Measurement of the Nuclear Level Density at High Spins

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The neutron spectrum from the reaction $^{92}Zr(^{64}Ni,1n)^{155}Er$ has been measured at an average spin of $52\hbar$ and for excitation energies between 30 and 36 MeV in ^{155}Er. Channel and spin selection have been obtained from the Darmstadt-Heidelberg Crystal Ball. The level density in ^{155}Er is derived within the framework of a Fermi-gas model. A level-density parameter of $a = A/(8.8 \pm 1.3)$ MeV^{-1} is deduced.

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The atomic nucleus constitutes a unique system in that it exhibits both microscopic features and statistical aspects commonly described in terms of a level density. The spin and excitation-energy dependence of the level density provides a stringent test for nuclear models. Moreover, since phase space governs the gross properties of a large class of nuclear reactions, a precise knowledge of the level density is required to understand all nuclear reactions involving statistical features. From the theoretical point of view, level densities are usually described in terms of a Fermi-gas model including shell effects which represent the impact of microscopic nucleonic motion on the average properties of nuclei.

Experimentally, the most direct and detailed information about nuclear level densities has been obtained from neutron-capture resonances.[1] Such information is, however, limited to low excitation energies and spins. The major source of knowledge about level densities at higher excitation energies and spins arises from particle-evaporation spectra in heavy-ion fusion reactions[2] analyzed in the framework of the statistical model. The information obtained so far, however, suffers from several uncertainties: The spin distribution of emitting nuclei is not known experimentally; moreover, the experimental particle spectra contain contributions from several steps in an evaporation cascade and, hence, represent a mix of spectra corresponding to the substantially different excitation energies. Consequently, full statistical-model calculations involving many additional parameters apart from the level densities are needed for a quantitative description of the various deexcitation steps.

In this Letter we present a new method to obtain direct information on nuclear level densities at high spins by measuring neutron spectra from heavy-ion fusion reactions in coincidence with a 4π multi-element γ-ray detector system. The Darmstadt-Heidelberg Crystal Ball was used to measure the spin distribution of the residual nuclei after neutron evaporation. As a consequence, it is possible to select the excitation energy and spin range for which the evaporation of *one and only one* neutron is the dominant exit channel. Such selection can be done with high efficiency because of the solid angle of almost 4π. Thereby, ambiguities involved in a comparison with a complex statistical-model calculation can be avoided.

The reaction $^{92}Zr(^{64}Ni,1n)^{155}Er$ at a bombarding energy of 239 MeV has been chosen for the present study. An isotopically enriched (95%) ^{92}Zr target of 320 $\mu g/cm^2$ was irradiated with a ^{64}Ni beam provided by the Max-Planck-Institut tandem postaccelerator facility at Heidelberg. The γ radiation from the residual nuclei was registered in 158 NaI modules of the Crystal Ball and in one Ge detector. Neutrons were detected with two 10×5-cm^2 cylindrical liquid scintillator counters (NE213) positioned at laboratory angles of 0° and 65° relative to the beam direction at a distance of 71 cm from the target. Standard pulse-shape discrimination techniques were applied to separate neutrons from γ

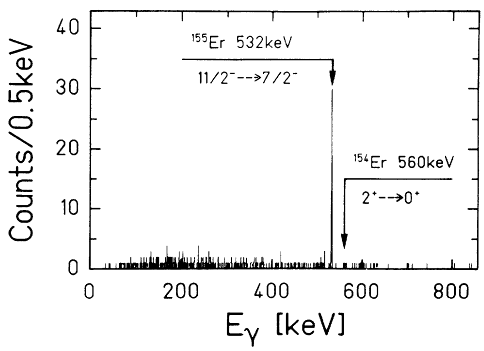

FIG. 1. Delayed Ge-detector spectrum for the fold cut (prompt fold > 31, delayed fold < 2) to select the $1n$ exit channel. The position of the isomeric transition in ^{154}Er is marked to illustrate the suppression of the $2n$ channel.

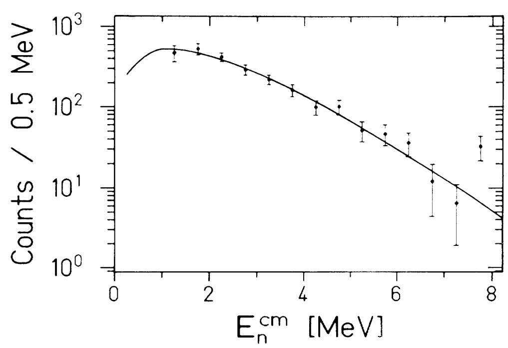

FIG. 2. Neutron spectrum for the same fold cut as in Fig. 1. The solid curve represents a least-squares fit to the data with use of Eqs. (1) and (2). The fit parameters are given in Table I.

rays. Neutron energy spectra were derived from the time of flight with respect to the pulsed beam. The neutron background due to scattering from the Crystal Ball elements and other surrounding material was measured separately by our placing cones of borated polyethelene (23 cm long) between the target and the neutron detectors. This contribution amounts to 6% of the observed neutron yield and was subtracted in the off-line analysis. The spectra have been corrected for the detector efficiency.[3] After transformation into the center-of-mass system both the spectral shape and yield at the two angles were found to be identical. Thus in the energy range studied there is no evidence for preequilibrium emission which would otherwise give rise to forward-peaked angular distributions as well as high-energy tails. Therefore, the spectra at 0° and 65° have been added to improve statistics.

The neutron spectrum from the $1n$ channel will directly reflect the level density of ^{155}Er, provided there is no significant competition from the $2n$ channel within the spin window to be selected. Such a contribution would bias the $1n$ spectrum towards higher energies. For $I_{CN} \geq 49\hbar$ the $1n$ channel is the dominant evaporation decay channel of the compound nucleus[4]; contributions from all other channels amount to less than 7%. This spin range can be selected by the requirement of more than thirty detectors responding per event within 5 ns of the beam pulse. Because of the finite multiplicity resolution, however, this fold cut contains contributions from ^{154}Er decays, arising from spins $I_{CN} < 49\hbar$. These contributions can be removed by the rejection of events with more than two delayed (10–110 ns) elements firing. The quality of this spin-range selection is demonstrated in Fig. 1 which shows the delayed (15–110 ns) Ge spectrum with this fold cut. Delayed transitions from the decay of the 11^- 40-ns isomer in ^{154}Er ($2n$ channel) are not observed.

Figure 2 shows the neutron spectrum under identical conditions after subtraction of the contribution due to neutron scattering from neighboring Crystal-Ball elements. A 10% contribution due to the $2n$ channel has also been subtracted. (Since the neutron multiplicity is 2, the actual channel yield is only 5%.) According to Blatt and Weisskopf[5] the $1n$ spectrum has been fitted with the expression

$$dN(\epsilon) = C\epsilon\rho(U)\,d\epsilon, \qquad (1)$$

where $U = E^* - B_n - E_{yr}(I) - \epsilon$ is the internal excitation energy of the residual nucleus, E^* is the total excitation energy, B_n the neutron binding energy, $E_{yr}(I)$ is the yrast energy at spin I, and ϵ is the average neutron kinetic energy. According to Snover[6]

$$\rho(U) = \left(\frac{\hbar^2}{2\Theta}\right)^{3/2} \frac{(2I+1)\sqrt{a}}{12(U+T)^2} \exp 2\sqrt{aU}. \qquad (2)$$

Here, Θ is the rigid-body moment of inertia, a the level-density parameter, and T the nuclear temperature with

$$U = aT^2 - T. \qquad (3)$$

The yrast energy at the corresponding average spin was determined by the extrapolation of the yrast line of ^{155}Er known[7] up to spin $\frac{85}{2}\hbar$ into the spin range of interest. The remaining free fit parameters are the level-density parameter a and the yield normalization constant C.

The results of the fits are listed in Table I. A level-density parameter $a = 17.6 \pm 1.4$ MeV^{-1} corresponding to $a = A/(8.8 \pm 1.3)$ MeV^{-1} is deduced. The error includes statistical and systematic errors, the latter mainly arising from the uncertainty in the absolute spin value,[4,8–10] estimated to be about $\pm 5\hbar$. The average

TABLE I. Inputs and results of the fit procedure.

$\langle I \rangle_{Er}$ ($\hbar$)	E^* (MeV)	$\langle E_{rot} \rangle$ (MeV)	C (MeV)	a (MeV^{-1})
52 ± 5	47.2 ± 1.7	17.6	$2.9^{+8.6}_{-2.0} \times 10^{-9}$	17.6 ± 1.4

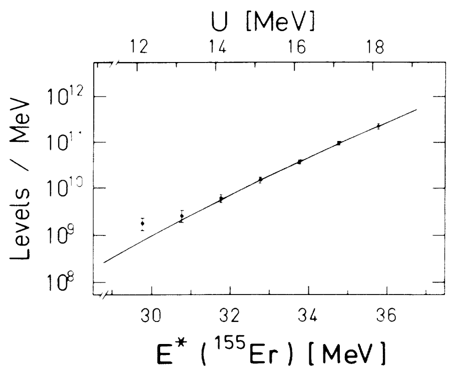

FIG. 3. Experimentally determined density of levels at an average spin of $52\hbar$ as a function of excitation energy in ^{155}Er. The excitation-energy interval is determined by the compound-nucleus excitation energy and the range of neutron energies measured. Only the statistical errors are indicated. Because of the error of the normalization constant C the absolute value of the level-density scale is uncertain by a factor of 4. The conversion of total excitation energy E^* into the intrinsic energy U has been performed for the average spin of $I_{\rm Er}=52\hbar$, with an extrapolation of the known yrast line. The solid line shows the result of a calculation with $a=(A/8.8)$ MeV^{-1}

excitation energy in ^{155}Er after neutron evaporation as determined from $E^*=47$ MeV and the neutron binding and average kinetic energies ($B_n=9.9$ MeV; $\langle\epsilon\rangle=2.2$ MeV) agree within 0.5 MeV with the average total γ-ray energy $E_{\rm sum}=34.6\pm1.0$ MeV registered in the Crystal Ball for the applied fold cut.

According to Eq. (1) the level density in the residual nucleus can be derived directly from the measured neutron spectrum by our dividing out the neutron energy and the constant C. The resulting level density for an average spin $\langle I\rangle_{\rm Er}=52\hbar$ is shown in Fig. 3 as a function of the excitation energy in ^{155}Er. The solid line shows the result of a calculation with $a=A/8.8$ using Eq. (2). This value is consistent with systematics[1] established for low excitation energies and spins.

It should be pointed out that, although energetically possible ($B_n=7.9$ MeV), a second neutron is not emitted at an average excitation energy of 17 MeV above the extrapolated yrast line in ^{155}Er. One possible explanation would be a reduction of the available thermal excitation energy, with the remaining energy tied up in deformation, possibly because of trapping in a superdeformed minimum[11] due to shell effects. (A superdeformed band was recently found in the neighboring nucleus ^{152}Dy.[12]) If the energy for neutron emission is reduced by 3 MeV (at $I\sim52\hbar$) to suppress the emission of a second neutron, then a different value of $a=(A/10.3)$ MeV^{-1} would be obtained. (Another possibility is that the evaporation of only the second neutron is influenced by shell effects after the cooling brought about by the emission of the first neutron.) This discussion illustrates a difficulty in the determination of the level-density parameter a, namely that it depends on the choice of the energy available for neutron emission. If the $1n$ channel could be observed in a case where there is no suppression of neutron emission, the level density could be unambiguously measured. (Experiments of this type with a Crystal Ball should still be feasible despite an order-of-magnitude reduction in the channel yield.)

In summary, a new experimental approach has been described which allows a direct determination of nuclear level densities at high spins. It is based on the measurement of neutron spectra for the $1n$ channel in coincidence with a 4π multielement γ-detector system which provides exit channel and spin selection. Ambiguities in the determination of level densities usually encountered in the analysis of particle-evaporation spectra are thereby avoided.

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[1]W. Dilg *et al.*, Nucl. Phys. **A217**, 269 (1973).

[2]R. Stockstad, in *Treatise on Heavy-Ion Science,* edited by D. A. Bromley (Plenum, New York, 1985), Vol. 3, p. 83.

[3]L. Kurz, LBL Report No. UCRL 11-359, 1965 (unpublished).

[4]A. Ruckelshausen *et al.*, Phys. Rev. Lett. **56**, 2356 (1986).

[5]J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (Wiley, New York, 1952).

[6]K. Snover, Ann. Rev. Part. Nucl. Sci. **36**, 545 (1986).

[7]F. Beck *et al.*, to be published.

[8]A. Ruckelshausen *et al.*, Phys. Rev. Lett. **58**, 1584 (1987).

[9]D. J. G. Love *et al.*, Phys. Rev. Lett. **57**, 551 (1986).

[10]R. V. F. Janssens *et al.*, Phys. Lett. B **181**, 16 (1986).

[11]W. Kühn *et al*, Phys. Rev. Lett. **51**, 1858 (1983).

[12]P. J. Twin *et al.*, Phys. Rev. Lett. **57**, 811 (1986).