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TITLE:
HIGH RESOLUTION INELASTIC GAMMA-RAY MEASUREMENTS WITH A WHITE NEUTRON SOURCE FROM 1 TO 200 MeV

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High Resolution Inelastic Gamma-ray Measurements with a White Neutron Source from 1 to 200 MeV

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Abstract

Measurements of prompt gamma rays following neutron-induced reactions have recently been made at the spallation neutron source at the WNR target area of LAMPF using germanium detectors. These experiments provide extensive excitation function data for inelastic neutron scattering as well as for other reactions such as (n,α), (n,nα), (n,p), (n,np), (n,nnp) and (n,xn) for $1 \leq x \leq 11$. The continuous energy coverage available from 1 MeV to over 200 MeV is ideal for excitation function measurements and greatly extends the energy range for such data. The results of these measurements will provide a database for interpretation of gamma-ray spectra from the planned Mars Observer mission, aid in radiation transport calculations, allow verification of nuclear reaction models, and improve the evaluated neutron reaction data base.

Introduction

Recently a program of measurements using high resolution Ge detectors to measure neutron-induced gamma-ray production cross sections has been implemented at the Weapons Neutron Research (WNR) target area at the Los Alamos Meson Physics Facility (LAMPF). White neutron sources such as the proton spallation target at the WNR facility are well suited to measuring excitation functions because data are measured simultaneously at all neutron energies. A similar series of measurements on structural materials (e.g. Fe, Cr, Ni, etc.) was performed at the Oak Ridge Electron Linear Accelerator (ORELA) facility [1], which provides useable neutron fluxes up to 40 MeV. With the 800 MeV proton beam of LAMPF, intense neutron fluxes from below 1 MeV to over 200 MeV are obtained. This energy range and the high intensity available make the WNR a unique facility for neutron research.

The good energy resolution of Ge detectors allows identification of individual gamma rays from transitions between excited states of product nuclei. When used in conjunction with a white neutron source, Ge detectors can provide excitation function data for reactions such as $(n,9n\gamma)$, which are difficult to measure by other means, as well as data from $(n,n'\gamma)$, (n,p), $(n,n\alpha)$, (n,np) and other reactions.

Motivation for the present studies has come from a variety of sources: the Mars Observer mission to map the elemental composition of the surface of Mars, the need for improved data for heating, shielding, and radiation transport calculations, and the desire to test nuclear reaction models. We shall describe recent experiments at the WNR facility, present some preliminary results and give examples of some of the applications of the data.

Experimental Design

The WNR neutron source has been described in detail elsewhere [2]. The proton beam has a structure that consists of macro pulses, typically 725 μs long, with each macro pulse containing micro pulses with widths on the order of 1/2 ns. The spacing between micro pulses may be varied, but is typically 1.8 μs. The neutron production target is a tungsten cylinder 7.5 cm long and 2.5 cm in diameter. The earlier experiments which will be described were performed on an 18 m flight path at 15 degrees with respect to the incident proton beam. Currently the measurements are carried out on a 41 m flight path at 30 degrees with respect to the incident proton beam. The neutron beam spot on the 18 m flight path is rectangular in shape, 8.9 cm wide by 9.3 cm high. The 41 m flight path is collimated to a 7.6 cm diameter circle. A schematic diagram of the last collimator and detector shed of the 41 m flight path is shown in fig. 1. Measurements of the beam profile at the sample using a small plastic scintillator show a very sharp beam profile with a uniform intensity distribution.

Charged particles are swept out of the incident neutron beam by arrays of permanent magnets located just beyond the neutron shutters. The beam is stopped 10 m from the detectors in a large beam stop of magnetite and concrete blocks. The 18 m flight path was evacuated from beyond the permanent magnet array to just in front of the fission chamber (about 2 m upstream from the sample position). The 41 m flight path is not evacuated at present.

The neutron flux is monitored during experiments using a thin fission ionization chamber [3] containing separate foils of ^{235}U and ^{238}U. The fission chamber is located 4.2 m upstream from the sample as shown in fig. 1. 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 [4] with an accuracy of about 10%. The flux on the 18 m, 15 degree flight path is shown in fig. 2.

High purity Ge (HPGe) detectors were chosen for their good energy resolution and ease of use. With some effort and increased complexity the time resolution may be improved without loss of efficiency by the technique described in [5]. We used the slow risetime rejection technique to improve the time resolution because detector efficiency is not critical in this application. Typical time resolutions obtained are 12 ns at E_γ = 200 keV and 5 ns at E_γ = 1 MeV. There is some variation in timing with pulse height (time walk) for which a correction is made during the analysis.

We have mainly used n-type Ge detectors due to their increased resistance to neutron damage compared to the p-type material [6]. Because our beam is well collimated and our samples are usually relatively low mass, we have not observed appreciable neutron damage in any of the detectors in two months of running. The efficiencies (relative to a 7.6 cm diameter X 7.6 cm long NaI detector) of the detectors used range from 12 to 30%. The energy resolution obtained from the data varied from 1.8 keV to 3.0 keV full width at half maximum at 864 keV, depending on the detector and count rate. The maximum instantaneous (averaged over 1.8 μs) count rate used was 40 k counts/s. Typically we run at an instantaneous rate of about 10 k counts/s.

To filter out some of the lower energy gamma rays and to reduce the scattered neutron intensity at the detectors we mount a 2.2 cm thick ^{6}LiD shield in front of the detectors. In the earlier experiments the detectors were shielded and collimated with Pb. For our measurements using Pb samples the background produced by scattered neutrons striking the Pb collimator was a problem. In our later measurements we used a 5 cm thick layer of tungsten powder sealed in a cylindrical tube constructed from an inner tube of plastic and an outer tube of 1 mm thick steel. These collimators have proved far superior to the Pb in reducing backgrounds, especially those due to excitation of Pb.

Most of the samples were larger than the beam spot, and were supported by a thin plastic frame. The samples were oriented at a 45 degree angle with respect to the incident beam.

The data are buffered during a macro pulse and read out between macro pulses to reduce the system dead time. 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 raw event data are also stored on disk and then backed up to 8 mm tape.

Data Analysis

The raw data allow us to take advantage of the full resolution available from our data acquisition electronics by replaying the data into larger 2D arrays if necessary. Normally 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 the time dependent dead time of the time to digital converter and the time walk, and we subtract the time-random and wraparound background. If desired the data may also 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 fission events are projected out of the 2D fission chamber spectrum and binned into neutron energy bins identical to the Ge data. From these data a flux spectrum is generated. Finally, the flux 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

A sample spectrum taken on the 41 m flight path with an ^{56}Fe sample isotopically enriched to 99.87% is shown in fig. 3. The reactions observed are indicated above the peaks as are the transition energies. This spectrum was projected from our 2D array of TOF vs PH for incident neutrons in the energy range 27.1 to 29.0 MeV. These data were acquired in 20 hours of running. Absolute cross sections calculated from the data are plotted in fig. 4 for the ^{56}Fe(n,n'γ) reaction populating the first excited state of ^{56}Fe, and for the ^{56}Fe(n,2nγ) 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 [1], and extend the energy range covered from 40 to 200 MeV. Preliminary data on the ^{204,206,207,208}Pb(n,xγ) reactions were obtained in 1989 on the 18 m flight path. This year more extensive data were acquired on ^{207}Pb on the 41 m flight path. The major goal of this experiment is to measure the (n,xn) reactions, where $2 \leq x \leq 11$, populating the first excited states of the even Pb isotopes which are known down to ^{198}Pb. Reactions on ^{208}Pb have been observed up to (n,11n) which has a threshold of almost 78 MeV. These data should provide a good test of preequilibrium and other reaction models used to describe such intermediate energy reactions.

A complicating factor in the Pb experiments and others is existence of long lived nuclear states in the product nuclei. For states with lifetimes on the order of our time resolution (approx. 5 ns) or less there is no problem. For times in the range greater than 5 ns to around 100 ns the time and hence neutron energy resolution is degraded. For decays with lifetimes much greater than 100 ns we get at best only the cross section integrated over all neutron energies which contribute to the reaction. In these cases we can turn to model calculations to help get a more complete picture of the decay. Using a statistical and preequilibrium nuclear reaction code such as GNASH [7] we can use the prompt transition cross sections and additional information such as measured total cross sections to constrain the calculations. In turn the model can predict the decay of the longer lived states.

Data have been acquired for the Mars Observer Mission to map the elemental composition of the surface of Mars using a gamma-ray spectrometer. Samples which were measured to determine the cross sections for strong transitions include: C, B_4C, BN, SiO_2, Mg, Al, Si, S, Ca, Ti, Fe, Cr, Mn, and Ta. 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 (1) the incident cosmic ray flux, both the energy spectrum and composition, (2) the neutron spectrum produced at the planets surface, and (3) the cross sections for gamma-ray production as a function of neutron energy up to energies as high as a few hundred MeV. Extending the energy range and improving the data base on gamma-ray production will make more accurate interpretation of this data possible.

Future plans include continuing to improve the measurements on the Pb isotopes and extending the measurements to the study of fission fragments from heavy nuclei.

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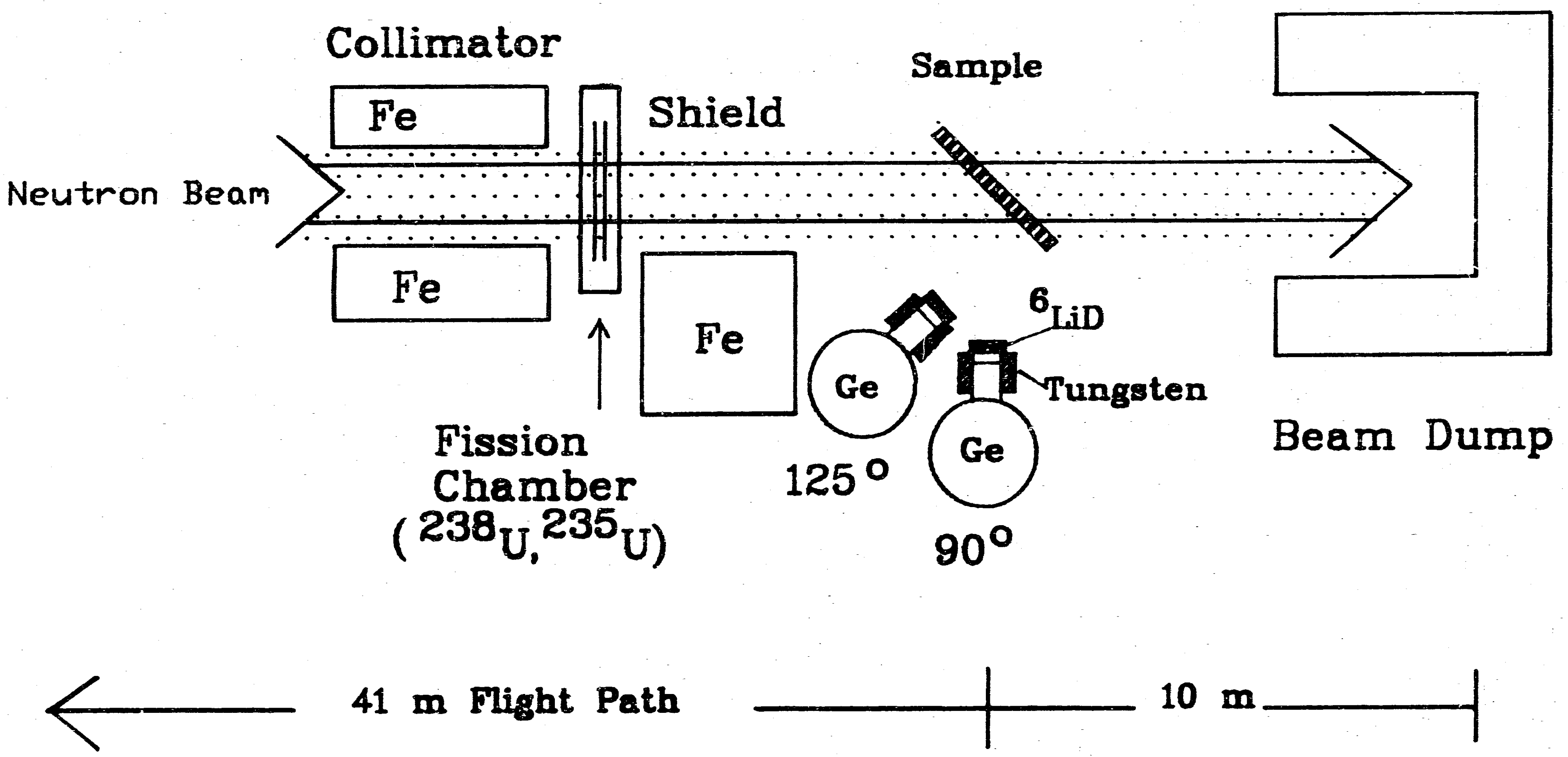
Figure Captions

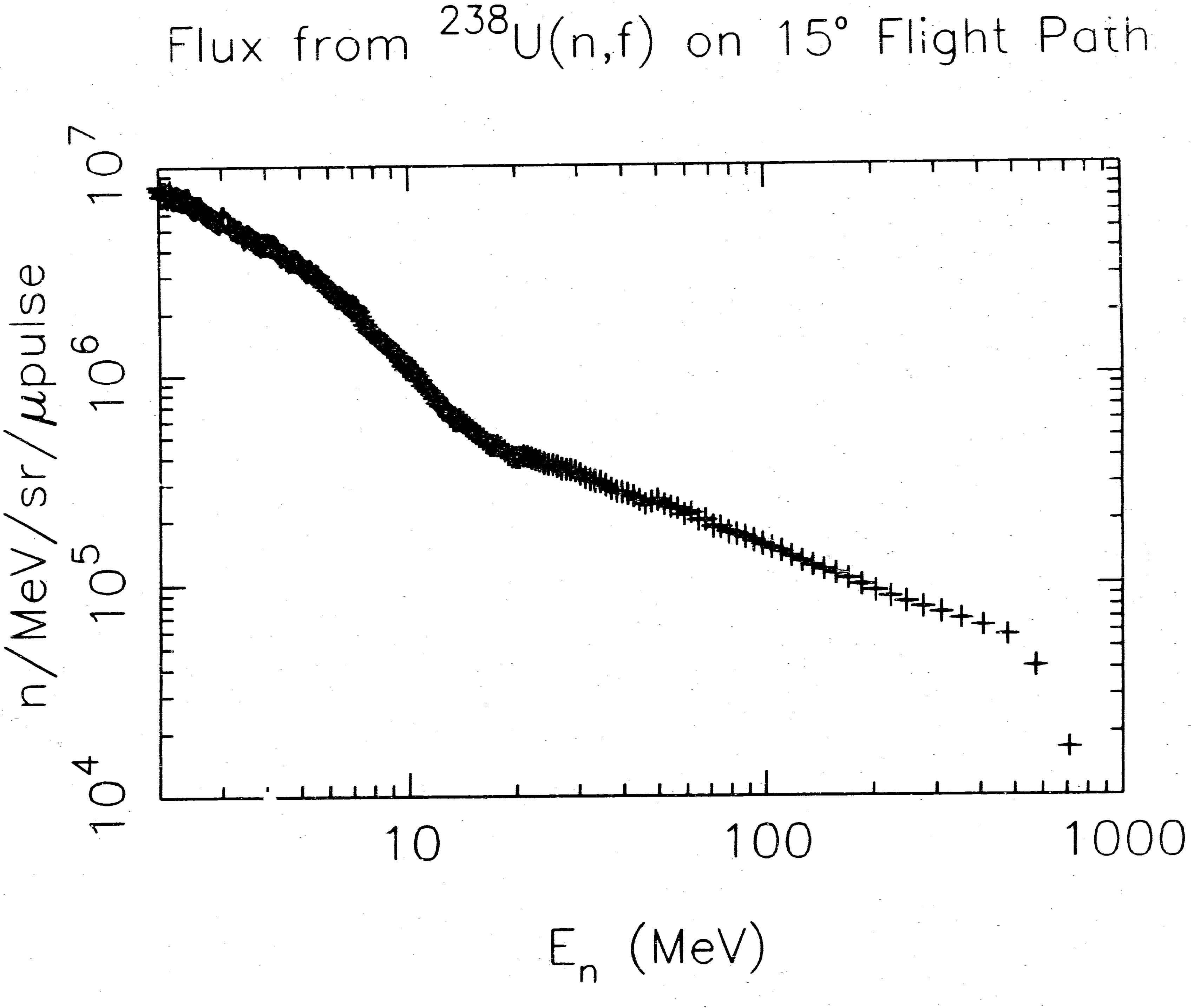
Fig. 1. Schematic diagram of the current Ge detector system. The neutron production target, its bulk shield, neutron shutters, and permanent magnet arrays are not shown. The Ge detectors are typically 25 to 50 cm from the scattering sample. Typical samples are 10 cm by 15 cm and range in thickness from 0.8 to 6.5 mm depending upon the density.

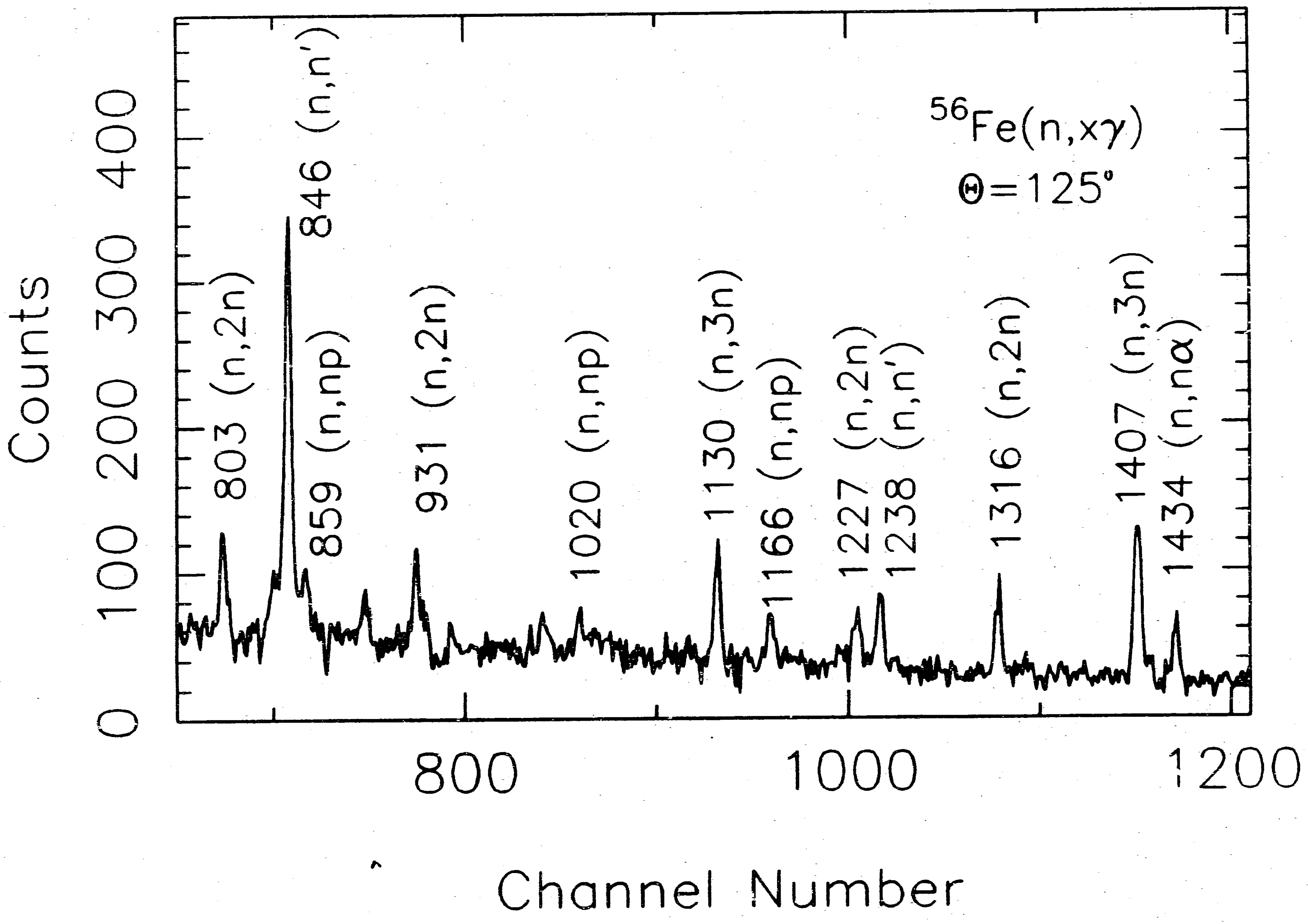
Fig. 2. The neutron flux as measured by the fission reaction on ^{238}U on the 15 degree flight path. The flux is expressed in units of neutrons per MeV per steradian per micro pulse. For the 18 m flight path the beam solid angle is 33 μsr. Typical beam conditions give an average of 16 k micro pulses per second.

Fig. 3. A pulse height spectrum projected from the 2D array of data for $^{56}Fe(n,x\gamma)$. This projection corresponds to incident neutron energies from 27.1 to 29.0 MeV. The transition energies and the associated reactions are listed above the peaks. These data were acquired in a 20 hour run.

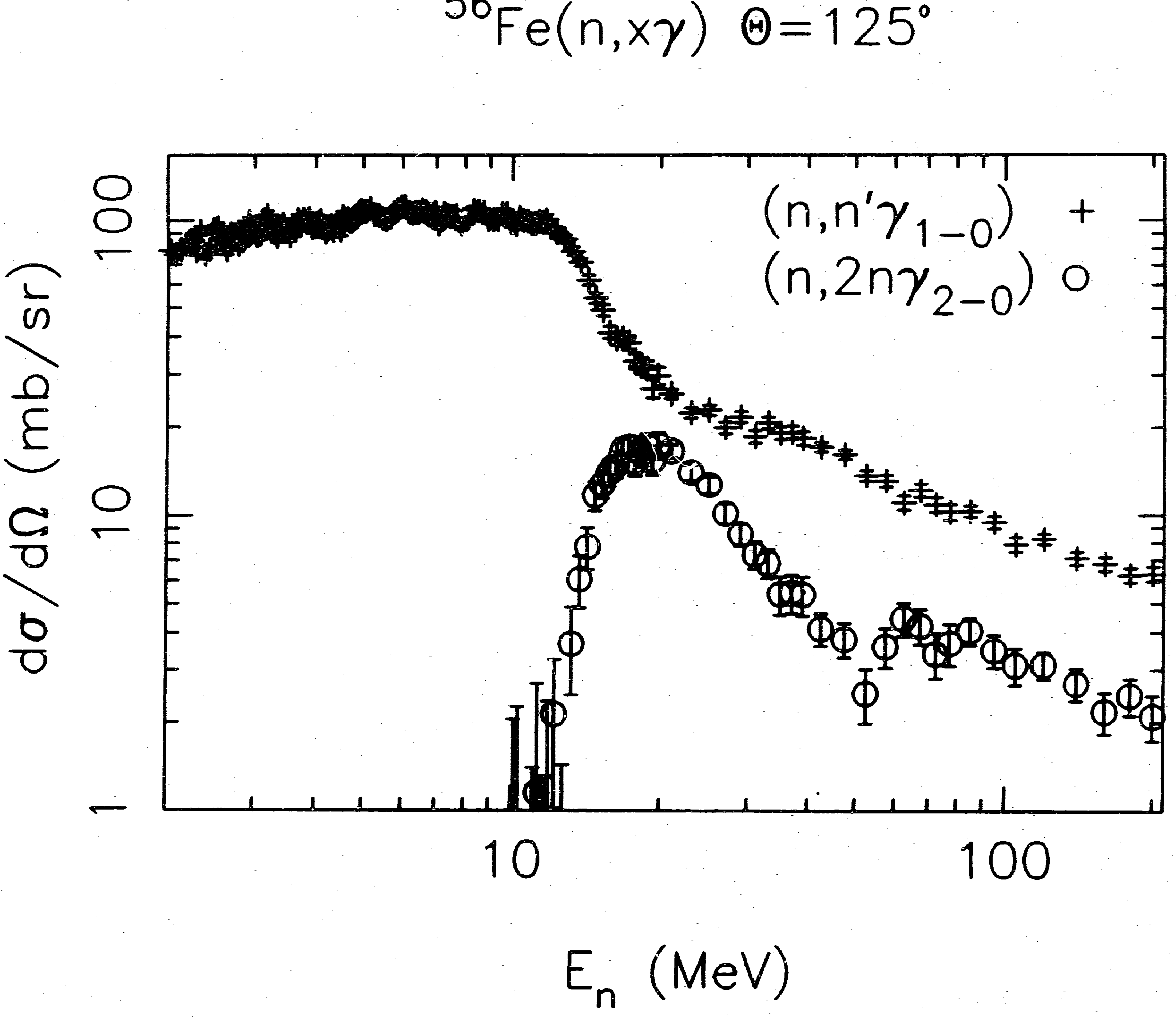
Fig. 4. The measured excitation functions for inelastic scattering from ^{56}Fe populating the first excited state of ^{56}Fe and for the (n,2n) reaction populating the second excited state of ^{55}Fe. The error bars show the statistical errors only.


Collimator
Fe
Fe
Neutron Beam
Shield
Fe
Fission Chamber (^{238}U, ^{235}U)
Sample
^{6}LiD
Tungsten
Ge
Ge
125°
90°
Beam Dump
41 m Flight Path
10 m


Flux from $^{238}U(n,f)$ on 15° Flight Path
n/MeV/sr/μpulse
10^7
10^6
10^5
10^4
10
100
1000
E_n (MeV)



^{56}Fe(n,xγ)
Θ=125°
803 (n,2n)
846 (n,n')
859 (n,np)
931 (n,2n)
1020 (n,np)
1130 (n,3n)
1166 (n,np)
1227 (n,2n)
1238 (n,n')
1316 (n,2n)
1407 (n,3n)
1434 (n,nα)
Counts
0
100
200
300
400
800
1000
1200
Channel Number


^{56}Fe(n,xγ) Θ=125°
(n,n'γ$_{1-0}$) +
(n,2nγ$_{2-0}$) ○
dσ/dΩ (mb/sr)
100
10
1
10
100
E$_n$ (MeV)

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