TESTING THE LEVEL DENSITY OF EXCITED NUCLEI FROM EVAPORATIVE PARTICLE SPECTRA*

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The transition of the level density parameter $a_{\rm eff}$ from the low excitation energy value $a_{\rm eff} = A/8$ MeV^{-1} to the Fermi Gas value $a_{\rm FG}$ ~A/15 MeV^{-1} was discovered a few years ago in studying particle spectra evaporated from hot compound systems of $A \sim 160$. A number of experiments have been recently performed to confirm the earlier findings and extend the investigation to other mass regions and to higher excitation energies. Difficulties have been evidenced in extracting the nuclear temperature from the slope of the particle spectra because of angular momentum induced effects at relatively low excitation energy and of the onset of cluster and IMF emission at excitation energies $\epsilon \geq 3$ MeV/u. In the mass region $A \sim 110$, the transition to the FG value has been found at an excitation energy per nucleon larger than that for $A \sim 160$, as expected from theoretical predictions. For lighter mass nuclei, experiments do not show a departure from the $a_{\rm eff} = A/8$ MeV^{-1} value. On the contrary the need of an excitation energy dependent level density parameter has been evidenced in the mass region $A \sim 200$. The effect of this level density on the statistical model predicted pre-scission multiplicities is very important. Deformation induced effects on proton spectra have been also searched for. Experimental proton spectra do not show remarkable differences setting gates on bands characterized by different deformation (oblate,prolate,SD) in the ^{152}Dy residual nucleus.

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1. Introduction

The level density in highly excited nuclei is a topic of interest in nuclear physics from the experimental [1] as well as from the theoretical [2] viewpoints. In the Fermi Gas (FG) approach to the nuclear level density, a key quantity is the level-density parameter a, which is simply related to the density of single-particle levels $g(\epsilon_F)$ at the Fermi energy ϵ_F and reflects the properties of the single-particle potential. The excitation energy E_x is related to the nuclear temperature T by

$$E_x = aT^2 .$$

Therefore the experimental knowledge of E_x and T allows the definition of an effective level-density parameter $a_{\rm eff}$.

It is well known that for excitation energies of the order of the neutron separation energy, $E_x \sim 8$ MeV, the empirical value of the level-density parameter is $a_{\rm eff} \approx A/8$ MeV^{-1}, where A is the mass number. This has to be compared with the expected value from the FG model $a_{\rm FG} \approx A/15$ MeV^{-1}. The disagreement between the FG value and the one at low excitation energy is well understood as an effect of the finite size of the nucleus and of the increase of the nucleon effective mass at the Fermi energy produced by the coupling of the single-particle motion to other degrees of freedom. This last correlation is predicted [3, 4] to disappear for a temperature larger than the one of typical nuclear low-lying excited states, so that a transition to the FG value of the level density parameter $a_{\rm eff}$ is expected in increasing the excitation energy of the nucleus.

The knowledge of the level density parameter $a_{\rm eff}$ as a function of excitation energy and mass of the nucleus is not only interesting in itself, but also of crucial importance in interpreting heavy ion reactions designed to determine whether equilibration takes place and in nuclear astrophysics [5].

The transition of the level density parameter to the FG value was discovered few years ago in studies of the alpha particle spectra emitted from the decay of highly excited nuclei of mass $A \sim 160$ [6, 7]. In the last years a number of experiments, reviewed in this paper, have been realized in the effort of confirm the earlier findings for $A \sim 160$ nuclei and extend the investigation of the level density in other mass region, higher excitation energies and nuclear deformations.

2. Experiments in the mass $A \sim 160$ region

The first experiments in the $A \sim 160$ region studied the coincidences between evaporation residues and alpha particles emitted at backward angles in the reactions of 19 and 35 MeV/u ^{14}N $+^{154}$Sm [6, 7], which are characterized by a wide distribution in the transferred linear momentum, producing a continuum of sources of different mass and excitation energies. Several points of those earlier measurements have been verified in successive investigations using the ^{60}Ni + ^{100}Mo reactions at 9, 11, 13, 17 MeV/u [8, 9]. Ni-induced reactions were chosen because of the nearly complete momentum transferred, which better define the emitting source. In this case p, d, t, ^{4}He and neutron spectra were measured.

The determination of the level density parameter is generally obtained from the relation $E_x = aT^2$ by correlating the daughter nucleus of mass A and excitation energy E_x with the nuclear temperature T characterizing the Maxwellian distribution of the evaporated particles. The quantity experimentally determined is the slope of the particle spectra, the apparent temperature T_{app}. Because of the length of the deexcitation chain, the measured T_{app} reflects not only the temperature of the particles populating the nucleus A at the excitation energy E_x, but also that of particles emitted in later steps of the cascade, corresponding to lower excitation energies and masses. The derivation of T is achieved by unfolding slopes (T_{app}) with the measured multiplicity (M) at excitation energies $E_{x,1}$ and $E_{x,2}$ ($E_{x,1} \leq E_{x,2}$):

$$T = \frac{T_{\text{app},2} \times M_2 - T_{\text{app},1} \times M_1}{M_2 - M_1}\,.$$

In few cases "quasi-first chance " spectra of the emitted particles have been obtained directly by a subtraction procedure. The assumption, in both cases, is that the cascade originating at $E_{x,2}$ includes also that at $E_{x,1}$.

Results in terms of the inverse level density parameter $K = A/a$ versus T obtained in this way are shown in Fig. 1. The transition to the FG value is located at an excitation energy of $\epsilon \sim 1.3$ MeV/u (note that ϵ is the excitation energy in the daughter nucleus after the particle emission). The shape of the alpha particle spectra was also reproduced by statistical model calculations in which energy independent $\langle K \rangle$-values were used [7], having values ranging from $\langle K \rangle = 8$ MeV at the lower excitation energy to $\langle K \rangle = 14$ MeV at the higher one. The average inverse level density parameters $\langle K \rangle$ determined in this way are very close to that for the first step of the decay, derived from the measured T_{app} and multiplicities, demonstrating that the bulk of the alpha particle emission in this mass region samples directly the higher excitation energy region. Statistical model calculations, however, are not reproducing the measured multiplicities [8].

Further results from the ^{60}Ni + ^{100}Mo reactions are summarized as follows:

1) The initial temperature determined at an average excitation energy of $E_x = 290$ MeV was found to be the same ($T = 4.6$ MeV) regardless of the type of particle and their multiplicity and apparent temperature.

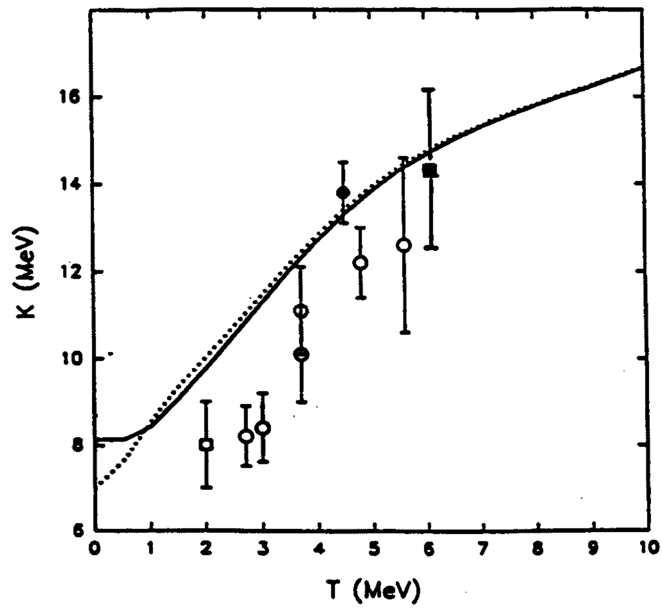

Fig. 1. Inverse level density parameter K vs temperature T for $A \sim 160$. Open dots $^{14}N+^{154}Sm$; full dots $^{60}Ni+^{100}Mo$. Lines are calculations from Ref. [25].

The value of the level density parameter extracted in this way was $a = A/14$ MeV^{-1}, in good agreement with the previous measurements based on incomplete fusion reactions and alpha particle spectra. It is observed also that the differences between the measured slope of the evaporative spectra T_{app} and the initial temperature depends on the type of particles through their multiplicity. As an example, the ratio T/T_{app} is 2 for neutrons ($M_n \sim 15$), 1.25 for protons ($M_p \sim 1.3$) and only 1.1 for alpha particles ($M_\alpha \sim 0.9$).

2) At higher bombarding energies a saturation of multiplicity and apparent temperature for protons was observed, as shown in Table I, correlated with an increase of the yield for d and t. This was interpreted as a signature that the protons are not any longer sampling the hottest compound nuclei. Furthermore, an excitation energy balance can be obtained from the measured multiplicity values and average kinetic energy (correcting for average binding energies and rotational energy). The results shown in Fig. 2 clearly demonstrate that below $\epsilon \sim 2$ MeV/u the energy balance based on the energy of the compound system. Raising up to $\epsilon \sim 3$ MeV/u, an important part of the excitation energy is missing, which is supposedly associated to the IMF emission. It seems therefore that at excitation energies between 2 and 3 MeV/u the emission of light clusters and IMF starts to play an important role in the deexcitation of the

hot nuclei [10]. This implies that in this excitation energy regime and above, light particles spectra might be used to study the level density parameter $a_{\rm eff}$ only if it is experimentally demonstrated that they are sampling the first stages of the decay.

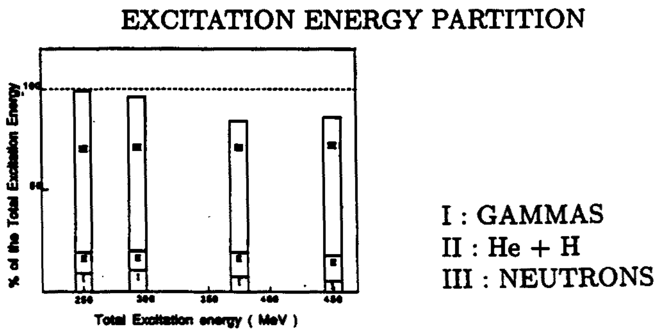

Fig. 2. Excitation energy balance for the ^{60}Ni+^{100}Mo reactions at 9, 11, 13 and 17 MeV/u.

TABLE I

Excitation energies, apparent temperatures, multiplicities and emission barriers for light particles emitted in the reaction ^{60}Ni+^{100}Mo.

E_x (MeV)	Particle	$T_{\rm app}$ (MeV)	M	B_c (MeV)
251	p	3.3 ± 0.1	1.1 ± 0.2	6.5 ± 0.8
	α	3.8 ± 0.1	0.6 ± 0.2	14.0 ± 0.5
292	p	3.6 ± 0.1	1.3 ± 0.2	5.5 ± 0.8
	α	4.1 ± 0.1	0.9 ± 0.2	13.0 ± 0.5
368	p	3.4 ± 0.2	1.6 ± 0.2	5.7 ± 0.2
	α	4.7 ± 0.3	1.2 ± 0.2	12.7 ± 0.4
456	p	3.7 ± 0.5	1.7 ± 0.2	4.7 ± 0.5
	α	5.0 ± 0.5	1.6 ± 0.2	11.9 ± 0.2

3. Experiments in lighter mass regions

Excitation energies and initial temperatures were derived for $A \sim 110$ nuclei by studying coincidences between heavy residues and alpha particles for the reaction 30 MeV/u ^{16}O and ^{32}S with Ag [11]. After correcting the initial temperature T for spin-off effects, the nuclear level density parameter

a_{eff} was determined to be in the range $a_{\mathrm{eff}} = A/11$ to $a_{\mathrm{eff}} = A/13$ MeV^{-1} at $\epsilon = 2 - 3$ MeV/u. Above $\epsilon \sim 3$ MeV/u the initial temperature levels off within the experimental errors. Therefore the apparent values of a_{eff} tend to increase again. Also in this case, successive measurements were performed by using low energy complete fusion reactions (^{32}S + ^{74}Ge at beam energies between 160 and 435 MeV delivered from the XTU Tandem in Legnaro and the SARA facility in Grenoble [12]). The corresponding A=106 compound system was populated at excitation energies $\epsilon = 0.5 - 2.2$ MeV/u. Alpha particle and proton spectra were compared with statistical model calculations from CASCADE in which different energy independent level density parameter $a_{\mathrm{eff}} = A/\langle K\rangle$ ($\langle K\rangle = 8 - 14$ MeV) are used. As a result, only at the higher bombarding energy the alpha particle spectrum seems to indicate the need of larger $\langle K\rangle$ values, the best fit being obtained by $\langle K\rangle = 9$ MeV. Considering only alpha particle data, the K-values from Wada *et al.* are reported in Fig. 3 together with $\langle K\rangle$-values obtained for the ^{32}S + ^{74}Ge reaction. Because the alpha particle multiplicity is rather low ($M_\alpha \sim 1$) and the alpha particles are generally emitted at the top of the cascade, we consider the latter $\langle K\rangle$-values as a lower limit but close to the inverse level density parameter at the top excitation energy. With this caution, the resulting agreement of the data is rather good and a transition to the FG value is detectable at $\epsilon \sim 2$ MeV/u, excitation energy which is larger in the $A \sim 160$ case, as expected [13].

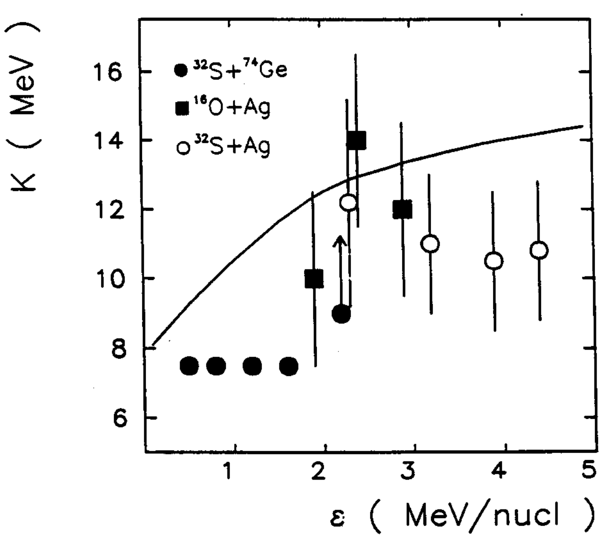

Fig. 3. Inverse level density parameter K vs temperature T for $A \sim 110$ nuclei. Points are experimental data from Ref. [11, 12]. Lines are calculations from Ref. [13].

Chibihi *et al.* reported a detailed investigation [14, 15] of the residues-light particle coincidences for the system 701 MeV ^{28}Si + ^{100}Mo with the Spin Spectrometer-Dwarf Ball system, extending the investigation for $A \sim 110$ nuclei in the excitation energy range $\epsilon = 1.3 - 3.0$ MeV/u. The analysis of the data was performed by correcting the measured slope of the particle spectra for the effects of the cascade length and than using the relationship $E_x = aT^2$. Results in term of level density parameter were found to be somewhere in disagreement with data of Wada *et al.* and Nebbia *et al.* It has been shown in detail in Ref. [12] that the disagreement is caused by the presence in this mass region of strong effects related to the angular momentum and to the transmission coefficients which influence the slope of the particle spectra. In this conditions extreme care has to be used in extracting information on the level density from the particle spectra.

An important confirmation of the features outlined above is contained in the work of Yoshida *et al.* [16]. Neutron spectra and multiplicity were measured for the reaction 26 MeV/u ^{40}Ar + ^{92}Mo, populating systems of mass $A \sim 109 - 127$ at excitation energies $\epsilon = 2.5 - 4.3$ MeV/u. The average level density parameter extracted from the data was $\langle K \rangle = 8 - 9$ MeV. In particular at $\epsilon = 2.4$ MeV/u, the experimental spectra are also very well described by CASCADE statistical model calculations using $\langle K \rangle = 8$ MeV. The authors claimed that their results were not in agreement with the results from Ref. [6-9, 11]. The average level density parameter $\langle K \rangle$ employed in statistical model calculations has to be considered as the result of the integration of $K(\epsilon)d\epsilon$ weighted on the corresponding multiplicity $M(\epsilon)$. For the $A \sim 110$ mass region we can simply consider $K = 8$ MeV for $\epsilon \leq 2.$ MeV/u and $K = 11$ MeV for $\epsilon \geq 2.0$ MeV/u. Weighting on the multiplicity values of Fig. 4, we obtain $\langle K \rangle = 8.5 - 9.1$ MeV for $\epsilon = 2.4 - 4.3$ MeV/u. This is because the weight of neutron multiplicity associated with the $K = 8$ MeV excitation energy region is very important also at the maximum excitation energy investigated. Furthermore we note that, despite the very large neutron multiplicity, $T_{\rm app}$ values are very close to the nominal T at the top of the cascade. As an example, the first chance neutron temperature should be $T = 4.5$ MeV at $\epsilon = 2.4$ MeV/u, to be compared with the experimental value of $T_{\rm app} = 4.0$ MeV determined for a cascade of 11 neutrons, 7 of which are emitted at $\epsilon \leq 1.0$ MeV/u ! Note that the ratio $T/T_{\rm app}$ for neutrons is significantly different in the $A \sim 160$ mass region as reported in the previous section. This means that also in case of the neutron emission from an $A \sim 110$ nucleus the energy spectrum is hardened by effects different from the nuclear temperature. Given the good reproduction of the spectra obtained from CASCADE, it seems that those effects are well accounted in the actual statistical model calculations. Also in this case, as shown in Fig. 4, the statistical model calculations are not capable of predicting correctly the

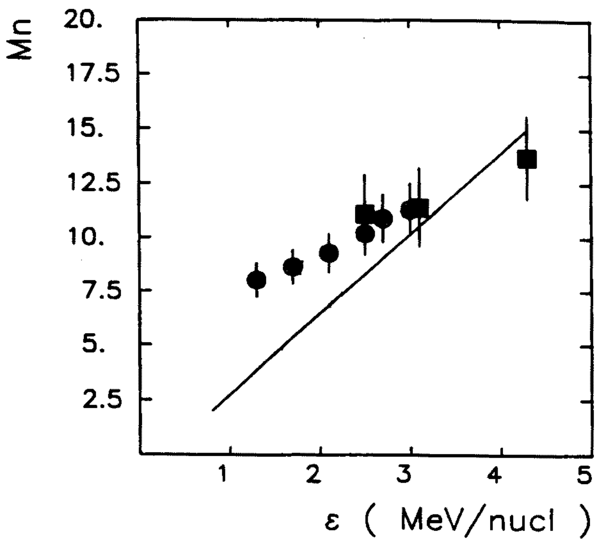

Fig. 4. Experimental neutron multiplicity for $A \sim 110$ nuclei (dots Ref. [14], squares Ref. [16]). CASCADE statistical model calculations are from Ref. [16].

excitation energy dependence of the neutron multiplicity.

Some experimental information is also available in case of lighter nuclei. The $^{32}S + ^{27}Al$ reaction has been extensively investigated in the past at the XTU Tandem up to 190 MeV bombarding energy. Light particles spectra [17], as well as hard γ-ray [18], were measured. This investigation was extended recently at 335 MeV bombarding energy in the 4π detection system AMPHORA at SARA. Furthermore, particle spectra emitted in the decay of hot ^{40}Ca nuclei were studied at the XTU Tandem, by using the reaction 130 MeV $^{16}O+^{24}Mg$ [19].

Generally, the slopes of the particle spectra in light systems are strongly determined by the angular momentum dependence of the phase space (*i.e.* by the position of the yrast line). Up to now, only average level density parameters $\langle K \rangle$ have been derived by comparing the experimental spectra with those predicted by statistical model calculations. In all cases, a rather accurate description of the experimental data (both particle and γ spectra) have been achieved by using $\langle K \rangle = 8$ MeV.

4. Experiments in the mass $A \sim 200$ region

The level density in the $A \sim 200$ region has been recently investigated by measuring alpha particle spectra in coincidence with evaporation residues in the reaction $^{19}F + ^{181}Ta$ at 90–140 MeV bombarding energies [20]. The motivation of this work was the importance of the level density information for nuclei usually considered in the study of fission dynamics. In fact the extraction of the fission times from experimental pre-scission particle multiplicities is achieved by using statistical model calculations.

It is found in this experiment that the shape of the alpha particle spectra are satisfactorily described by using an average inverse level density parameter $\langle K \rangle$ which increases with the excitation energy up to $K = 14$ MeV^{-1} at $E_x \sim 100$ MeV. This change in level density parameter appears to be much steeper in excitation energy as compared with the neighboring $A \sim 160$ region. Furthermore this type of calculation is not able to reproduce the bombarding energy dependence of the alpha particle multiplicity, reflecting the fact that in the model, in contradiction to the experimental evidence, the bulk of the alpha particle emission appears late in the deexcitation cascade, after some neutron cooling. In a second approach, calculations were performed in which excitation energy dependent level density parameters $K = K(E_x)$ were employed. We found that the energy spectra of the particles are very sensitive to relatively small changes in the excitation energy dependence of the phase space induced by using $K = K(E_x)$. A reasonable reproduction of the data, as shown in Figs 5, 6 is achieved by using the $K = K(E_x)$ values reported in Fig. 7. A much larger dependence of the multiplicity on the bombarding energy is now obtained, due to an increased contribution of particles emitted early in the decay. Thus, it seems that in the mass region $A \sim 200$ the only way to reproduce simultaneously the observed spectral shapes and multiplicities is the use of an excitation energy dependent level density parameter $K = K(E_x)$. Possible effects of the dynamic fission hindrance on the α particle multiplicities observed for the evaporation residues were explored using the code CASCADE to model the decay of the ^{200}Pb nucleus. Several calculations were carried out in which a constant or an energy dependent level density parameter was used and in which the statistical fission probability could be modified by an empirical (excitation energy dependent) reduction factor [21]. It is found that the evaporation residue α particle multiplicities, very sensitive to the level density assumption as noted previously, are essentially insensitive to the fission hindrance. The calculated α particle spectra results unchanged from the inclusion of fission hindrance. It is also interesting that the use of an energy dependent level density parameter did have a strong impact on the calculated emission prior to fission. In fact the predicted pre-scission neutron multiplicity at 140 MeV bombarding energy increased from $\nu = 2.0$ $(K = 8)$ to $\nu = 3.1$ $(K = K(E))$. This increase is similar to that obtained $(\nu = 3.3)$ by keeping $K = 8$ and introducing the fission hindrance. The combination of the two effects yielded the value $\nu = 3.4$ which is close to the extrapolated experimental value of $\nu \sim 3.7$. In the latter calculations more dramatic

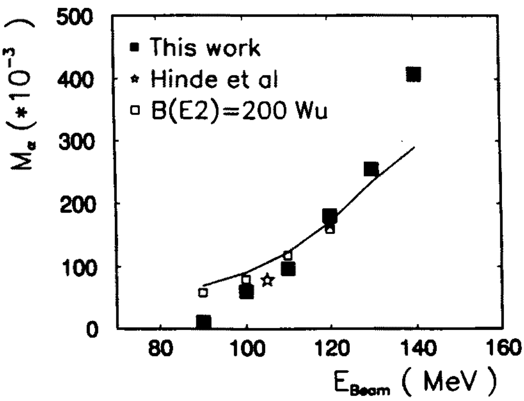

Fig. 5. Alpha particle multiplicity versus bombarding energy for the reaction $^{19}F+^{181}Ta$. Statistical model Monte Carlo calculations using inverse level density parameter $K = a/A$ dependent on the excitation energy are also shown.

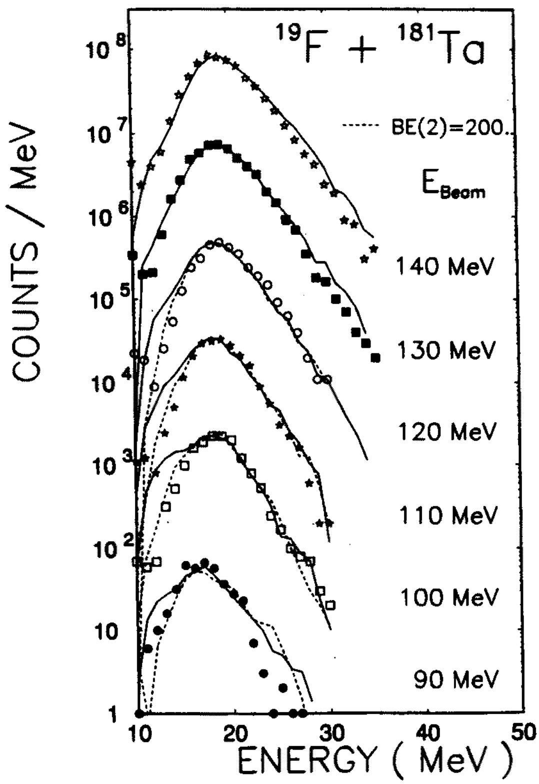

Fig. 6. As in Fig. 5 but for alpha particle spectra.

changes were seen in the proton and alpha particle pre-scission multiplicities, which increased by a very large factor (ν_p from 0.01 to 0.09; ν_α from 0.01 to 0.1), due to the introduction of the excitation energy dependence of the level density. It is interesting also that for the 140 MeV $^{19}F+^{181}Ta$ reaction the experimental mean center-of-mass energy of the alpha particles emitted prior to fission is $\langle\epsilon\rangle \sim 20$ MeV [22] to be compared with the experimental value in the evaporation residues channel $\langle\epsilon\rangle \sim 23$ MeV, which is well reproduced by statistical model calculations. This demonstrates that in the pre-fission channel other effects (larger deformations, changes in the binding energy), play a major role.

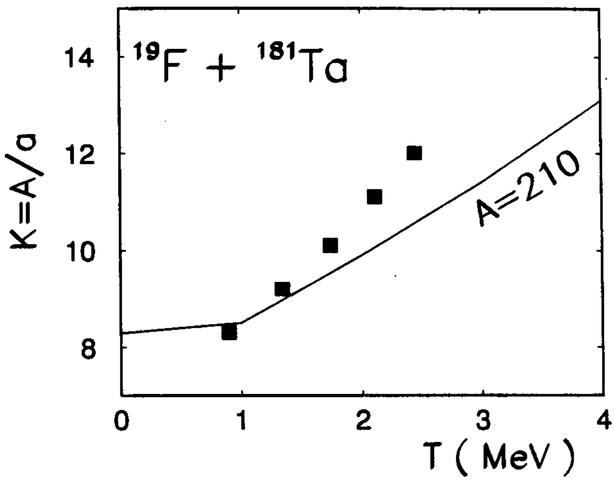

Fig. 7. Comparison between the inverse level density parameters derived from the analysis of the $^{19}F+^{181}Ta$ data and that from the theoretical calculations of Ref. [13].

4. Deformation dependent effects on the evaporative spectra

The dependence of the evaporative spectra on the nuclear deformation is an open problem in nuclear physics since long time [23]. In principle it is expected that excited compound nuclei at high angular momenta should exhibit large deformations. Particle emission from deformed nuclei is supposed to be characterized by a shift in the average energy because of the lowering of the emission barrier respect to the spherical case [24]. Furthermore, the level density of an elongated nucleus is also predicted to be different from that of the spherical one [2]. Therefore the possibility exists that also the apparent temperature of the particle spectra should retain signature from deformation effects.

Experimentally, the major problem is the discrimination between particles directly emitted from the deformed initial compound nucleus and those emitted in subsequent steps of the decay chain or from lower angular momenta. In this respect, one possible way is the selection of the deformation in final evaporation residues, making the hypotheses that deformed shapes in final residues, as the super-deformed ones, might be prevalently populated by deformed states in the initial compound nucleus.

An experiment has been performed measuring protons in coincidence with low energy γ-rays detected in the 4π detector GASP at Laboratori Nazionali di Legnaro. The reaction studied was 187 MeV ^{37}Cl on ^{120}Sn, populating ^{152}Dy residual nuclei via the $1p4n$ channel. This evaporation channel selects high angular momenta ($\langle J \rangle = 48\hbar$) in the compound nucleus. In Fig. 8 the proton spectra are reported by setting gates on the well known oblate, prolate and super-deformed bands. The experimental spectra seems to be scarcely sensitive to the selection of different shapes in the same nucleus. This appears as a demonstration that the particle decay phase from an highly excited compound nucleus is a typical example of chaotic process in which there is no particular connection between deformation of the parent and that of the daughter nucleus.

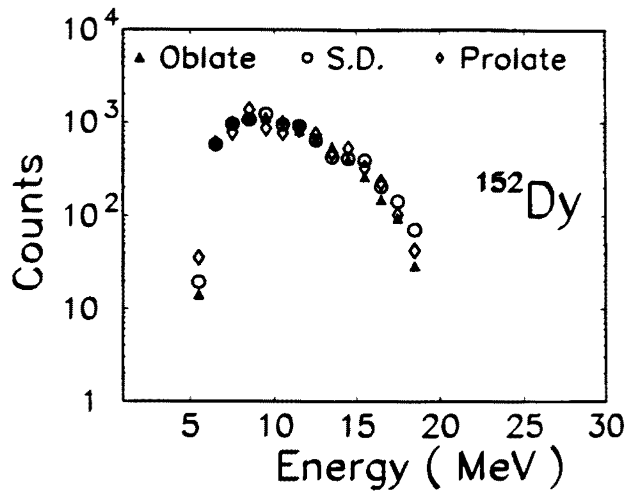

Fig. 8. Comparison between proton energy spectra measured in coincidence with different bands in the ^{152}Dy nucleus populated in the reaction ^{35}Cl+^{120}Sn at 187 MeV.

4. Conclusions

A transitions from the low energy level density parameter $a_{\text{eff}} = A/8$ MeV^{-1} towards the FG value $a = A/15$ MeV^{-1} have been evidenced in different mass regions ($A \sim 110, 160, 200$). For lighter systems or excitation energies $\epsilon \geq 3$ Mev/u, experimental difficulties are evidenced, due to the stronger effects related to the angular momentum and the onset of cluster and IMF emission. Further experimental work aimed to extend the present knowledge of the level density, should carefully solve the problem of determining the probe and/or the experimental technique most suitable to measuring the nuclear temperature and the excitation energy in hot nuclear systems.

The experimental work described here has been part of the collaboration between Padova, Legnaro and the Texas A&M University. Thanks are due to D. Fabris, G. Nebbia, G. Prete, K. Hagel, J.B. Natowitz and R. Wada. Helpful discussions with B. Fornal and P.F. Bortignon are acknowledged. I would like also to thank all members of the GASP collaboration.

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