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Development of a Spectrometer for the Measurement of (n,xp), (n,xd), and (n,xα) Cross Sections, Angular Distributions and Spectra at E_n = 15 MeV*

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ABSTRACT

A spectrometer to measure neutron-induced charged-particle producing reactions has been developed and yields data with greatly improved signal-to-background ratios. It consists of a magnetic quadrupole lens which focusses the charged particles onto a silicon surface barrier detector or a two-detector telescope which is more than 2 meters from the sample being irradiated. The efficiency of the spectrometer is calibrated experimentally and depends only on values for the (n,p) elastic cross section and the stopping power of polyethylene. Further development is underway to replace the surface-barrier ΔE counter with a proportional counter of larger area. This detector, combined with a larger E counter (surface barrier) could increase the effective solid angle by a factor of five.

The results for (n,xp), (n,xd) and (n,xα) cross sections are summarized for the eight target materials studied so far. Measurements of the charged particle spectra have established that cross sections for production of protons below 2.5 MeV are significant for some targets, in fact protons as low as 800 keV have been detected from aluminum. These low energy protons would be quite difficult to measure with conventional counter telescope spectrometers.

INTRODUCTION

Cross sections and spectra for neutron-induced charged-particle producing reactions are important in estimating materials damage effects from neutron bombardments. Two aspects of this damage, nuclear transmutation and hydrogen and helium production, are direct functions of the cross sections for (n,xn), (n,xd) and (n,xα) reactions. An additional factor in damage estimates, the energy distribution of primary recoil atoms from the lattice, is related to the spectra and angular distributions of particles emitted in neutron-induced reactions. In this context, alpha-particle angular distributions and spectra are important because the large alpha particle mass causes more energetic recoil atoms than neutron or proton emissions.

Radiochemical measurements can supply angle- and emission-energy integrated cross sections for many of these reactions. Because not all of the nuclei reached by charged particle emission are unstable, however, some cross sections must be measured using another technique. In addition, the radiochemical measurements are less useful in determining cross section systematics for neighboring nuclei, since without data differential in angle or energy, it is more difficult to determine the reaction mechanism involved.

Farrar and co-workers[1] have developed a technique to measure the helium produced in (n,xα) reactions. After a period of irradiation, the samples are analyzed for helium content by a mass spectrometer. This method appears not feasible for measuring hydrogen production, however.

Direct measurement of the charged particles produced is an alternative procedure. If such measurements are to extend to low emission energies, however, thin targets are required. Backgrounds caused by the interaction of neutrons or gamma rays with the detector or reaction chamber may then overwhelm the signal produced by the target of interest. Moving the detector farther from the neutron source permits additional shielding to be placed between detector and neutron source, but the solid angle is reduced at the same time.

EXPERIMENTAL TECHNIQUES

To reduce the background we move the solid state detectors 2 to 4 meters away from the target and the source. Then to increase the solid angle for detecting charged particles, we interpose a magnetic quadrupole lens between the target and the detectors. Considerable shielding can be placed between the neutron source and the detector in this arrangement. An additional advantage of the quadrupole lens is its directionality; that is, when it is adjusted to bring particles produced in the target to a focus on the detector, particles of the same energy produced in the reaction chamber are focussed away from the detector.

The original version of this spectrometer[2] utilized a quadrupole doublet, but this lens has now been replaced by a quadrupole triplet,[3] which has better transport properties and a higher field gradient.

Neutrons were produced by the Lawrence Livermore Laboratory rotating target neutron source. Beam currents of between 15 and 20 mA of 400 keV deuterons impinged on a rotating tritiated-titanium disc to produce 15-MeV neutrons with the T(d,n) reaction. Because of the thin targets used in these measurements, a high source strength was required. Typical intensities were about 3×10^{12} neutrons/sec into 4π steradians.

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Figure 1 is a diagram of the spectrometer and neutron source. The large mass of the quadrupole and associated shielding made it convenient to change reaction angles by sliding the entire assembly on a track rather than rotating it about the source; thus, the central axis of the spectrometer is located 5 cm from the position of the neutron source, denoted by the circled numbers on the figure, and is oriented perpendicular to the beam direction. Changes in reaction angle are made by sliding the assembly relative to the neutron source so that the radiator foil is at various θ angles between 0° and 78° to the deuteron beam, which correspond to reaction angles 90 + θ for the (n, charged particle) reaction.

For neutrons produced from the T(d,n) reaction induced by 400 keV deuterons, such changes result in a change in average neutron energy between 15.1 and 14.6 MeV as the reaction angle is changed.

The quadrupole transports particles of a given momentum from a specific point on the target to a specific point on the detector. Integrating over both these areas gives an efficiency function with a finite energy width. For the targets and detectors used in the present measurements, the peak had a width $\Delta E/E$ of about 35%, full-width at half-maximum.

Absolute values for the efficiency function at each gradient setting were determined by measuring the proton spectrum from a stopping target of polyethylene. This spectrum may be calculated from the incident neutron flux, the n-p elastic scattering cross section and the stopping power of polyethylene. Comparison of the observed spectrum with the calculated one yields the efficiency of the spectrometer.

In principle, the efficiency for other particles could be deduced from that for protons, since the trajectories in the magnetic fields will be functions of Z^2/ME, where Z is the charge and M and E the mass and energy of the particle. Thus, the efficiency for deuterons should peak at an energy half as large as that for protons and that for alpha particles at the same energy as that for protons. To check this, efficiency measurements were carried out with a CO_2 target as well as a CH_2 target. Over most of the energy range, the two measurements yielded consistent results. For high energy protons, the small pulse height in the ΔE counter caused some loss of coincidence efficiency (~20%) in the counter telescope. For this reason, the deuteron efficiency measurement was shifted in energy and used in analyzing alpha particle data, while proton and deuteron data were reduced using the measured proton or deuteron efficiency, respectively.

To cover the charged-particle energy range 1 to 14 MeV, measurements at nine field gradient settings are usually required. Figure 2 shows the result of one such measurement for the ^{27}Al(n,xp) reaction. The open circles denote the results of the measurement with the aluminum target in place; the x's show the results of a background measurement. Each of these two measurements was made in about forty minutes. The solid line marked "acceptance" gives the measured efficiency (= product of counter efficiency and the effective solid angle of the quadrupole). Note the favorable signal-to-background ratio even at a proton energy as low as 1.5 MeV.

RESULTS AND DISCUSSION

Data have been obtained for (n,xp), (p,d) and (n,xα) reactions on ^{27}Al, ^{46}Ti, and ^{48}Ti;[4] on ^{51}V and ^{93}Nb;[5] on ^{63}Cu and ^{65}Cu;[6] and on stainless steel 304 and 316.[7] Angle-integrated proton and deuteron spectra are shown for ^{63}Cu and ^{93}Nb targets in Figs. 3 and 4.

An impressive feature of the cross section data is that the proton spectra for some of the targets extend far below the Coulomb barrier (Al, ^{46}Ti and ^{63}Cu) while for other targets (^{48}Ti and ^{93}Nb) the spectrum below the Coulomb barrier falls rapidly. This difference is related to the importance of the (n,n'p) reaction for targets for which a sub-Coulomb-barrier peak is observed. In these targets, the neutron binding energy is larger in magnitude than the corresponding proton binding energy; thus, excited levels of the target nucleus within a given energy range have no neutron decay width but can emit a sub-Coulomb barrier proton. This width is expected to be small, but since the only other available channel is gamma decay, proton decay will occur in many cases. A similar sub-Coulomb-barrier decay is possible in the alpha-particle channel, if the alpha-particle binding energy is less than that for protons and neutrons. Some indication that second-stage alpha decay at present is found in the spectra for ^{46}Ti, ^{63}Cu and ^{93}Nb. Apparently, the small difference between B_α and B_p in these nuclei is not in general sufficient to compensate for the larger Coulomb barrier for alpha particles. Evidence that these sub-barrier particles are not due to some unknown spectrometer background is found in the absence of the low energy peaks for ^{48}Ti[4] and for the ^{51}V(n,xα) reaction,[5] where the binding energies are such that the (n,n'p) reaction on ^{48}Ti and (n,n'α) reaction on ^{48}Ti and ^{51}V should have small cross sections.

Integrated cross sections for the reactions studied are listed in Table 1. For these nuclei, large charged particle cross sections appear to be correlated with large compound nuclear contributions. Deuteron production cross sections are small for all the nuclei studied to date, and proton and alpha particle cross sections are small for nuclei with small neutron binding energies (i.e., those which are neutron-rich). Large variations (a factor of three or more) occur between proton and alpha production cross sections for various isotopes of the same element.

The development of this spectrometer has enabled charged particle spectra produced by neutron-induced reactions at E_n = 15 MeV to be measured over the range 1 to 15 MeV in emission energy. The signal-to-background ratio is increased significantly through use of the quadrupole lens between target and detector, with the result that charged particles with energies as low as 1 MeV could be detected. Data obtained to date indicate that for

Table I

Summary of Proton, Deuteron and Alpha Particle Cross Sections Measured with the Magnetic Quadrupole Spectrometer at 15-MeV Incident Neutron Energy. The errors on the proton, deuterons and alpha production cross sections are typically ± 12%, ± 40%, and 16% respectively.

Target	σ(n,xp)(mb)	σ(n,d)(mb)	σ(n,xα)(mb)
^{27}Al	405	19	121
^{46}Ti	664	9	98
^{48}Ti	85	2	28
^{51}V	91	7	17
SS316	252	8	48
^{63}Cu	323	9	56
^{65}Cu	44	9.8	13.5
^{93}Nb	51	8.5	14

many targets the total charged particle cross section will be significantly underestimated unless the measurements extend to energies below the Coulomb barrier.

Nuclei in the region already investigated have cross sections sufficiently large that the present spectrometer yields acceptable count rates. To extend these measurements to isotopes with smaller cross sections, an increased efficiency would be desirable. Efforts are presently underway to develop a detector telescope of larger area than presently used. A proportional-counter would serve as the ΔE detector and a larger area surface barrier detector would be the E detector. These modifications would increase the counting rate by about a factor of five and would allow cross sections as small as a few millibarns to be measured with good signal-to-background ratios.

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FIGURE CAPTIONS

Figure 1. Schematic drawing of the magnetic-quadrupole charged-particle spectrometer for neutron-induced reactions.

Figure 2. Raw data at one magnet setting for the proton spectrum at 45° from 15-MeV neutron bombardment of ^{27}Al. The proton production angle was 45° with respect to the incident neutrons. The circles denote data with a 2.4 mg/cm^2 aluminum foil in and the x's denote background with the foil out. The solid line is the measured acceptance function of the spectrometer.

Figure 3. Proton and deuteron spectra from 15-MeV neutron bombardment of ^{51}V. The data are integrated over the angular distribution of emitted particle. The curves are statistical model calculations described in Ref. 5.

Figure 4. Proton and deuteron spectra from 15-MeV neutron bombardment of ^{93}Nb. The data are integrated over the angular distribution of the emitted particle. The curves are statistical model calculations described in Ref. 5.

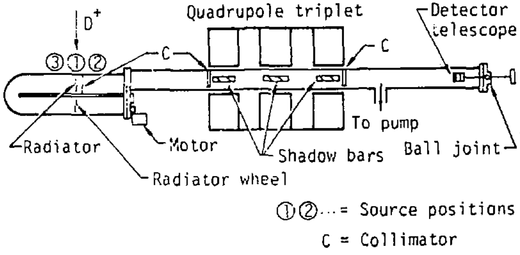

Figure 1

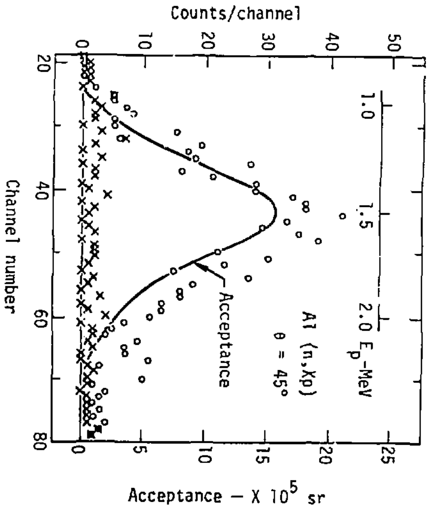

Figure 2

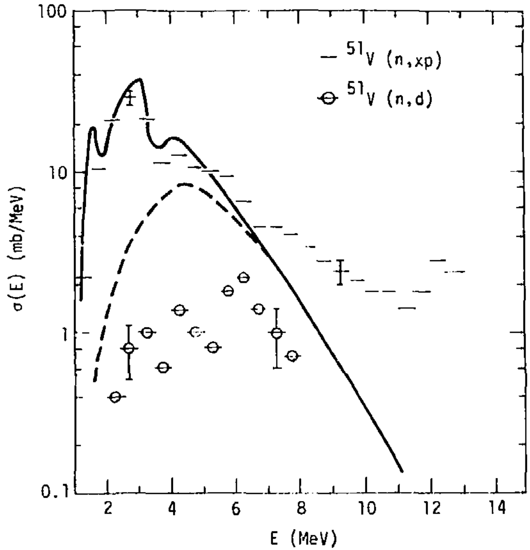

Figure 3

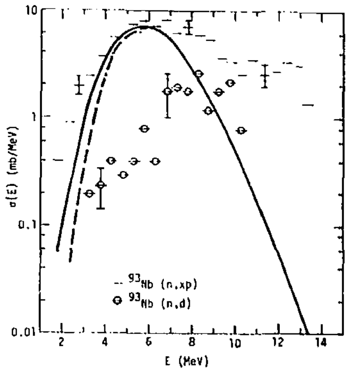

Figure 4