LA-UR- 97-1792

CONF-970512--16

Approved for public release; distribution is unlimited.

Title:

CHARGED PARTICLES PRODUCED IN NEUTRON REACTIONS ON NUCLEI FROM BERYLLIUM TO GOLD

RECEIVED
AUG 14 1997
OSTI

Author(s): Robert C. Haight, LANSCE-3

Submitted to: International Conference on Nuclear Data for Science and Technology, Trieste, Italy, May 19 - 24, 1997

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. The Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

CHARGED PARTICLES PRODUCED IN NEUTRON REACTIONS ON NUCLEI FROM BERYLLIUM TO GOLD

R. C. HAIGHT

Los Alamos National Laboratory
Los Alamos, NM 87545 USA

ABSTRACT

Charged-particle production in reactions of neutrons with nuclei has been studied over the past several years with the spallation source of neutrons from 1 to 50 MeV at the Los Alamos Neutron Science Center (LANSCE). Target nuclides include 9Be, C, 27Al, Si, 56Fe, 59Co, 58,60Ni, 93Nb and 197Au. Proton, deuteron, triton, 3He and 4He emission spectra, angular distributions and production cross sections have been measured. Transitions from the compound nuclear reaction mechanism to precompound reactions are clearly seen in the data. The data are compared with data from the literature where available, with evaluated nuclear data libraries, and with calculations where the selection of the nuclear level density prescription is of great importance. Calculations normalized at En = 14 MeV can differ from the present data by a factor of 2 for neutron energies between 5 and 10 MeV.

[Experimental work was performed with: S. M. Sterbenz, F. B. Bateman, T. M. Lee (Los Alamos), S. M. Grimes, C. E. Brient, F. C. Goeckner, R. S. Pedroni, V. Mishra, N. Boukharouba (Ohio University), O. A. Wasson (National Institute of Standards and Technology), H. Vonach (IRK Vienna) and P. Maier-Komor (TU Munich). Theoretical work is by M. B. Chadwick and P. G. Young (Los Alamos).]

1 Introduction

Although neutron-induced charged-particle production has been studied since the beginning of nuclear physics, detailed studies of the emission of protons, deuterons, tritons, 3He and alpha particles continue to challenge experimenters. The data base, which has increased rapidly in the last decade, is still modest in spite of increased demands for such data in basic and applied nuclear science. Present day needs include data over a much wider range of neutron energies and for previously unmeasured nuclides.

This report is on experimental work [1-6] performed at the Los Alamos Neutron Science Center (LANSCE) over the past few years. Our neutrons are produced by a spallation neutron source and cover the range from threshold to about 50 MeV. We observe the charged particles produced at four angles, but we have continuous coverage in neutron energy. These measurements are therefore complementary to other techniques.

A broad range of physics accessible through these techniques includes the determination of nuclear level densities, the transition of the nuclear reaction mechanism from primarily compound nuclear reactions to pre-equilibrium reactions, the general phenomena of pre-equilibrium particle emission, emission of clusters (e.g. deuterons, tritons, 3He and alpha particles), and, for light nuclei, inclusive reaction studies of three- and four-body final states. Applications of the data are to hydrogen and helium production for radiation damage studies and assessments for nuclear energy designs, neutron heating through KERMA factors, microdosimetry for biomedicine, and radiation effects in semiconductors used in computer chips for aeronautics and space and for large-scale physics experiments.

2 Experimental Approach

Fast neutrons are produced by the Target-4 spallation neutron source at LANSCE, also known as the WNR Spallation Neutron Source, by the interaction of the 800 MeV proton beam with a tungsten target. This source has been described at length in previous reports [7,8], and only a brief summary of typical parameters will be given here. The source is pulsed by using a highly bunched proton beam with a pulse width of 200 ps, and the pulse separation is typically 1.8 microseconds. Because the produced neutrons can undergo further scattering in the production target, the effective pulse width for the measurements discussed here is about 1 ns. There is, in addition, a macropulse structure characteristic of the LANSCE linear accelerator. We use the flight path at a neutron production angle of 90 degrees to emphasize neutrons below 50 MeV and de-emphasize higher neutron energies. The spectrum of neutrons produced has a broad peak around 2 MeV with a tail that extends up to at least 600 MeV [8]. For the measurements discussed here, the neutron beam is collimated to a beam 5 cm in width and height and is incident on samples foils 9.1 meters from the neutron source. Typical samples are thin foils, self-supporting where possible, of 10 cm diameter placed in the center of a reaction chamber. We have been fortunate to obtain isotopically enriched foils of isotopes of iron, nickel and 10B as well as very thin samples of silicon from our coworkers [1].

Charged particles are detected by four detectors at angles of 30, 60, 90 and 120 degrees with respect to the incident neutron beam. A diagram of this arrangement has been presented previously [2]. This selection of angles was chosen primarily to investigate the emission of particles from compound nuclei. It was also constrained by the size of an available reaction chamber and the need to add neutron shielding in the chamber. Detectors consist of two- or three-element coincidence counters. The first elements are either low-pressure gas proportional counters or silicon surface barrier detectors, both used as transmission detectors to identify the particle type. The second elements are silicon surface barrier detectors 500 microns thick and 450 mm^2 in area, and these are used for good timing (better than 3 ns over the entire range). The third elements are 1 cm thick CsI(Tl) scintillators viewed by photodiodes, and these allow us to stop protons up to 50 MeV. Signals from these detectors are processed by conventional electronics and analyzed by CAMAC-based FERA systems [9], which allow us to accumulate data quickly and then read out the data between macropulses.

3 Typical Data

The physics of charged-particle emission involves several different and competing reaction mechanisms, which vary in their relative importance for emission of protons, deuterons, tritons, 3He and alpha particles. Cross sections for producing all but protons and alpha particles are rather small at the neutron energies we have studied up to 50 MeV, and our data analysis is further along for alpha-particle emission. Therefore the following discussion will focus on (n,xalpha) reactions.

Typical alpha-particle emission spectra are shown En= 24-26 MeV (24-28 MeV for 197Au) in Figure 1 for three samples where the predominant reaction mechanisms are very different: 9Be, 60Ni, and 197Au. [This incident neutron energy was chosen to illustrate the capability to provide data where there are significant gaps in the literature. The regions from 8 to 13 MeV and above 15 MeV are particularly problematic for monoenergetic neutron sources. Our data treat all neutron energies on an equal footing.] In 9Be, the reaction mechanism is complex and includes components from sequential particle emission and from three and four-body phase-space disintegration of the compound nucleus, 10Be, into 2 neutrons and 2 alpha particles. The physics of this reaction is discussed in another paper in this conference [10]. The reaction on 60Ni proceeds primarily by statistical decay of the compound nucleus, and is controlled by factors such as the nuclear level density in the residual nuclei both from the (n,alpha) reaction as well as competing channels such as (n,n'). Statistical emission from the compound nucleus 198Au in the third example is dominated by neutron emission because of the large Coulomb barrier against the emission of charged particles. Therefore the alpha-particle emission spectrum here is primarily due to pre-equilibrium emission.

Statistical emission from the compound nucleus has been our principal focus so far. The example of alpha-particle production from nickel isotopes can be understood in a pictorial way, and here we refer to a companion paper in this conference [11]. Total alpha-particle production has been measured in the range from threshold to 50 MeV for 58Ni,60Ni, and 59Co (Figure 2). The threshold and magnitude of the cross sections depends on the Q-value for the (n,alpha) reaction whose competition comes mainly from neutron emission from the compound nucleus, that is from the (n,n') reaction, which has a Q-value of zero. Because 58Ni has a very low level density due to being very close to a doubly-closed shell nucleus, neutron emission from the compound system 59Ni competes weaker with alpha-particle emission than in the other compound nuclei, 61Ni and 60Co. Thus the cross section for alpha-particle production is significantly higher in 58Ni than for 60Ni and 59Co. For all of these nuclides, the alpha-particle production is seen to increase nearly monotonically in the full region up to 50 MeV.

Evidence for what we call "alpha-particle trapping" appears the alpha-particle emission spectra from the 60Ni sample. Alpha-particles can be "trapped" in excited nuclear levels if these levels cannot readily decay by neutron or proton emission. For such states, the only competing channel is the relatively slow gamma-ray decay. For excited states in 60Ni, reached by 60Ni(n,n'), the region between 6.29 MeV (the alpha-particle separation energy) and 9.53 MeV (the proton separation energy) (see Figure 3) satisfies the trapping requirements. Since emission of zero-energy alpha particles or protons is impossible because of the Coulomb barrier, the trapping region is more like 9.5 MeV (so that the alpha particle can have at least 3 MeV) and 11.5 MeV (where the proton can have no more than 2 MeV). This region of excitation in 60Ni will be populated by 60Ni(n,n') for incident neutrons beginning from about 10.5 MeV due to the fact that the emission temperature is on the order of 1 MeV [12]. Above 13 MeV or so, this trapping region will be reached less often because of the higher level density at higher excitations. Figure 4 shows the presence of low-energy alpha particles (Eα = 3-6 MeV) for En=11.5-12 MeV and not for 9-9.5 MeV. The transition is smooth from the onset at about 9.5 MeV to a maximum near 12 MeV and then decreasing at higher energies.

4 Future Directions

Because of the complementarity of spallation and monoenergetic neutron sources, it is clear that both need to continue vigorously in the measurement of neutron-induced charged-particle production. We are in the process of extending our studies to more angles, to better definition of the angle of production, to a larger solid angle for particle detection, to the use of other isotopic samples, and to higher neutron energies. Energy variations of the cross sections and spectra can be studied well with the spallation source, and we are concentrating on the measurement of possible fluctuations [see e.g. Ref. 11]. Finally, higher neutron energies are of interest for applications including medical radiotherapy, dosimetry, accelerator transmutation of waste, and radiation effects on semiconductors. An increased emphasis on precompound particle emission and perhaps multiple particle emission is also expected and needs to be investigated. For these reasons, we are establishing a capability to go to at least 150 MeV neutron energy. A more forward angle for neutron production will be chosen to increase the flux of the high energy neutrons on the samples.

References:

1. The experimental work here was done in collaboration with many researchers including S. M. Sterbenz, F. B. Bateman, T. M. Lee (LANL), S. M. Grimes, C. E. Brient, R. S. Pedroni, N. Bouhkarouba, V. Mishra (Ohio University), O. A. Wasson, A. Carlson (NIST), H. Vonach (IRK, Vienna), and P. Maier-Komor (TU-Munich). Theoretical analysis and calculations are due to M. B. Chadwick and P. G. Young (LANL).
2. S. M. Grimes, C. E. Brient, F. C. Goeckner, F. B. Bateman, M. B. Chadwick, R. C. Haight, T. M. Lee, S. M. Sterbenz, P. G. Young, O. A. Wasson, and H. Vonach, "The 59Co(n,α) Reaction from 5 to 50 MeV," Nucl. Sci. Eng. **124**, 271 (1996).
3. R. C. Haight, F. B. Bateman, S. M. Sterbenz, S. M. Grimes, O. A. Wasson, P. Maier-Komor and H. Vonach, "An Update on (n,charged particle) Research at WNR," Proc. International Workshop on Nuclear Data, Del Mar, California, December, 1995, and in Fusion Technology (to be published).
4. S. M. Sterbenz, F. B. Bateman, T. M. Lee, R. C. Haight, P. G. Young, M. B. Chadwick, F. C. Goeckner, C. E. Brient, S. M. Grimes, H. Vonach, and P. Maier-Komor, "The 56Fe(n,xα) Reaction from Threshold to 30 MeV," Proc. Int. Conf. Nuclear Data for Science and Technology, ed. J.K. Dickens, Gatlinburg, Tennessee, May 9-13, 1994 (American Nuclear Society, LaGrange Park, Illinois, 1994) p. 314.
5. R. C. Haight, T. M. Lee, S. M. Sterbenz, F. B. Bateman, S. M. Grimes, R. Pedroni, V. Mishra, N. Boukharouba, F. C. Goeckner, O. A. Wasson, and H. Vonach, "Alpha-particle Emission from Carbon Bombarded with Neutrons Below 30 MeV," Proc. Int. Conf. Nuclear Data for Science and Technology, ed. J.K. Dickens, Gatlinburg, Tennessee, May 9-13, 1994 (American Nuclear Society, LaGrange Park, Illinois, 1994) p. 311.
6. R. C. Haight, T. M. Lee, S. M. Sterbenz, F. B. Bateman, S. M. Grimes, R. Pedroni, V. Mishra, N. Boukharouba, F. C. Goeckner, O. A. Wasson, A. D. Carlson, C. M. Bartle, P. Maier-Komor, and H. Vonach, "Neutron-induced Charged-particle Emission Studies below 100 MeV at WNR, " Proc. Int. Conf. Nuclear Data for Science and Technology, ed. J.K. Dickens, Gatlinburg, Tennessee, May 9-13, 1994 (American Nuclear Society, LaGrange Park, Illinois, 1994) p. 154.
7. P. W. Lisowski, C. D. Bowman, G. J. Russell, S. A. Wender, Nucl. Sci. Eng. **106**, 208 (1990).
8. H. Condé, R. Haight, H. Klein and P. Lisowski, Proc. Int. Conf. on Nuclear Data for Science and Technology, Jülich 13-17 May, 1991, ed. S. M. Qaim, (Springer-Verlag, Berlin 1992) p. 386
9. FERA: Fast Encoding and Readout ADC Data Acquisition System, Lecroy Research Systems Corporation, Chestnut Ridge, New York.

10. V. G. Pronyaev, S. Tagesen and H. Vonach, "Reaction Mechanisms in the Be-9 + n Systems Leading to the Decay into Two Neutrons and Two Alpha Particles," this Conference.
11. R. C. Haight, F. B. Bateman, S. M. Sterbenz, M. B. Chadwick, P. G. Young, S. M. Grimes, O. A. Wasson, P. Maier-Komor, H. Vonach, "The 58,60Ni(n,xalpha) Reactions from Threshold to 50 MeV," this Conference.

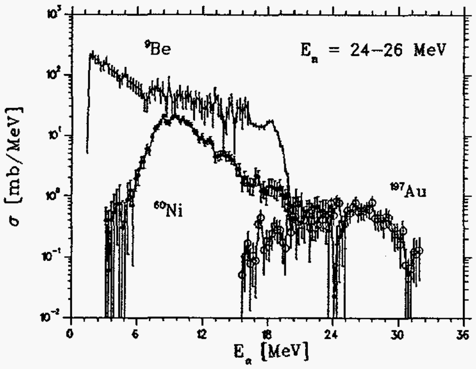


Figure 1 - Alpha particle emission spectra from Be, 60Ni and Au for neutron energies from 24 to 26 MeV (24-28 MeV for Au). The beryllium data are at 30 degrees and multiplied by 4π; the others are angle-integrated.

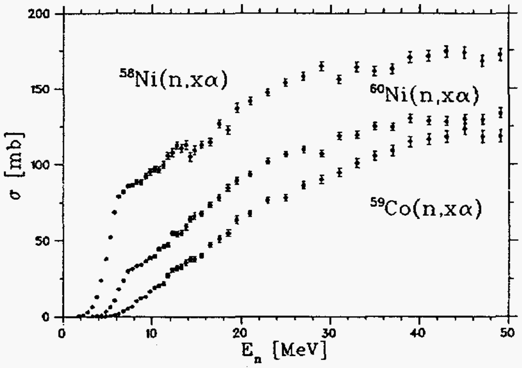
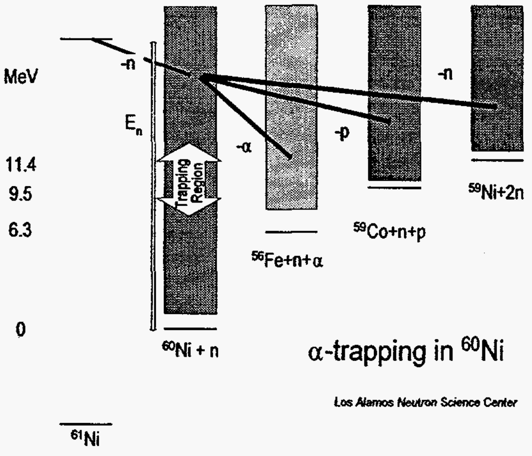


Figure 2 - Cross section for alpha-particle production as a function of neutron energy for 58Ni, 60Ni, and 59Co.



Los Alamos Neutron Science Center

Figure 3 - Energetics of neutron-induced reactions on 60Ni.

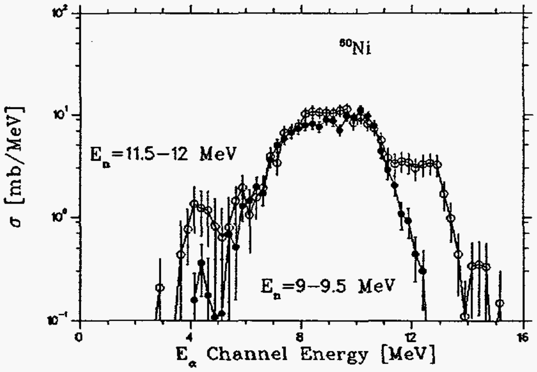


Figure 4 - Angle-integrated alpha-particle spectra for the 60Ni sample for neutron energies of 9-9.5 MeV (solid circles) and 11.5-12 MeV (open circles). The excess alphas between 3 and 6 MeV for the higher incident neutron energy indicate alpha-particle trapping.