ray production will make more accurate interpretation of the Mars Observer data possible. Our higher energy data should also provide benchmarks for improving the predictive capabilities of nuclear models in the medium energy range, as well as serving as a database for improving radiation transport calculations.

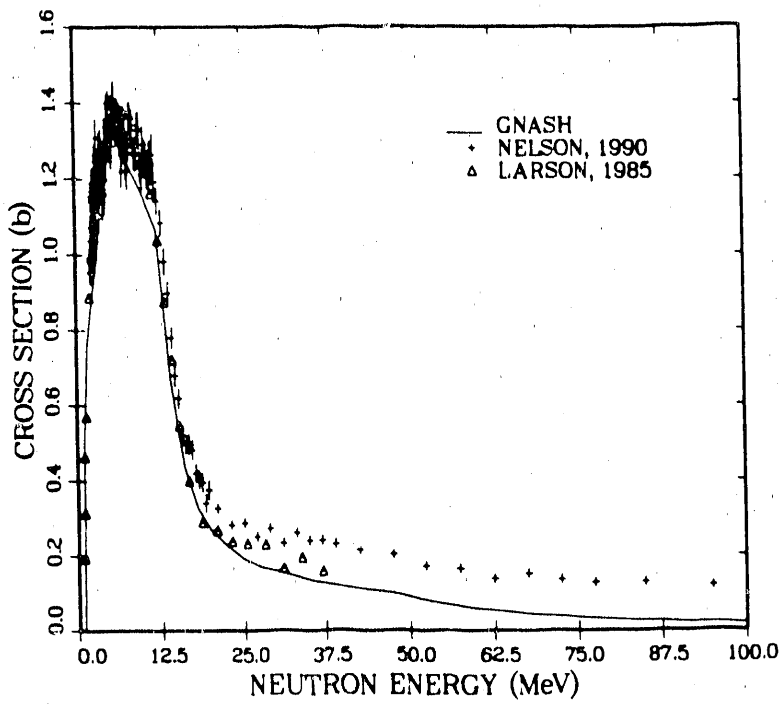

Fig. 4. The excitation function for $^{56}Fe(n,n'\gamma)$ populating the first excited state of ^{56}Fe.

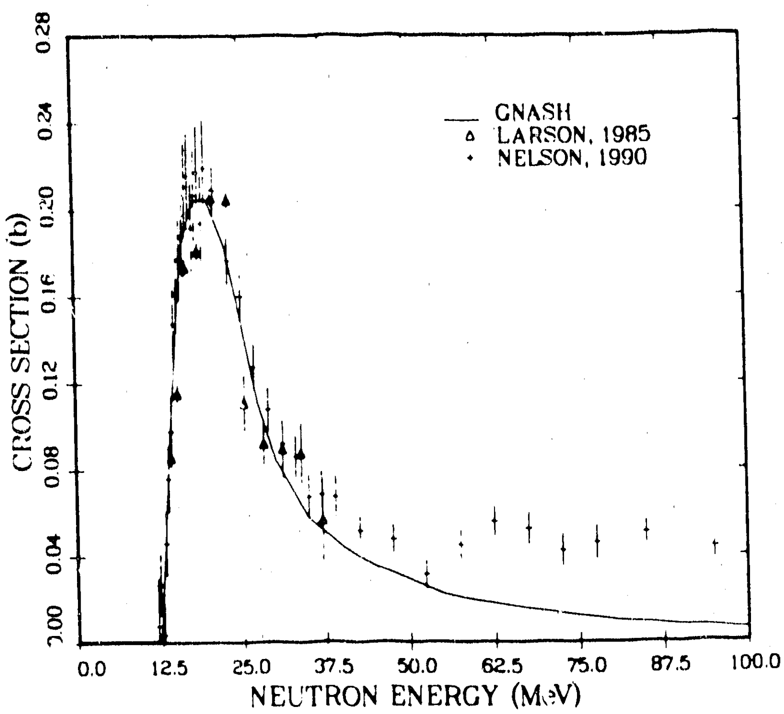

Fig. 5. The excitation function for the $^{56}Fe(n,2n)$ reaction populating the second excited state of ^{55}Fe.

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