Title:

AN UPDATE ON (N, CHARGED PARTICLE) RESEARCH AT
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Submitted to:

International Nuclear Data Workshop, Del Mar, CA, Dec. 4-6,
1995; Proceedings: Fusion Engineering & Design

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Form No. 836 R5
ST 2629 10/91

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An Update on (n,charged particle) Research at WNR

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ABSTRACT

Neutron-induced reactions producing light charged particles continue to be investigated at the spallation fast-neutron source at the Los Alamos Neutron Science Center (LANSCE). New data on the cross sections for alpha-particle production for neutrons on ^{58}Ni and ^{60}Ni are presented from threshold to 50 MeV. Recent changes in the experiment now allow protons, deuterons, tritons, ^3He and alpha particles to be identified.

1. Introduction

Neutron-induced reactions producing light charged particles (isotopes of hydrogen and helium) are important for basic physics and applications. Despite large experimental efforts expended over the years in the study of these reactions, only recently have there been successful efforts to obtain accurate data over wide regions in incident neutron energy and in the angular distributions of emitted charged particles. In the past, only activation measurements have successfully attacked a wide range of incident neutron energies, and for many important materials, the activation approach is difficult or impossible because of the characteristics of the residual nuclei (especially if they are stable).

We focus our research¹ on studying these reactions at four angles over a wide range in neutron energy, typically from threshold to 50 MeV, using the WNR spallation source of fast neutrons at the Los Alamos Neutron Science Center, LANSCE, formerly known as LAMPF.² Others [e.g. Refs. 3-5] study the same reactions with monoenergetic sources over smaller neutron energy ranges but with greater angular range for the outgoing charged particles. For the common energy range, therefore, these different approaches are complementary.

This report is an update on our studies at LANSCE. We report new cross sections for alpha-particle production on ^{58}Ni and ^{60}Ni , and we describe a change in the detector arrangement that will allow us to identify protons, deuterons, tritons, ^3He and alpha particles.

2. Experiment

The experimental arrangement has been described previously.¹ Neutrons are produced by the WNR spallation neutron source² using the 800-MeV proton beam from LANSCE incident on a tungsten target. The flight path at 90-degree production angle emphasizes the neutron spectrum from below 1 MeV to over 50 MeV and de-emphasizes the part of the spectrum above 100 MeV. We originally thought that the neutron spectrum at this flight path would be useful only to 20 or 30 MeV for these measurements, but analysis of the data has shown that cross sections can be obtained with statistics of better than 10% up to 50 MeV if neutron energy intervals of 2 MeV are taken at the upper part of the range.

Neutrons from the source are collimated to a 5 cm by 5 cm square beam and the corners of this beam are cutoff by triangular collimators in the corners of the squares to give a beam shape illustrated in Figure 1. The additional, corner collimation was found to reduce scattered neutrons from hitting the target frame, and consequently the backgrounds, determined by blank target runs, are now much reduced. (In the nickel data presented below, they are less than 5%, which is quite remarkable given the thin targets used.)

Charged particles emitted in the reactions are detected by three-element telescopes at four angles, 30, 60, 90 and 135 degrees. These angles were chosen to study compound-nuclear and pre-equilibrium reaction mechanisms and to provide angle-integrated cross sections. For the alpha-emission investigations, the first detector in the telescopes has been a thin, low-pressure-gas proportional counter which allows detection of alpha particles well below 2 MeV. The second detector is a 500 μm silicon surface barrier detector which will stop alpha particles below 33 MeV. The third detector, which so far has not been used in the analysis of alpha-particle emission, is a 1 cm thick CsI(Tl) scintillator viewed by a photodiode. This final detector is useful for studying proton emission above 10 MeV and alpha-particle emission above 35 MeV. The chamber and detectors are illustrated in Figure 2.

The data are acquired by CAMAC-based FERA electronics⁶ and the XSYS system.⁷ Analysis is performed with programs written in the SPEAKEZ language.⁸

III. Alpha-particle production cross sections for ^{58}Ni and ^{60}Ni

Alpha-particle production was studied from threshold to 50 MeV incident neutron energy on targets of ^{58}Ni and ^{60}Ni , which were isotopically enriched to over 99%. The targets were 10 cm in diameter and had thicknesses of 3.38 and 2.98 mg cm^{-2} respectively. The

emission spectra were integrated over emission energy and angle to obtain the cross sections. Data on the double differential cross sections will be presented elsewhere.

Our results for the $(n, x\alpha)$ cross sections are presented in Figure 3 from threshold to 50 MeV. We bin the data in 0.5 MeV bins up to 15 MeV, 1.0 MeV-wide bins from 15 to 20 MeV and 2 MeV-wide bins from 20 to 50 MeV. Except at energies below 6 MeV where there might be structure,³ this binning should represent well the excitation function. It is seen that, similar to our results for $^{59}\text{Co}(n, x\alpha)$,⁹ the cross sections increase monotonically over this entire range with perhaps a flattening of the cross section near 50 MeV.

Literature values of other investigations are presented in Figures 4 and 5 from threshold to 20 MeV, the traditional region of evaluated nuclear data, along with the ENDF/B-VI evaluations.^{10,11} To our knowledge there are no evaluated or experimental data, other than ours, above 20 MeV. For ^{58}Ni , the previous experimental data include activation cross sections for $^{58}\text{Ni}(n, \alpha)^{55}\text{Fe}$ in the range below the $(n, n'\alpha)$ threshold¹² or where the $(n, n'\alpha)$ cross section is believed to be small,¹³ helium production cross sections near 10 and 15 MeV,^{14,15} and charged particle measurements.^{3,16-19} It should be noted that the activation measurements for this isotope are difficult because there is only a low-energy x-ray to detect following electron capture in the decay of ^{55}Fe . Our data are in good agreement with the charged-particle emission and helium accumulation measurements. The activation cross sections, however, appear to be high by 25% or so. The ENDF/B-VI evaluation was prepared well before most of these data were available.

For ^{60}Ni , activation measurements are not possible because the residual isotopes, ^{57}Fe and, for the $(n, n'\alpha)$ reaction, ^{56}Fe are stable. Our result are in reasonable agreement with helium production cross sections near 10 and 15 MeV,^{14,15} and with charged-particle-emission measurements.¹⁶⁻¹⁹ As found in the ^{58}Ni case, the ENDF/B-VI evaluation for ^{60}Ni overestimates the cross section from threshold to about 14 MeV where it was constrained by measured values. The disagreement with our data can be as large as 75%.

IV. Changes in the experimental apparatus

For future studies, we have replaced the low pressure gas proportional counters with 100 micron silicon surface-barrier detectors. This change allows us to separate the isotopes of hydrogen and helium emitted in nuclear reactions, whereas before we were only able to separate hydrogen from helium and not the individual isotopes. The degree of separation is indicated in Figure 6 where we plot the delta-E versus the E pulse height for all neutrons incident on a silicon target. Excellent separation of protons, deuterons, tritons, ^3He and alpha particles is obtained with this arrangement. Of particular interest in these data is the cluster emission of deuterons, tritons, and ^3He as tests of pre-equilibrium reaction models. Targets for which data are being analyzed include C, N, O, Al, Si, ^{56}Fe , Nb, Y, and Ta.

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Figures:

1. Shape of beam with corner collimators added to the 5 by 5 cm² square collimation. Superimposed is the shape of the circular target at a typical angle of 42 degrees.
2. Chamber and detectors used to measure charged particles emitted in neutron-induced reactions. The nickel data reported here were taken with the proportional counters as shown. In more recent experiments, the proportional counters are replaced with 100 micron thick silicon surface barrier detectors to give particle identification as shown in Figure 6.
3. Present results for ⁵⁸Ni (n,xα) and ⁶⁰Ni (n,xα) cross sections for neutron energies up to 50 MeV. The error bars shown are statistical. In addition, an overall (correlated) systematic error of 8% below 15 MeV increasing to 15% at 50 MeV should be added due to uncertainties in solid angle, flux normalization, target thickness, and angle integration.
4. Present results for ⁵⁸Ni(n,xα) cross sections up to 20 MeV compared with ENDF/B-VI and literature values are from activation (solid diamonds, Ref. 12, and open diamond, Ref. 13), helium accumulation (open triangle, Ref. 14, and solid triangle, Ref. 15), and charged-particle detection (open square with cross⁴, open square⁵, solid square¹⁶, open circle¹⁷, open diamond with plus¹⁸). The results of Ref. 3 are not shown because they pertain to the question of fluctuations near threshold, which is a different problem and will be discussed elsewhere.
5. Present results for ⁶⁰Ni(n,xα) cross sections up to 20 MeV compared with ENDF/B-VI and measurements from helium accumulation (open triangle¹⁴, and solid triangle¹⁵), and charged-particle detection (solid square¹⁶, open circle¹⁷, open diamond with plus¹⁸, and open diamond¹⁹).
6. A delta-E vs. E spectrum of the 100 micron silicon delta-E detector and the 500 micron E-detector of the 60-degree telescope with a target of silicon. The maximum energy stopped in the E-detector is 9 MeV for protons, 12 MeV for deuterons, 15 MeV for tritons, 32 MeV for ³He and 36 MeV for alpha particles. More energetic particles are stopped by the CsI(Tl) detector behind the two silicon detectors.

Target frame
at 42 degrees

Figure 1

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6