HIGH NUCLEAR EXCITATION AS A NUCLEAR FORCE PROBE

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In the years since Bethe[1] first derived a statistically based expression for the energy level densities in excited nuclei, particle evaporation experiments at energies in excess of 20 Mev such as that of Eisberg and Igo[2] have shown a disappointing fit to theory. Temperatures deduced from particle evaporation spectra are too low, or what amounts to the same thing, the energy level densities apparently increase faster with excitation energy then the simple theory based on a square or harmonic oscillator well predicts. It is the purpose of this short note to point out (1) that this is to be expected from actual nuclei because of the diffuseness of the actual nuclear potential well and (2) that level densities of highly excited nuclei are a sensitive measure of the details of the shape of the nuclear potential well.

As an example of the effect of the shape of the nuclear potential well on nuclear temperature and energy level density, a calculation was carried out using the diffuse well shape adopted by Ross, Mark, and Lawson[3] to fit Barschall's[4] low-energy neutron scattering data:

$$V(r) = V_0/\{1 + \exp[b(r - a)]\}. \qquad (1)$$

Using the WKB approximation and adopting the empirically fitted constants of Ross et al., the individual-particle level density above the Fermi level was found to be conveniently approximated by the formula

$$\varphi(\epsilon) = c\epsilon^{1/2}[1 + 0.02(\epsilon - \epsilon_f)^2], \qquad (2)$$

where ϵ is expressed in Mev and the first term alone is the expression for the square well.

Closely following the development of the electron theory of metals[5] and assuming a free nucleon gas in the potential well given by Eq. (1), the excitation energy as a function of gas temperature was easily derived:

$$Q \approx \left(\frac{\pi}{2}\right)^2 \frac{N}{\epsilon_f}(kT)^2 - \frac{3}{5}\left(\frac{\pi}{2}\right)^4 \frac{N}{\epsilon_f{}^3}(kT)^4 + 0.171\frac{N}{\epsilon_f}(kT)^4$$
$$\equiv \alpha(kT)^2 + \beta(kT)^4, \qquad (3)$$

where kT and all other energies are expressed in Mev, N is the number of nucleons, and ϵ_f is the Fermi energy, the energy of the last filled state at zero temperature. The first two terms result from a square well. The third term resulting from the nuclear lip is one hundred times as large as the second term which was justifiably ignored in previous work. Contrary to the square well $(kT)^4$ dependence, the nuclear lip introduces a sizable fourth power dependence on the temperature as illustrated in Table I for $N = 100$. Bethe[1] had treated the dependence of nuclear level density on temperature in a more general way than for the quadratic dependence customarily adopted, by calculating the nuclear level density for an arbitrary power relationship between Q and T. Similarly Rosenzweig[6] has recently estimated the nuclear level density for an arbitrary power relationship between $\varphi(\epsilon)$ and ϵ. The over-all nuclear level density is found by taking the inverse Laplace transform of the Helmholz free energy[7] which in turn was easily derived from Eq. (3):

$$\rho(Q) = \alpha^{1/4}\pi^{1/2}Q^{-3/4}\exp[2(\alpha Q)^{1/2} + \tfrac{1}{3}\beta(Q/\alpha)^{3/2}]. \qquad (4)$$

For β and α derived from 1-3 Mev neutron scattering experiments, the additional term in the exponential would yield a factor of 35 in the level density at excitation energies of 50 Mev, a factor of only 2.4 at 20 Mev.

Several details such as separate wells for neutrons and protons, orbital momentum effects, pairing, and spin-orbit coupling should be incorporated into this simple theory; but the primary effect of the nuclear well shape appears straightforward. Precise determinations of particle spectra should prove very useful in determining the shape and extent of the over-all nuclear force field. The usefulness of the data increases rapidly with excitation energy and indeed, the method is limited to excitation energies in excess of 20 Mev.

It is hoped that this correction to the high-

Table I. The rise in calculated temperature with excitation energy for a diffuse well as compared with that for a square potential well.

Q (Mev)	7	14	28	44	63
kT (square well)	1.0	1.4	2.0	2.5	3.0
kT (diffuse well)	0.94	1.3	1.7	2.0	2.3

energy theory will extend the excellent recent interpretation of thermal neutron cross sections by Rosenzweig,[6] Bloch,[8] and Ross.[9] Particle spectra from highly excited nuclei are currently being interpreted with a more elaborate theoretical treatment in order to arrive at the shape of the nuclear potential.

[1]H. A. Bethe, Revs. Modern Phys. 9, 69 (1937).
[2]R. M. Eisberg and G. J. Igo, Phys. Rev. 93, 1039 (1954).
[3]Ross, Mark, and Lawson, Phys. Rev. 102, 1613 (1956); 104, 401 (1956).
[4]H. H. Barschall, Phys. Rev. 86, 431 (1952).
[5]R. H. Fowler and E. A. Guggenheim, Statistical Thermodynamics (Cambridge University Press, Cambridge, 1952), Chap. XI, pp. 452-458.
[6]N. Rosenzweig, Phys. Rev. 105, 950 (1957); 108, 817 (1957).
[7]I. N. Snedden and B. F. Touschek, Proc. Cambridge Phil. Soc. 44, 391 (1948).
[8]C. Bloch, Phys. Rev. 93, 1094 (1954).
[9]A. A. Ross, Phys. Rev. 108, 720 (1957).

CAPTURE GAMMA RAYS FROM O^{15} AND O^{16} IN THE REGION OF THE GIANT RESONANCE*

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Measurements of the 90° yield ground-state γ rays resulting from the capture of protons into the giant resonance region of O^{15} and O^{16} have been using the Princeton FM cyclotron. This Letter reports principally the results of the reaction $N^{15}(p,\gamma)O^{16}$ ($Q = 12.11$ Mev).

The reaction $N^{15}(p,\gamma_0)O^{16}$ is the inverse of the reaction $O^{16}(\gamma,p_0)N^{15}$ where γ_0 and p_0 represent transitions to the ground state of the residual nucleus. The latter reaction has been studied by several authors[1-3] in the region of the giant resonance using the bremsstrahlung continuum as a source of high-energy photons. A detailed study of the giant resonance region of O^{16} is more readily made from the inverse process $N^{15}(p,\gamma_0)O^{16}$ using protons with a well-defined energy. The results of such a study are reported in this Letter for the region of excitation in O^{16} between 21 and 26 Mev. A detailed study of photodisintegration of O^{16} in this energy region has a particularly direct bearing on the understanding of the giant resonance phenomenon because the closing of the $1p$ shell at O^{16} allows a relatively explicit theoretical treatment to be made for this nucleus. Elliott and Flowers[4] have calculated the properties of the $J^\pi = 1^-$, $T = 1$ states arising from the $p^{-1}d$ and $p^{-1}2s$ configurations in O^{16}. These states are responsible for electric dipole absorption from the O^{16} ground state and should give rise to the giant resonance according to the Wilkinson[5] model which explains the giant resonance in terms of single-particle excitations of the ground state. Elliott and Flowers found their calculations to be in substantial agreement with previous[1,2] investigations of the $O^{16}(\gamma,p)N^{15}$ reaction so that it is of interest to test their shell-model predictions more fully.

The experimental details will be given in a fuller report of this investigation; only a brief description is given here. The external proton beam from the Princeton FM cyclotron was reduced in energy with polyethylene absorbers to extend the range of variability of the proton beam energy from its unattenuated range of 14.5 to 19.5 Mev, so as to cover the range of the giant resonance, 9.5 to 15 Mev. The beam passed through a cylindrical gas cell $1\frac{1}{2}$ in. long, $\frac{3}{8}$ in. in diameter, which contained N^{15} gas at a pressure of 930 mm Hg. The end windows of the cell were of 0.0005-in. Mylar sheet. The N^{15} gas used has an isotopic purity of 98.7%. Gamma radiation from the target was detected in a 3 in.×3 in. NaI crystal 7 cm from the center of the target, and the pulses were analyzed in a 200-channel analyzer gated on only for the duration of the cyclotron beam pulse. To minimize the effect of pulse pile-up in the counter, the current pulses from the photomultiplier were delay-line clipped to 0.2 μsec, and all pulses corresponding to an energy less than 10 Mev were eliminated at this stage by a biased transistor preamplifier. The larger pulses, passed by the biased preamplifier, were lengthened and fed to the analyzer.

Measurements were made at 29 proton energies. The beam current varied with energy, being about 3×10^{-5} μa at the lowest proton energy with the