PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 53, No. 3
September 1999
pp. 395–404

Experimental investigations of the nuclear level density by using heavy ion reactions

G VIESTI, M LUNARDON, D FABRIS, G NEBBIA, M CINAUSERO*, E FIORETTO*, G PRETE*, J B NATOWITZ†, K HAGEL† and R WADA†
Dipartimento di Fisica dell' Universitá di Padova and I.N.F.N., I-35131 Padova, Italy
*I.N.F.N., Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy
†Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA

Abstract. The transition of the level density parameter a_{eff} from the low excitation energy value $a_{\text{eff}}=A/8$ MeV^{-1} to the Fermi gas value $a_{\text{FG}}\sim A/15$ MeV^{-1} was discovered a few years ago 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. Furthermore, precision coincidence experiments have been done in the lead region in which evaporation residues are tagged by low energy gamma-rays. Those experiments open the possibility of a detailed study of the level densities in nuclei where the shell effects are important.

Keywords. Heavy-ion reactions; measured light-charged-particle multiplicity and energy spectra; deduced level density parameter mass dependence features.

PACS Nos 21.10.Ma; 25.70.Gh; 25.70.Jj; 27.80.+w

1. Introduction

The level density in excited nuclei is a topic of current interest in nuclear physics from the experimental as well as from the theoretical point of view [1].

It is well known that at low excitation energies the level density is strongly influenced by the shell structure of the nucleus. Such effects, which are particularly important for nuclei having proton and neutron numbers at the shell closures, are predicted to disappear with increasing excitation energy [2].

In the Fermi gas (FG) approach, a key quantity is the level-density parameter a, which is simply related to the density of single-particle levels $g(\epsilon_{\text{F}})$ at the Fermi energy ϵ_{F} and reflects the properties of the single-particle potential. In the simplest approach, the excitation energy E_x is related to the nuclear temperature T by the relation $E_x = aT^2$. Therefore, the experimental knowledge of E_x and T allows the definition of an effective level-density parameter a_{eff}. It is well known that for excitation energies of the order of the neutron separation energy, $E_x\sim 8$ MeV, the average empirical value of the level-density parameter is $a_{\text{eff}} \approx A/8$ MeV^{-1}, where A is the mass number. This has to be compared with the expected value from the FG model $a_{\text{FG}} \approx A/15$ 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 temperatures larger than that associated to the low-lying excited states, so that a transition to the FG value of the level density parameter $a_{\rm eff}$ is expected.

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 modelling heavy ion reactions designed to determine whether equilibration takes place and in nuclear astrophysics [5].

Results of experiments devoted to explore the excitation energy dependence of the level density, from tepid to hot nuclei, are reported and discussed in this paper.

2. Experiments on hot nuclei

The transition of the level density parameter to the FG value was discovered few years ago in the study of the alpha particles emitted at backward angles in the reactions of 19 and 35 MeV/nucleon ^{14}N+^{154}Sm [6], 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 9–17 MeV/nucleon [7]. Such 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 quantity experimentally determined is the slope of the particle spectra, i.e. the apparent temperature $T_{\rm app}$. Because of the length of the deexcitation chain, the measured $T_{\rm app}$ is determined not only by the first-chance particles emitted in the decay of the nucleus A at the excitation energy E_x, but also by those particles emitted in later steps of the cascade, corresponding to lower excitation energies and masses. The derivation of T, the temperature of the nucleus after the first chance emission, is achieved by unfolding slopes ($T_{\rm app}$) with the measured multiplicity (M) at two excitation energies $E_{x,1} \leq E_{x,2}$:

$$T = (T_{\rm app,2} \times M_2 - T_{\rm app,1} \times M_1)/(M_2 - M_1).$$

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 $E_{x,1}$.

An increase of the inverse level density parameter $K = A/a$ in increasing the excitation energy of the composite system was clearly evidenced. The transition to the FG value is located at an excitation energy of $\epsilon \sim 1.3$ MeV/nucleon (note that ϵ is the excitation energy in the daughter nucleus after the particle emission).

Furthermore, the initial temperature was found to be the same ($T = 4.6$ MeV) at an average total excitation energy of $E_x = 290$ MeV regardless of the type of particle considered, demonstrating that the thermal equilibrium was achieved.

In a second set of measurements, $A \sim 110$ nuclei were studied by coincidences between heavy residues and alpha particles from the reactions of 30 MeV/nucleon ^{16}O and ^{32}S on Ag [8]. Successive measurements were performed by using low energy fusion reactions (^{32}S + ^{74}Ge at beam energies between 5 and 13.6 MeV/nucleon delivered from the XTU

Tandem in Legnaro and the SARA facility in Grenoble [9]). The corresponding $A = 106$ compound system was populated at excitation energies $\epsilon = 0.5 - 2.2$ MeV/nucleon. After combining the data from the different experiments, a transition to the FG value was detected at $\epsilon \sim 2$ MeV/nucleon, an excitation energy larger than that in the $A \sim 160$ case, as expected from theoretical predictions [10].

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 [11], as well as hard γ-ray [12], were measured. 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 [13].

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 has been achieved by using the parameter $\langle K \rangle = 8$ MeV.

3. Level density of excited nuclei in the lead region

We have then considered the nuclei in the region of ^{208}Pb, where the shell corrections are very large, with the aim of experimentally mapping out the two transitions in the level density parameter as a function of the excitation energy: the disappearance of the shell effects and then the transition to the fermi-gas model value.

As a part of this investigation we have studied the fusion reactions ^{11}B + ^{198}Pt$\rightarrow$^{209}Bi* and ^{10}B + ^{198}Pt$\rightarrow$^{208}Bi* at bombarding energies $E_{\rm beam} = 55 - 90$ MeV. The experiment was performed at the XTU Tandem accelerator in Legnaro. Low energy γ-rays were detected with the GASP spectrometer [14] up-graded with two large BGO crystals (10 cm $\times$ 10 cm) to detect high energy γ-rays. A complete description of the operation of the large BGO detectors in coincidence with the GASP spectrometer is given in ref. [15]. The charged particles detector array ISIS (Italian Silicon Sphere) was used [16], up-graded by some CsI(Tl) scintillators to stop energetic protons. We collect 200×10^6 events in the case of the ^{11}B irradiation at 75 MeV for coincidences between ISIS and GASP (trigger conditions: 2 HPGe and 3 inner ball elements). The corresponding coincidences between energetic protons hitting the CsI(Tl) scintillators were in this case only 2.6×10^6 events. The statistics collected in the ^{10}B irradiation at 60 MeV was 150×10^6 events and 0.9×10^6 events, respectively.

The experiment was specifically designed to track down the disappearance of shell effects in the nucleus ^{208}Pb from the proton evaporation feeding directly the excited ^{208}Pb in the first step of the deexcitation cascade. In fact, the ^{11}B + ^{198}Pt reaction at 75 MeV bombarding energy populates the ^{209}Bi compound nucleus at an excitation energy of $E_x = 68.1$ MeV when a complete fusion reaction is considered [17]. In this case, the average angular momentum is estimated from the systematics to be $\langle J \rangle \sim 20\hbar$. The bombarding energy for the ^{10}B irradiation was selected to be $E_{\rm beam} = 60$ MeV, so that the ^{208}Bi compound nucleus is populated at an excitation energy of $E_x = 58.1$ MeV. The difference in the excitation energies obtained with the two beams is supposed to correspond to the emission of the first neutron from the decay of the ^{209}Bi CN. The proton spectrum

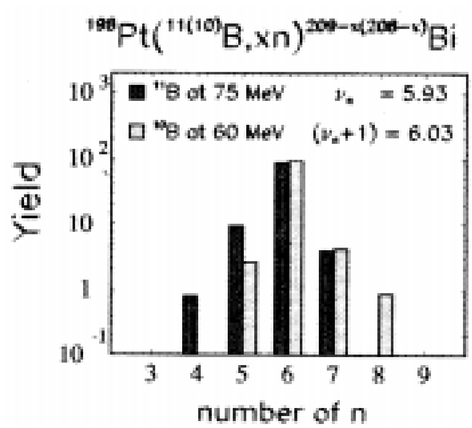

Figure 1. Relative yield distribution of the Bi isotopes produced in the ^{11}B- and ^{10}B-induced reactions.

measured in the ^{10}B induced reaction accounts for the emission of protons in the deexcitation chain of the ^{209}Bi compound nucleus when the particle emitted in the first step is a neutron, i.e. for protons emitted in the second or latest steps of the decay. Consequently, the difference between the proton spectra obtained in the two reactions is due only to the particles which populate the ^{208}Pb excited nucleus in the ^{209}Bi decay. It is, however, worth mentioning that the average angular momentum for the ^{10}B induced reaction is estimated to be $\langle J \rangle \sim 15\hbar$, which is lower than the one associated with the ^{11}B beam. The mismatch in the angular momenta distributions between the two reactions cannot be avoided. However, their effect on the proton emission can be disregarded, as predicted by statistical model calculations.

A direct test of the assumptions made in selecting the two reactions can be obtained by looking directly to the distribution of the Bi evaporation residue in the xn channels which are strongly populated in the two reactions. Results are reported in figure 1. It appears that the relative yields of the ^{202}Bi and ^{203}Bi nuclei are the same in the two reactions, as expected. A difference in yield is evident in the case of the ^{204}Bi nucleus which is sensitive to the angular momentum mismatch discussed above.

The average numbers of evaporated neutrons derived from the residues distribution are $\nu_n^{^{11}\mathrm{B}} = 5.93$ and $\nu_n^{^{10}\mathrm{B}} = 5.03$, giving a difference $\Delta\nu_n = 0.9$, very close to the expected difference of one unit between the two reactions. The result is even better ($\nu_n^{^{11}\mathrm{B}} = 6.04$ and $\nu_n^{^{10}\mathrm{B}} = 5.06$, $\Delta\nu_n$=0.98) if the data relative to the ^{204}Bi and ^{205}Bi nuclei are excluded, that is equivalent to cut the higher partial waves in the CN decay reducing the angular momentum mismatch.

The energy spectra of the protons in coincidences with transitions in final Pb evaporation residues are reported in figure 2. In the same figures it is reported the sum spectrum obtained by using as weighting factors the experimental yield derived from the discrete γ-ray spectra.

The high energy tails of proton spectra in coincidence with the ^{204}Pb nucleus were fitted with Maxwellian distributions deriving the apparent nuclear temperatures $T_{\mathrm{app}}^{^{11}\mathrm{B}} = 1.24 \pm 0.09$ MeV and $T_{\mathrm{app}}^{^{10}\mathrm{B}} = 0.99 \pm 0.09$ MeV. The reported uncertainties take also

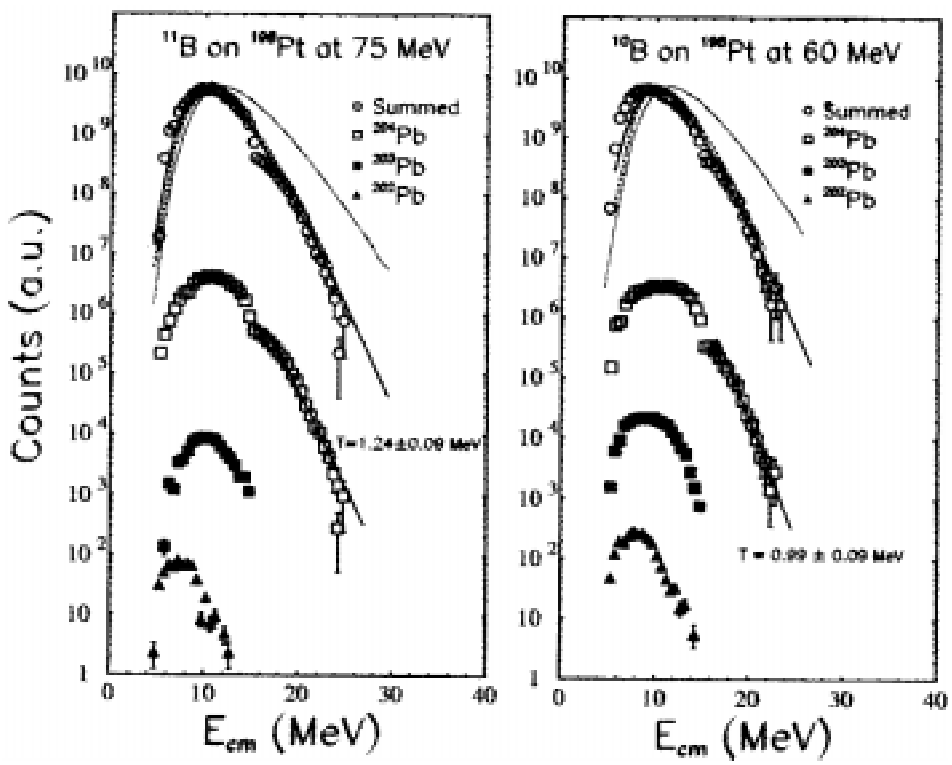

Figure 2. Energy spectra of the protons emitted in coincidence with the different Pb isotopes in the reactions induced by ^{11}B (left) and ^{10}B (right). Statistical model calculations are also shown for different level densities: Reisdorf (dashed lines), $a = A/10$ MeV^{-1} (solid line) and $a = A/21$ MeV^{-1} (dotted line).

into account the small dependences of the best-fit $T_{\rm app}$ parameter on the assumed average barrier ($B_c = 9.5 \pm 0.5$ MeV) and on the fitting region. The multiplicity of the decay channel ending in the ^{204}Pb nucleus was obtained for both reactions from the $\gamma - \gamma$ matrix, relative to the sum of the ER yields in the xn channel which accounts for the bulk of the fusion-evaporation cross section.

Consequently, the temperature associated to the decay from the ^{209}Bi initial compound nucleus to the ^{208}Pb in the first step of the $p4n$ deexcitation chain is obtained from the measured apparent temperatures and relative multiplicities as

$$T(^{208}\mathrm{Pb}) = (\mathrm{M}^{^{11}\mathrm{B}} \times \mathrm{T}_{\mathrm{app}}^{^{11}\mathrm{B}} - \mathrm{M}^{^{10}\mathrm{B}} \times \mathrm{T}_{\mathrm{app}}^{^{10}\mathrm{B}})/(\mathrm{M}^{^{11}\mathrm{B}} - \mathrm{M}^{^{10}\mathrm{B}}) = 1.63 \pm 0.28\,\mathrm{MeV}.$$

This temperature is associated to a thermal excitation energy $E_{\rm th}$ in the daughter ^{208}Pb nucleus $E_{\rm th} = E^{*}_{^{209}\mathrm{Bi}} - E^{\rm rot}_{^{208}\mathrm{Pb}} - S_p - E_p^{\rm kin} = 49.5$ MeV.

It is possible to compare the result obtained in the present work with predictions from the excitation energy dependent parameterization of the level density given by Reisdorf [18] and with the two limiting values corresponding to a cold nucleus where the shell corrections dominate and to an highly excited nucleus where such corrections disappeared. The comparison, presented in figure 3, shows that at the excitation energy of

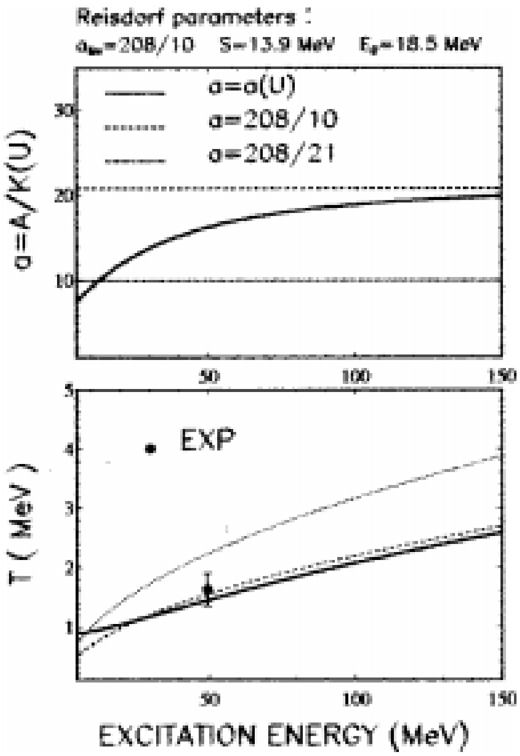

Figure 3. Comparison between the temperature value determined in this work and predictions from different level density prescriptions.

$E_{\rm th} \sim 50$ MeV in the ^{208}Pb nucleus the nuclear temperature is very far from the value associated to the level density parameter $a \sim A/21$ MeV^{-1}, which characterizes the cold nucleus. On the contrary, the experimental nuclear temperature is in agreement with the values associated to the Reisdorf parameterization and to the asymptotic value $a \sim A/10$ MeV^{-1}. The result reported in figure 3 is in agreement with the findings of a recent work on the reactions ^{207,208}Pb($n, xn\gamma$) for neutron energies from 3 to 200 MeV [19].

We note that, despite in the Reisdorf approach the level density parameter is not yet in its asymptotic value, there is a rather reduced difference between the temperatures associated with the excitation dependent level density parameter $a = a(U)$ and the asymptotic value at high excitation. The uncertainty of our temperature measurement does not allow to distinguish between the two temperature predictions.

To further test the level density of the nuclei around ^{208}Pb we have also compared the experimental data with the predictions from complete statistical model calculations. Since the deexcitation chains involve several nuclei, the model calculations cannot be used to study specifically the level density in a given nucleus. The comparison between model predictions and experimental data offer, however, the opportunity of testing in a global way the level density in the mass region around the ^{208}Pb as defined by the limiting values $a \sim A/10$ MeV^{-1} or $a \sim A/21$ MeV^{-1} or as parameterized as a function of the excitation energy and of the shell corrections by Reisdorf.

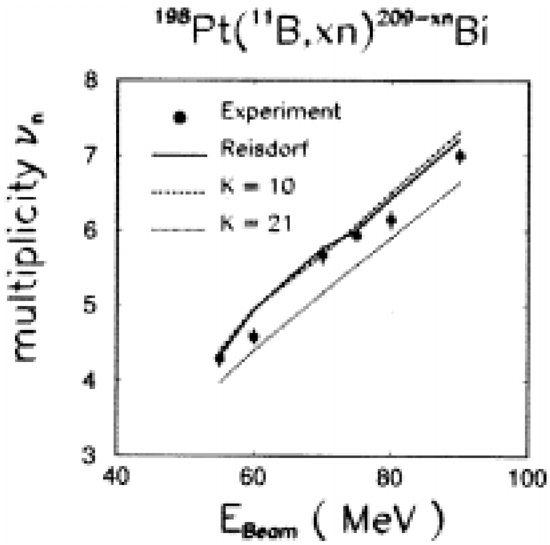

Figure 4. Comparison between the measured neutron multiplicities and the predictions from statistical model calculations using different level density parameters.

To this end the CASCADE code was used, using either the constant level density parameter $a = A/K$ or the Reisdorf parameterization. We first compare in figure 4 the average neutron multiplicity ν_n as derived from the distribution of the Bi isotopes produced in the xn decay with the SM predictions. It appears that the calculations employing the Reisdorf parameterization give a very precise account of the experimental ν_n in the range of bombarding energies explored in this work. The good reproduction of ν_n reflects the capability of the model of predicting well the relative distribution of the Bi isotopes at all bombarding energies.

The same good descriptions were also obtained by looking at the experimental ν_n in coincidence with one proton, i.e. associated to the Pb isotope distributions. Because neutrons are certainly emitted all the way down during the decay, they are sampling also the level density of the more neutron deficient, cold Bi (or Pb) isotopes. Those nuclei are supposed to be characterized by shell effects which are lower than those in the ^{208}Pb nuclei.

In figure 4 the experimental data is also compared with the predictions from calculations employing a constant level density parameter $a = A/K$ using the extreme values of $K = 10$ and 21 MeV. It is well known that the average kinetic energy of the evaporated neutrons increases by increasing the K value and therefore the predicted average number of the neutrons is lower, when the $K = 21$ MeV value is used. The relevant fact in figure 4 is that the calculations employing the constant level density parameter $K = 10$ also reproduce well the experimental ν_n.

To understand the low sensitivity of the statistical model calculations to the details of the level density, we have computed the average temperature T associated to each neutron emission in the 75 MeV ^{11}B+^{198}Pt reaction when the two parameterizations of the level density are considered. It is found that the difference of the temperature estimates (and then the difference in the average kinetic energy of the neutrons) is generally very small, with the exception of last neutron which is emitted in the region of low excitation energy where the effects due to the shell corrections are magnified.

Equivalent results are obtained by comparing the experimental 'summed' proton spectra with the predictions from statistical model calculations, as shown in figure 2. The calculated spectra using the Reisdorf parameterization as well as the constant value $a = A/10$ MeV^{-1} fit well the experimental spectra. On the contrary the level density parameter $a = A/21$ MeV^{-1} predicts unrealistic shapes for the proton spectra. We note that, following the statistical model predictions, the 'summed' proton spectra contain in large part particles which are emitted at the higher excitation energies, being therefore far from the region where shell effects dominate.

High energy γ-rays have been measured in the present experiment at all bombarding energies in both ^{11}B- and ^{10}B induced reactions by using the two, large volume BGO detectors. The high energy gamma-rays are in this case of special interest. In fact it is well known [20] that the statistical tail at $E_\gamma \leq 8$ MeV, is sensitive to the level density of the nuclei in the latest steps of the decay cascade, for which we expect a very large influence of the shell corrections. It is therefore expected that the ratio between the statistical tail ($E_\gamma \leq 8$ MeV) and the giant dipole resonance region ($E_\gamma \geq 8$ MeV) should be a sensitive probe for the level density parameterization used in the statistical model calculations. Furthermore, high energy gamma-ray spectra emitted in the decay of the neutron deficient ^{200}Pb compound nucleus have been extensively studied in the past giving the opportunity of comparing two systems (^{200}Pb and ^{209}Bi) quite different from the point of view of the shell corrections.

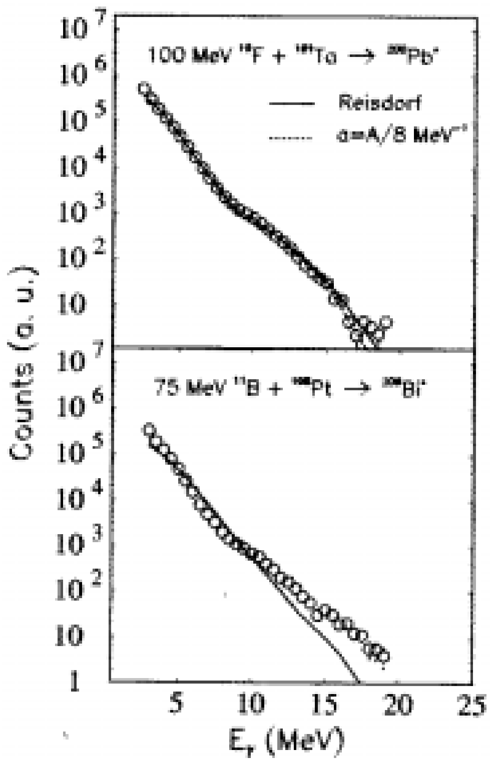

Figure 5. High energy γ-ray spectra measured in the present work.

In figure 5 spectra are reported from the two reactions ^{19}F+^{181}Ta at 100 MeV and ^{11}B+^{198}Pt at 75 MeV, which are populating compound nuclei at a rather equivalent excitation energy. The high energy spectrum from the first reaction is rather well accounted for by using constant parameter $a = A/8$ MeV^{-1} as well as the Reisdorf level density parameters and published GDR parameters [21]. Results are different when the ^{11}B+^{198}Pt is considered. In this case the description of the experimental spectra is rather poor and the deviations between experiment and model predictions increases by decreasing the bombarding energy. This means that the statistical model fails in giving a sufficiently good description of the phase space at low excitation energies even if the more detailed parameterization of the level densities available is used.

4. Conclusions

The study of the excitation energy dependence of the level density is a topic of continuous interest in nuclear physics.

Transition 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 ($A \sim 110, 160$).

In the mass region $A \sim 200$ we are presently investigating the diminishing of the effects due to the shell structure in increasing the excitation energy. Experimental results about 50 MeV excitation energy in the ^{208}Pb confirm that the bulk of the shell effects are already washed out. Nevertheless, the level density parameter seems still far from its predicted asymptotic value. High energy γ-rays seems to be a very important tool to study the level density at excitation energies of few tens of MeV. Furthermore we would also like to explore, increasing the bombarding energy, the second transition from the asymptotic average level density parameter towards the FG value, as suggested from earlier investigations [22,23]. In this attempt extreme care has to be taken due to the onset of the incomplete fusion already below 10 MeV/nucleon bombarding energy, as already reported from γ-ray particle correlation studies.

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 for measuring the nuclear temperature and the excitation energy in hot nuclear systems.

Acknowledgement

The experimental works described here have been part of collaborations between Padova, Legnaro and the Texas A&M University and several other groups. Special thanks are due to the members of the GASP collaboration for the experiments performed at this facility.

References

[1] A Bohr and B R Mottelson, *Nuclear Structure* (Benjamin, Reading, MA, 1969 and 1975) vols I and II

[2] A V Ignatuk *et al*, *Sov. J. Nucl. Phys.* **21**, 255 (1975)
[3] P F Bortignon and C Dasso, *Phys. Lett.* **B189**, 381 (1987) and references therein
[4] A K Kerman and S Levit, *Phys. Rev.* **C24**, 1029 (1981)
B Lauritzen, G Puddu, P F Bortignon and R A Broglia, *Phys. Lett.* **B246**, 329 (1990)
[5] P Donati *et al*, *Phys. Rev. Lett.* **72**, 2835 (1994)
[6] K Hagel *et al*, *Nucl. Phys.* **A486**, 429 (1988)
[7] M Gonin *et al*, *Phys. Lett.* **B217**, 406 (1989); *Phys. Rev.* **C42**, 2125 (1990)
[8] R Wada *et al*, *Phys. Rev.* **C39**, 497 (1989)
[9] G Nebbia *et al*, *Nucl. Phys.* **A578**, 285 (1994)
[10] S Shlomo and J B Natowitz, *Phys. Rev.* **C44**, 2878 (1991)
[11] B Fornal *et al*, *Phys. Lett.* **B255**, 325 (1991) and references therein
[12] B Fornal *et al*, *Z. Phys.* **A340**, 59 (1991)
[13] B Fornal *et al*, *Phys. Rev.* **C44**, 2588 (1991)
[14] D Bazzacco *et al*, *Phys. Lett.* **B309**, 235 (1993)
[15] G Viesti *et al*, *Nucl. Phys.* **A604**, 81 (1996)
[16] E Farnea *et al*, *Nucl. Inst. Meth.* **A400**, 87 (1997)
[17] M Lunardon, PhD Thesis, (University of Padova 1998) to be published
[18] W Reisdorf, *Z. Phys.* **A300**, 227 (1981)
[19] H Vonach *et al*, *Phys. Rev.* **C50**, 1952 (1994)
[20] M Kicinska-Habior *et al*, *Phys. Rev.* **C41**, 2075 (1990)
[21] R Butsch *et al*, *Phys. Rev.* **C41**, 1530 (1990) and references therein
[22] D Fabris *et al*, *Phys. Rev.* **C50**, R1261 (1994)
[23] B J Fineman *et al*, *Phys. Rev.* **C50**, 1991 (1994)