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Level densities and barriers of deformed ^{59}Cu nuclei with $28\hbar \leq J_{\rm av} \leq 34\hbar$

B. Fornal* and G. Prete
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, I-35020 Legnaro (Padova), Italy

G. Nebbia, F. Trotti, and G. Viesti
Istituto Nazionale di Fisica Nucleare and Dipartimento di Fisica dell' Università di Padova,
I-35131 Padova, Italy

D. Fabris, K. Hagel, and J. B. Natowitz
Cyclotron Institute, Texas A&M University, College Station, Texas 77843
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The spectra of α particles emitted from narrow windows of angular momentum with $28\hbar \leq J_{\rm av} \leq 34\hbar$ show systematic deviations from spectra calculated using the statistical model as the spin of the emitter increases to values for which strong deformations are predicted. The barrier reduction and the enhancement of the level density needed to reproduce the experimental spectra have been determined.

Heavy ion induced fusion reactions are capable of producing compound nuclei with high angular momenta, high excitation energies, and large deformations.[1] Particles emitted in the deexcitation of these compound nuclei carry essential information on nuclear shapes and related level densities and provide new information on nuclear structure far above the yrast line.

The statistical theory appears to fit emission data even for compound nuclei at excitation energies and angular momenta far from those for which the theory was originally developed.[1,2] Normally, models like the rotating liquid drop (RLDM) are used to predict quantitatively the spin dependence of the deformation and the Fermi Gas model is used to calculate the level density at high excitation energy. Inverse cross sections are obtained from optical model calculations even though it is well understood that $\sigma_{\rm inv}$ for excited nuclei may be different from that of the ground state. Further tests of the statistical model at high excitation energy and spin are of crucial importance in studies of nuclear structure and dynamics using heavy ion beams.[3,4]

In this work we have derived, for narrow windows of angular momentum, the spectra of charged particles emitted from the decay of ^{59}Cu at 60–80 MeV of excitation, formed in the fusion of ^{32}S$+^{27}$Al. The ^{32}S$+^{27}$Al system was chosen because previous experiments indicated a strong influence of deformation of the particle spectra.[5] For the highest J windows, the nuclei are predicted to be strongly deformed.[6] A comparison of the spin-isolated experimental spectra with those calculated using the statistical model, indicates significant barrier reduction and level density enhancement for such nuclei. The experiments were performed at the XTU Tandem of the Laboratori Nazionali di Legnaro.

High statistics singles spectra of light charged particles (H and He isotopes) were collected at 12 laboratory angles ranging from 30° to 150° for bombarding energies of ^{32}S from 100 to 150 MeV in 10 MeV steps. Targets of 0.5–0.2 mg/cm^2 of ^{27}Al were used. A set of four three element silicon telescopes was employed. Relative normalization was done using an ionization chamber as a monitor at $\theta_{\rm lab}=8°$. Absolute cross sections were derived calibrating the Faraday cup by the Rutherford scattering from a gold target.

In a second experiment, the light particle-light particle coincidences have been studied at 150 MeV bombarding energy.[7] The measured data, together with the available fusion cross sections[8] and evaporation residue distributions,[9,10] make the ^{32}S$+^{27}$Al system a unique benchmark for evaporation calculations. Based on previous studies of comparable reactions,[4] no significant contribution from preequilibrium emission is expected in the spectra. A direct proof of the evaporative origin of the light particles is that the shapes of the energy spectra taken at different laboratory angles fit nicely with each other once converted in the center-of-mass system.

Figure 1 shows a comparison between the experimental spectra for α emission from ^{59}Cu nuclei and the spectra calculated using the CACARIZO[5] code with the standard parameter set of Ref. 9. CACARIZO is the Monte Carlo version of CASCADE[11] which performs an evaporation calculation which follows completely the statistical decay of the nucleus from any populated states of given spin and excitation energy.

As evidenced in Ref. 5, the lowest measured energy, 100 MeV, the α particle spectra are quite well described by the statistical model using the input parameters of Ref. 9 (i.e., T_l from optical model potentials,[12] RLDM yrast line[6] and the Lang level density formula).[13] This is not surprising because the excitation energy of the compound nucleus is quite low ($E_x=59$ MeV) and the critical angular momentum for fusion $l_{\rm crit}=27\hbar$ as derived from cross sections.[8] This kind of calculation was also successful in the case of the charged particle decay of ^{67}Ga compound at $E_x=116$ MeV and $l_{\rm crit}=38\hbar$.[14] For these two reactions, the compound nucleus is predicted to be spherical at low angular momentum and slightly oblate near these values of $l_{\rm crit}$. A direct proof of the dominant spherical

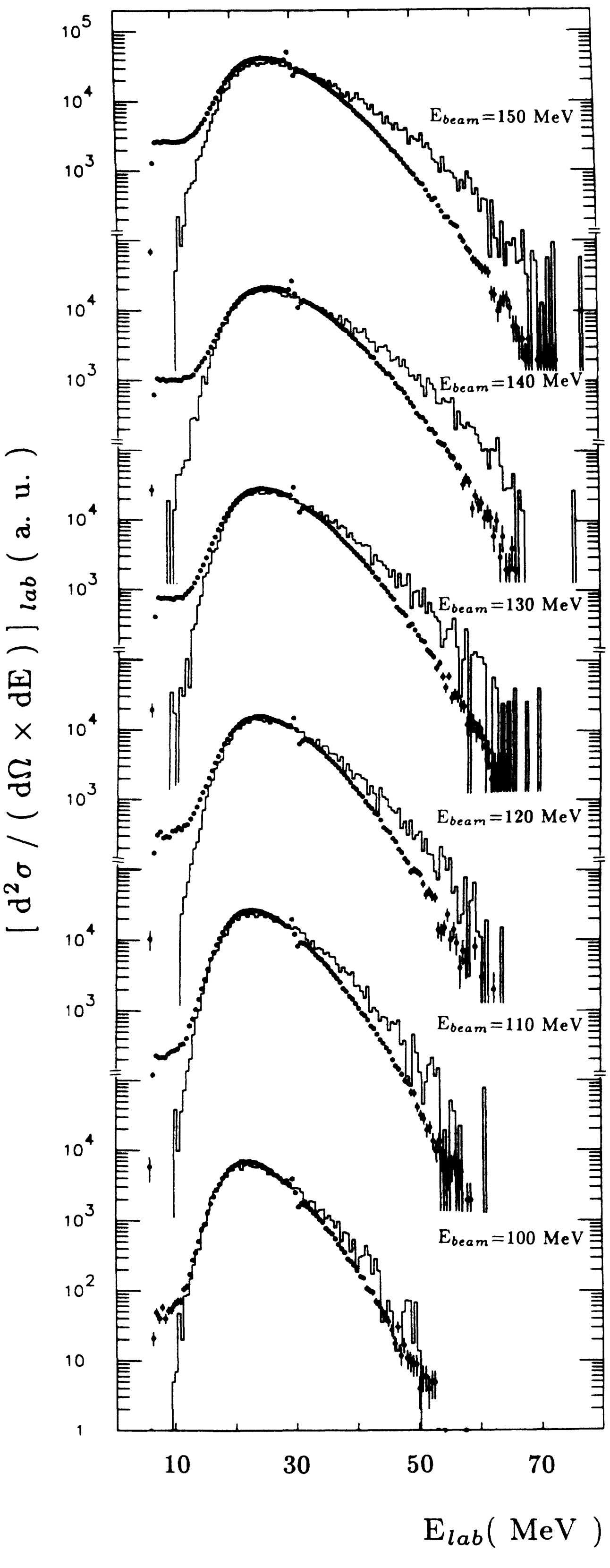

FIG. 1. Laboratory spectra (dots) of α particles emitted at $\theta_{lab} = 30°$ after the fusion of $^{32}S + ^{27}Al$ at 100 to 150 MeV compared with statistical model Monte Carlo calculations (histogram) using the input data set from Ref. 9.

shapes of $A \sim 60$ nuclei at $l \leq 30\hbar$ has been recently obtained by studying the giant dipole resonance decay of highly excited states of ^{63}Cu.[15] At even higher angular momenta such nuclei are predicted to become strongly deformed. This is confirmed in both ^{67}Ga and ^{59}Cu experiments by the increasing deviation of the experimental data from the statistical model calculations as the spin increases.

The α-particle spectra in Fig. 1 show increasing deviations with increasing projectile energy. As shown in previous work,[5,14] an adjusted statistical model calculation in which emission barriers are lowered and spin dependent increases of the level density are incorporated is able to reproduce such deviations.

An example of the very good reproduction of the experimental data obtained by such adjusted calculations is shown in Fig. 2. In the present work we are able to go beyond the average adjustments by isolating the emission from those regions of angular momenta for which large deformations of the nucleus are predicted. This was accomplished by first reconstructing the center of mass spectra from the $\theta_{lab} = 30°$ spectra. The same final results are obtained by using other lab angles.

We assume that the statistical model with standard parameters which describes sufficiently well the decay of ^{59}Cu up to $27\hbar$ at $E_x = 59$ MeV excitation, will do as well for the same spin range at slightly higher excitation energies (up to $E_x = 81$ MeV corresponding to the 150 MeV irradiation).

We have therefore calculated the spectra associated with the low spin values ($0-27\hbar$) at the excitation energies corresponding to the irradiations at 110, 120, 130, 140, and 150 MeV and subtracted these spectra from the experimental ones. In Table I are reported the critical angular momenta for fusion l_{crit}, which determine the upper limit of the spin window and the average value of the spin J_{av} in the resultant window associated with each difference spectrum shown in Fig. 3.

The high spin selection emphasizes the differences between the experimental spectra and the standard calculations (cf. Figs. 1 and 3) at low as well as at high alpha energy, where the role of emission barriers and level density can be studied.[5,14]

A lowering of the emission barrier associated with the onset of deformation is expected to lead to an increased yield of low energy particles as well as an extra production of energetic particles carrying away larger angular momentum (the amplification factor described in Ref. 3). For the calculation the emission barrier has been lowered by using potential radii in the O.M. which increase with increasing angular momentum up to 1.3 times larger than the standard ones. This produces a decreasing value of the emission barrier for alphas as reported in Table I. The barrier lowering is close to that calculated for emission along the major axis of nuclei having deformations like those predicted by Mustafa,[17] in agreement with the findings of the ^{67}Ga experiment. The lowering of the emission barrier results in a better reproduction of the low energy part of the alpha spectra but the high energy tail is still overpredicted.

The emission of energetic particles is also governed by

TABLE I. Statistical model parameters extracted from the data.

$E_{\rm beam}$ (MeV)	E_x in ^{59}Cu (MeV)	$l_{\rm crit}$[a] ($\hbar$)	$J_{\rm av}$[b] ($\hbar$)	$B_\alpha/B_{\alpha,\rm sph}$[c] (MeV)	ΔE[d] (MeV)	$\rho_{\rm exp}/\rho_0$[e] (MeV)
100	58.6	27		1.0		
110	62.1	30	28.0	0.96	5.2	12
120	67.8	33	29.5	0.92	6.2	22
130	71.3	34	32.3	0.88	8.5	46
140	77.0	38	32.8	0.83	8.9	68
150	80.6	39	34.2	0.81	10.2	95

[a] Critical angular momentum for fusion from experimental cross sections of Ref. 7 using a diffuseness $\Delta = 3.5\hbar$ in the angular momentum distribution as in Ref. 8.

[b] Average spin value associated with the spin window from $27\hbar$ to $l_{\rm crit}$.

[c] Fractional barrier relative to that of a spherical nucleus. The barrier lowering is obtained by increasing the radius values in the optical model potentials.

[d] Excitation energy increase due to the lowering of the yrast line at $J = J_{\rm av}$.

[e] Enhancement factor in the level density at $J = J_{\rm av}$ and 17 MeV excitation above the RLDM yrast line. Estimated uncertainties are a factor of 2.

the (E_x,J) functional dependence of the level density which determines the competition between different decay channels. The nuclear deformation, at a given excitation energy, is expected to increase the level density.[17] An increase in deformation as a function of the angular momentum would then cause a spin dependent enhancement in the level density which distributes the decay flux in the channels different with respect to the distributions observed for a spherical nucleus. This spin dependent enhancement produces a softening of the alpha spectra and an increase of the proton emission[14] relative to that obtained assuming a rigidly rotating spherical nucleus. The change in the level density may be simulated in the calculation in different ways. In this work, as in the case of the adjusted calculation discussed above, we increase the density by lowering the energy of the yrast line.

The results of these changes in the model are shown in Fig. 3. The description of the experimental high spin spectra is quite good both for the spectral shapes and for the absolute cross sections for α emission when the adjustments are made.

We report in Table I for each value of the average spin $J_{\rm av}$ the excitation energy increases ΔE resulting from the lowering of the yrast line needed to reproduce the experimental data of Fig. 3. We stress that this excitation energy increase is only an artificial way to change the spin dependence of the level density which is expressed in the Lang formula for spherical nuclei.

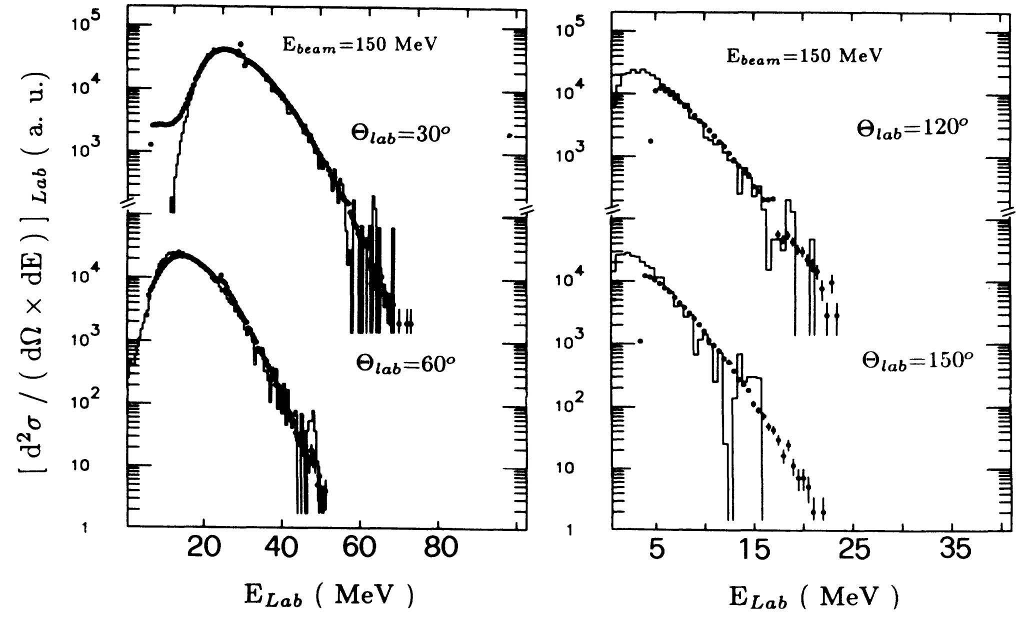

FIG. 2. Laboratory spectra (dots) of α particles emitted at $\theta_{\rm lab} = 30°$, 60°, 120°, and 150° after the fusion of ^{32}S+^{27}Al at 150 MeV compared with adjusted statistical model Monte Carlo calculations (histogram).

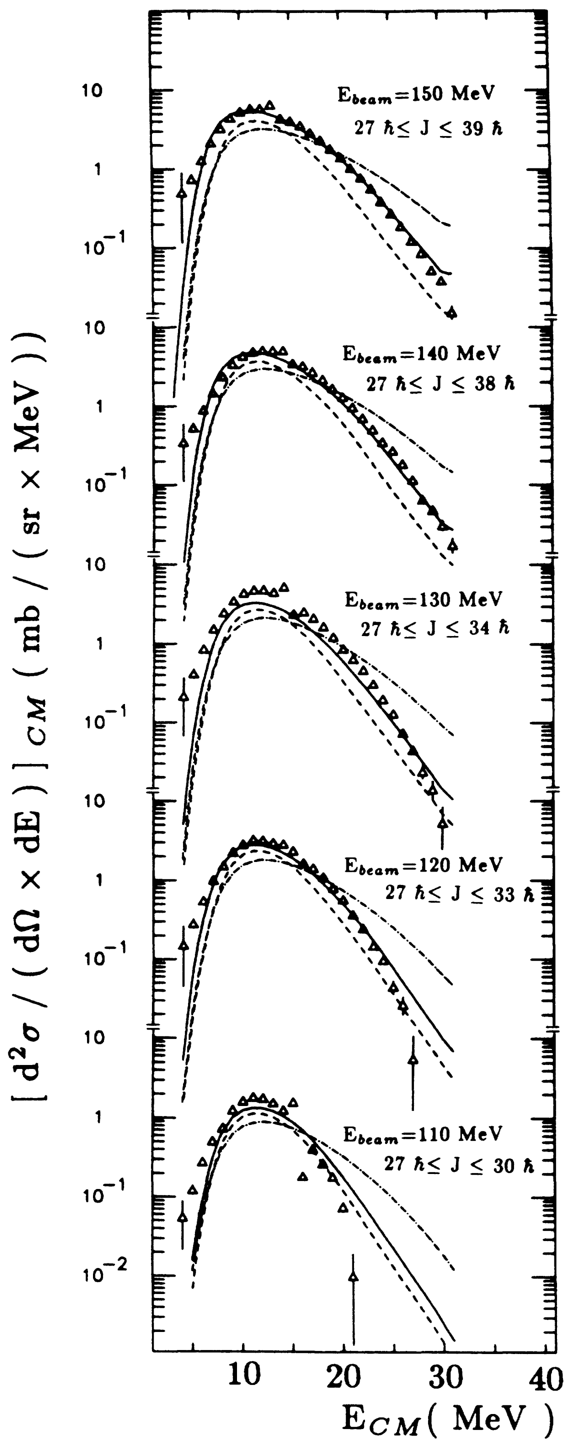

FIG. 3. Comparison of the resultant center of mass spectra of α particles after subtraction of the low spin calculated spectra using the input parameters of Ref. 9 (dash-dotted line) or the adjusted ones: yrast line lowered (dashed line), yrast line lowered and barrier reduced (solid line), see Table I.

The $\Delta E(J)$ can be converted into "experimental" level density using the Lang formula for an excitation energy $E_x - E_{\text{yrast}}(J) + \Delta E(J)$. Therefore it is possible to estimate directly the enhancement factor of the level density relative to that of the spherical nucleus case. The enhancement factor is reported in Table I for a value of 17 MeV excitation above the RLDM yrast line which is an average value for the residual nucleus after the emission of alpha particles from the high spin windows.

Because several yrast lines reproduce the data reasonably well, we estimate an uncertainty of a factor 2 on the level density enhancement factor.

In taking explicit account of the deformation in the level density, the intrinsic nuclear excitations and the collective degrees of freedom may be considered independently. Toke and Swiatecki have derived a prescription for the intrinsic level density parameter a which takes into account the diffuse surface region for the deformed nuclear shapes.[18] Using this prescription with the shape parameters extracted for our case from the two center model of Mustafa[17] we obtain an enhancement factor of ~ 1.2 for the intrinsic level density. This value is low compared to that determined from our data, and it suggests the greater importance of other effects.

Bjornholm, Bohr, and Mottelson have discussed the importance of the collective rotational state contribution to the level density of deformed nuclei.[19] Calculations of the level density including the collective enhancement have been performed by Huizenga *et al.*[20] and Dossing and Jensen[21] for heavy nuclei ($A > 100$) at low spin and excitation energy. This collective enhancement was estimated to contribute typically a factor of ~ 40 for heavy statically deformed nuclei. This is close to the enhancement found at $J_{\text{av}} = 32\text{–}34\hbar$ for ^{59}Cu. However, given that large shape fluctuations may occur for nuclei with excitation energies well above the yrast line, the observed enhancements may reflect excitations of other degrees of freedom.

In summary, for the nucleus ^{59}Cu a lowering of the emission barrier and a collective enhancement of the level density seems to take place as soon as dynamical deformation is induced by populating high spin states. This is in agreement with RLDM predictions of sizeable deformations for this nucleus in the $J = 30\text{–}40\hbar$ range.

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*Permanent address: Institute of Nuclear Physics, Cracow, Poland.

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

[2] E. Vogt, in *Advances in Nuclear Physics*, edited by M. Baranger and E. Vogt (Plenum, New York, 1968), Vol. 1, p. 261.

[3] M. Blann and T. T. Komoto, Phys. Rev. C **24**, 426 (1981).

[4] G. La Rana *et al.*, Phys. Rev. C **35**, 373 (1987).

[5] R. K. Choudhury *et al.*, Phys. Lett. **143B**, 74 (1984).

[6] S. Cohen, F. Plasil, and W. Swiatecki, Ann. Phys. **82**, 557 (1974).

[7] F. Trotti, thesis, University of Padova, 1986 (unpublished).

[8] G. Rosner *et al.*, Phys. Lett. **150B**, 87 (1985).

[9] F. Puhlhofer *et al.*, Phys. Rev. C **16**, 1010 (1977).

[10] T. M. Cormier *et al.*, Phys. Rev. C **15**, 654 (1977).

[11] F. Puhlhofer, Nucl. Phys. **A280**, 267 (1977).

[12] D. Wilmore and P. E. Hodgson, Nucl. Phys. **55**, 673 (1964); P. E. Hodgson, Annu. Rev. Nucl. Sci. **17**, 1 (1967); F. G. Perey, Phys. Rev. **131**, 745 (1963); J. R. Huizenga and G. Igo, Nucl. Phys. **29**, 462 (1961).

[13] D. W. Lang, Nucl. Phys. **77**, 545 (1966).

[14] Z. Majka *et al.*, Phys. Rev. C **35**, 2125 (1987).

[15] M. Kicinska-Habior *et al.*, Phys. Rev. C **36**, 612 (1987).

[16] S. E. Vigdor and H. J. Karwowski, Phys. Rev. C **26**, 1068 (1982), and references therein.

[17] M. G. Mustafa *et al.*, Phys. Rev. C **25**, 2524 (1982).

[18] J. Toke and W. J. Swiatecki, Nucl. Phys. **A372**, 141 (1981).

[19] S. Bjornholm, A. Bohr, and B. R. Mottelson, in *Proceedings of the Third International Symposium on the Physics and Chemistry of Fission, Rochester, 1973* (IAEA, Vienna, 1974), Vol. 1, p. 367.

[20] J. R. Huizenga *et al.*, Nucl. Phys. **A223**, 589 (1974).

[21] T. Dossing and A. S. Jensen, Nucl. Phys. **A222**, 493 (1974).