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New Approaches To Nuclear Level Densities Through Particle Emission Measurements*

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Abstract. With the intense spallation neutron source at the Los Alamos Neutron Science Center (LANSCE), new approaches to nuclear level densities are being explored through neutron-induced reactions and measurements of the resultant particle emission. This continuous-in-energy neutron source has been used to study Ericson fluctuations, charged-particle emission cross sections and spectra, gamma-ray production and, recently, neutron emission. Examples of each will be discussed. The FIGARO array of neutron and gamma-ray detectors has been developed in the past year to allow measurement of neutron emission in a "double time-of-flight" experiment. The incident neutron energy is determined by time-of-flight over a 21-meter flight path with gamma rays from the induced reaction. Neutron emission spectra from this reaction are then measured by time-of-flight over a flight path of typically 1 meter. Data on ^{56}Fe(n,n') and other inelastic reactions are presented, and the relevance to determination of nuclear level densities are discussed.

INTRODUCTION

The density of excited nuclear levels continues to be a subject of great interest in basic and applied nuclear science. Recent developments in calculating the nuclear level density by Monte Carlo shell model methods [1] and combinatorial approaches (for example Ref. [2]) make use of basic theoretical developments and high-speed computers. The connection between level densities at the neutron separation energy and the structure and symmetry of low-lying levels is also being vigorously pursued [3].

On the experimental side, steady progress is being made in characterizing the low-lying excited states of nuclei and in resonances just above the neutron separation energy [4]. Particle-emission studies were carried out several years ago with reactions induced by light charged particles (e.g. Ref. [5]) to shed light on the density of unresolved levels with excitation between the low-lying resolved states and the neutron separation energy. These studies were sensitive also to the angular momentum dependence of the nuclear level density especially as it is described by the spin cut-off parameter in semi-empirical descriptions such as that of Ignatyuk [6]:

$$\rho(U,J)=\frac{2J+1}{24\sqrt{2}a^{1/4}(U-\delta)^{5/4}\sigma^3}\exp[2\sqrt{a(U-\delta)}-\frac{(J+1/2)^2}{2\sigma^2}]$$

where the level density parameter varies with excitation energy

$$a(U)=a\{1-[1-\exp(\gamma U))\delta W/U\}$$

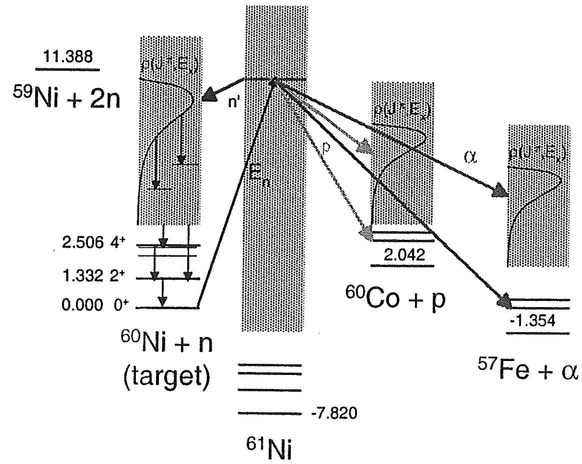
Modern theories indicate that the nuclear level density is more complex than this formulation. The spin-cutoff parameter describes only very approximately the angular momentum dependence. The transition between low-lying states of well-characterized symmetry and higher-lying states that merge into a Fermi gas is also not treated well in detail. And, perhaps most importantly, the experimental data base is extremely sparse, consisting generally of low-lying resolved levels and resonances of spin J$\pm$1/2 and J$\pm$ 3/2 just above the neutron separation energy. For a few medium-mass nuclides, there are also charged particle resonance data, which have been essential in discussions of the distribution of level spacings, widths, and parity ratios.

The increasing capabilities of spallation neutron sources have made possible experimental studies of reactions to provide data to test models of nuclear level densities. Particle-emission measurements together with gamma-ray production can be made over a wide range of incident neutron energies. This paper surveys our work at the Los Alamos Neutron Science Center (LANSCE) in charged-particle emission studies and the development of techniques to measure neutron-emission, all as functions of incident neutron energy.

DETERMINATION OF NUCLEAR LEVEL DENSITIES FROM NEUTRON-INDUCED REACTIONS

The type of reactions discussed here are shown in Figure 1. Here we take as an example neutron-induced reactions on ^{60}Ni with the resultant products being neutrons, protons, or alpha particles and leaving the residual nuclei in excited states that decay principally by gamma-ray emission. The emission spectra of these particles are determined by their transmission probability and by the available phase space, which is the nuclear level density in the residual nucleus. Both of these factors depend on the energy of the emitted particle and, correspondingly, the excitation energy in the residual nucleus. If the reaction proceeds through a compound nucleus, then the emission probability is a competition among the outgoing channels.

FIGURE 1. Schematic representation of the possible reactions of a neutron with ^{60}Ni showing the formation of the compound excited nucleus ^{61}Ni and



the channels reached by emission of a neutron, proton or alpha particle.

With a neutron source that is continuous in energy, a distribution of excited states in the compound nucleus, ^{61}Ni in this case, is sampled. When the excitation energy is not too high, the widths of these excited states can be comparable to their spacing. The resulting fluctuations can be analyzed for the nuclear level density.

Ericson Fluctuations

The approach of Ericson [7] relates the fluctuations in the excitation functions of nuclear reaction cross sections to nuclear level densities for the case of compound nuclear reactions where the level widths in the compound nucleus are comparable to their spacing. Spallation neutron sources can have very narrow pulse widths so that the time-of-flight technique gives excellent resolution for the energy of the incident neutron if a sufficiently long flight path is used. Examples of such experiments are the good resolution total cross section measurement of silicon [8] and the related (n,p) and (n,alpha) reactions on silicon to resolved final states [9]. Typical data for the latter are shown in Fig. 2 where the overall energy resolution is approximately 20 keV at 8 MeV incident neutron energy, due to the 3 ns resolution of the detector. If that resolution were better, then the overall resolution at 8 MeV could be reduced to better than 10 keV with a slightly modified neutron production target.

The range of excitation energies probed by fluctuations is of course well above the neutron separation energy. For silicon, it is in the range of 13–23 MeV in ^{29}Si, a range difficult to access by other methods. For heavier nuclides, the excitation energy range is lower because of the larger level density. The level densities resulting from the fluctuation analysis appear to be consistent to 50% or so, which is not as precise as one might wish. But the uniqueness of this approach in this energy range makes the fluctuation studies still very attractive.

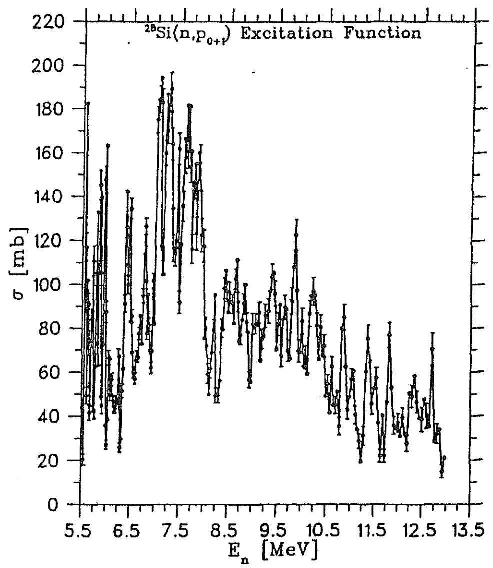


FIGURE 2. Excitation function of the $^{28}Si(n,p)^{28}Al$ reaction where the residual ^{28}Al nucleus is left in either the ground or first excited state.

Smooth Excitation Functions

In the statistical decay of a compound nucleus, the probability of a particular reaction channel depends on the competition with other channels. The cross section for a particular channel decreases as other channels open up, and this effect has been used to deduce the level density for states populated by the competing channels. [10]. For inclusive reactions such as (n,alpha), not only does the number of competing channels increase with neutron energy, but the number of (n,alpha) channels also increases. Thus there is a competition between inclusive reactions such as (n,n') and (n,alpha).

An example of data taken at WNR/LANSCE is for the ^{60}Ni(n,xalpha) excitation function which is dominated by the (n,alpha) channel for neutron energies below 10 MeV. The principal competing channel in (n,n'). Because the level density in the residual nucleus ^{57}Fe from the (n,alpha) reaction is well known, the cross section for this reaction depends on the level density of excited states in ^{60}Ni populated by (n,n'). Figure 3 gives an example of the data, which have led to better understanding of the level density in ^{60}Ni [11].

This approach has the advantage of putting level densities to a stringent test in accounting for cross sections. The disadvantage is that the nuclear level density probed is averaged over a range of excitation energies, in this case over at least a 1 MeV range of excited states in ^{60}Ni. In cases where the level density is not known in any of the residual nuclei, only ratios of level densities can be inferred.

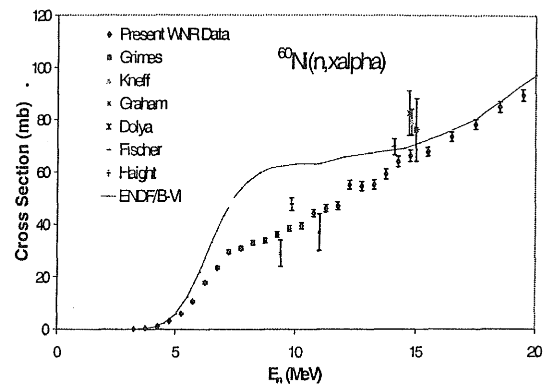


FIGURE 3. Excitation function of the ^{60}Ni(n,xalpha) reaction showing the WNR/LANSCE data compared with other measurements and the ENDF/B-VI evaluation.

Charged-Particle Emission Spectra

Charged-particle emission spectra have been measured in reactions induced by protons and alpha particles to infer nuclear level densities (e.g. Ref. Sherr). Neutron-induced reactions can also be used for the same purpose and with some advantages: the residual nuclei are usually different; (n,p) reactions are in general influenced less by direct reactions than (p,p'); and, with a continuous-in-energy neutron source, the evaporation spectra as a function of incident neutron energy can indicate the presence of non-statistical reaction mechanisms. Figure 4 shows, at the higher neutron energy, the onset of pre-equilibrium proton emission from Ref. [12].

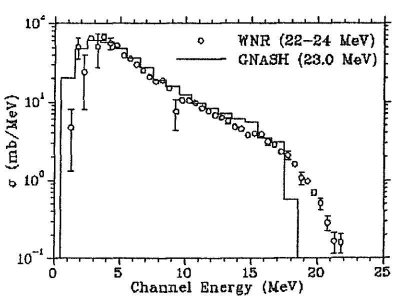


FIGURE 4. Proton emission spectrum from neutron reactions with silicon at incident neutron energies 22-24 MeV.

Particle-emission spectra are particularly useful as they make the connection between the resolved low-lying levels and the unresolved levels at higher excitation energy. Thus the spectra can be normalized where we know quite well the nuclear level density and then be used to infer the level density at higher excitation.

Neutron Emission Spectra

To complete the suite of neutron-induced reactions, we are beginning to measure neutron emission spectra induced by spallation neutrons at WNR/LANSCE. The goal, besides providing data for applications, is to investigate nuclear level densities through (n,n') and other reactions. Neutron emission spectra have been measured before with monoenergetic neutrons, but not generally only a few incident neutron energies have been investigated. For neutron energies where there are no truly monoenergetic source, such as in the "gap region" between 8 and 13 MeV and above 17 MeV, the data in the literature are very sparse.

Our approach is to tag the interaction by detecting a gamma ray. Neutrons emitted from the reaction are then detected by time-of-flight from the sample to neutron detectors 1 to 2 meters away. An example of very recent data for iron, tagged by the 847 keV gamma-ray in ^{56}Fe, is shown in Figure 5. Besides the observed discrete emitted neutron bands, the continuum emission, as a function of incident neutron energy, will show any evidence of non-statistical emission and will reflect the nuclear level density with a "filter" of the required 847 keV gamma rays. With a high-resolution gamma ray detector, other gamma-ray transitions will offer different filters in angular momentum and excitation energy. Further details on the technique are given in Ref. [13].

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REFERENCES

1. Y. Alhassid, *Proc. 11th Int. Symp. on Capture Gamma-Ray Spectroscopy and Related Topics,* Pruhonice,Czech Republic, September 2-6, 2002 (to be published).
2. S. Hilaire, thesis.
3. T. von Egidy, *Proc. 11th Int. Symp. on Capture Gamma-Ray Spectroscopy and Related Topics,* Pruhonice,Czech Republic, September 2-6, 2002 (to be published).
4. S. Mughabgab, private communication (2002).
5. R. Sherr and F. P. Brady, Phys. Rev. 124, 1928 (1961).
6. A. V. Ignatyuk, G. N. Smirenkin and A. S. Tishin, Yad. Fiz. 21, 485 (1975); Sov. J. Nucl. Phys. 21, 255 (1975).
7. T. Ericson, Phys. Rev. Lett 5, 430 (1960); Ann. Phys. (N.Y.) 23, 340 (1963).
8. V. Mishra, N. Boukharouba, S. M. Grimes, K. Doctor, R. S. Pedroni, and R. C. Haight, Phys. Rev C44, 2419 (1991).
9. F. B. Bateman, S. M. Grimes, N. Boukharouba, V. Mishra, C. E. Brient, R. S. Pedroni, T. N. Massey, and R. C. Haight, Phys. Rev. **C55**, 133 (1997).
10. J. R. Huizenga, H. K. Vonach, A. A. Katsanos, A. J. Gorski, and C. J. Stephan, Phys. Rec. 182, 1149 (1969).
11. C. Y. Fu, Nucl. Sci. Eng. 135, 246 (2000).
12. F. B. Bateman, R. C. Haight, S. M. Sterbenz, M. B. Chadwick, P. G. Young, and S. M. Grimes, Phys. Rev. C **60**, 064609-1 (1999).
13. R. C. Haight, J. M. O'Donnell, L. Zanini, M. Devlin, and D. Rochman, *Proc. 11th Int. Symp. on Capture Gamma-Ray Spectroscopy and Related Topics,* Pruhonice,Czech Republic, September 2-6, 2002 (to be published).

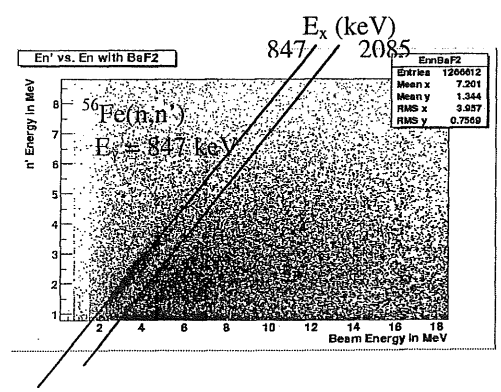

FIGURE 5. Neutron emission spectrum from neutrons incident on iron from 2 to 20 MeV.