Hot nuclei in reactions induced by heavy projectiles, protons and antiprotons

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ABSTRACT

Light projectiles like protons and antiprotons with several GeV kinetic energy enable a very efficient heating of nuclei, similar to what is routinely achieved in nucleus-nucleus collisions. At the same time, the excitation of the collective modes in nuclei is minimized, making possible for the first time the study of the heat effects exclusively. The scarcity of multifragmentation in antiproton induced reactions on heavy targets seems to show that when such a phenomenon occurs in a nucleus-nucleus collisions it is most likely driven by initial compression and angular momentum rather than heat.

1. Hot Nuclei

In the recent years the properties of strongly heated nuclei have been extensively investigated up to the limits of stability of nuclei. Theoretical models have predicted the existence of a maximum thermal energy that a nucleus can sustain. Above this energy -or corresponding temperature- the ensemble of interacting nucleons cannot be considered anymore as a selfbound object called "a nucleus" (Bonche et al 1984, 1985, Suraud 1987, Baldo et al 1994). The limiting temperature is predicted to depend on the structure of the considered nucleus. Indeed, the Coulomb field in a nucleus plays a destabilizing influence that makes heavy nuclei more suscebtible to temperature effects than light ones (Levit and Bonche 1985). For the same reason, when considering a variety of isotopes with the same Z, a neutron-rich isotope is expected to sustain a higher temperature than a neutron-deficient one (Suraud et al 1987). It has been stressed by different authors that the nuclear equation of state is directly related to the limiting temperature that the nucleus is able to sustain before reaching instabilities (Levit and Bonche 1985, Song and Ku 1991).

Usually, the observation, in the exit channel of a nuclear reaction, of many nucleons and rather small composite particles is considered as a signature of the new state beyond the nucleus. The corresponding transition is called either multifragmentation (Moretto and Wozniak 1993) or vaporization. Both terms are loosely defined, the latter usually refers to final states with all particles lighter than Li whereas the former implies the break up of the nucleus in more than two major pieces with a number of accompanying lighter particles (note that binary fission accompanied by particles of mass equal to or smaller than α-particles is not considered as multifragmentation). Vaporization is expected at higher excitation energy than multifragmentation.

2. Hot Nuclei in Nucleus-Nucleus Collisions

2.1 A Selection of the Different Exit Channels as a Function of Energy Damping (example of the 29 MeV/nucleon Pb+Au reactions)

Many attempts have been made in order to bring a nucleus close to the transition state where it ceases to behave as a selfbound object. In most cases the heating process implies the interaction of heavy nuclei, either at moderate energies (i.e. with projectiles at about 1/3 of light velocity as in GANIL, MSU or RIKEN) or in peripheral collisions of much more energetic projectiles (as at SIS) (Gelbke 1995, Trautmann 1995). At moderate bombarding energy the heating proceeds through a stochastic exchange of nucleons between the interacting nuclei (Quednau et al 1993) leading to particle-hole excitations in both nuclei. For asymmetric entrance channels massive transfer or incomplete fusion can aso be achieved for the most central collisions (Piasecki 1995). The resulting excitation energies depend critically upon the impact parameter. Moreover in addition to the excitation of the intrinsic degrees of freedom, collective degrees of freedom such as the rotation, the compression and the deformation modes get also excited. Thus, most of the time, one is led to study the properties of two nuclei (the projectile- and target-like nuclei) whose many degrees of freedom have been simultaneously excited. This is a very challenging problem. Indeed, most often, the decay products from the projectile-like and target-like nuclei are not all fully separated in phase space, making the event by event study hazardous. Moreover, in addition to the products from projectile- and target-like nuclei, there exist products from the neck which has initially built up between the two nuclei or fragments emitted prior to equilibrium rendering the investigations even more delicate (Lecolley 1995, Lopez 1995, Töke 1995).

An illustration of this type of nucleus-nucleus collisions is given in Fig.1. The Pb projectile impinges on a Au target at 29 MeV/nucleon and the characteristic properties of the Pb-like reaction products are measured as a function of the associated neutron multiplicity (Piasecki et al 1991, Bresson et al 1992). The latter quantity acts as a filter on energy dissipation i.e. on impact parameter (Galin and Jahnke 1994). For peripheral collisions characterized by a low neutron multiplicity, the Pb-like nuclei are only weakly excited and end up as evaporation residues. With increasing energy deposition, the Pb-like nuclei evaporate more and more nucleons (the residue charge decreases), and most often undergo binary splitting (standard fission). Finally, for the most dissipative collisions, binary fission gives way progressively to multiple fragments of rather low Z's such as in a process being often referred to as multifragmentation. Dedicated studies of the latter events have been performed (Lecolley et al 1994) showing, first, that the reaction remains essentially binary in a first stage for all dissipated energies and second, that most of the initial energy can be damped in the most central collisions. There is thus the possibility to bring the considered nuclei of masses close to 200 to excitation energies of about 1000 MeV (or temperatures of the order of 7-8 MeV, using the Fermi gas approximation with a level density parameter a=A/13) when most of the energy is to be found in thermal energy (Fig.2, Lopez 1995). Another dedicated study of the nuclear temperature as a function of excitation energy (Fig.3, Morjean et al 1995) has not shown any deviation from the Fermi liquid regime up to excitation energies of 5 MeV/nucleon, in contradiction with what has been shown elsewhere in peripheral collisions (Pochodzalla et al 1995) for a similar system at a bombarding energy twenty times higher. There is no indication of phase transition when considering the caloric curve shown in Fig.3.

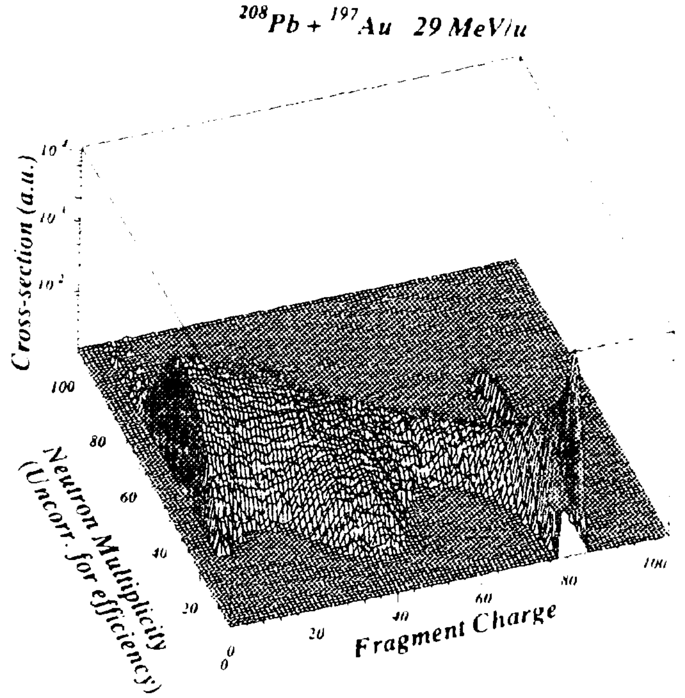

Fig.1: Z distribution of the Pb-like reaction products after a 29 MeV/nucleon Pb interaction with Au as a function of the associated neutron multiplicity (as adapted from Bresson 1993)

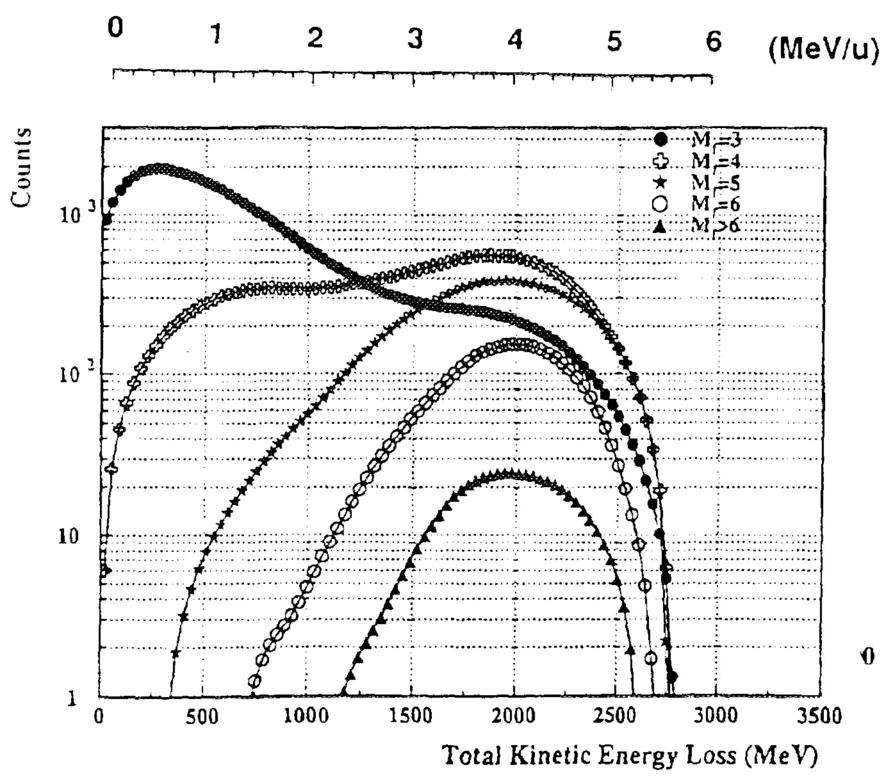

Fig.2: Distribution of the multifragment events (all fragments with Z>8 whatever their source) with multiplicity M_f as a function of dissipated energy (from 29 MeV/nucleon Pb+Au, Lopez 1995)

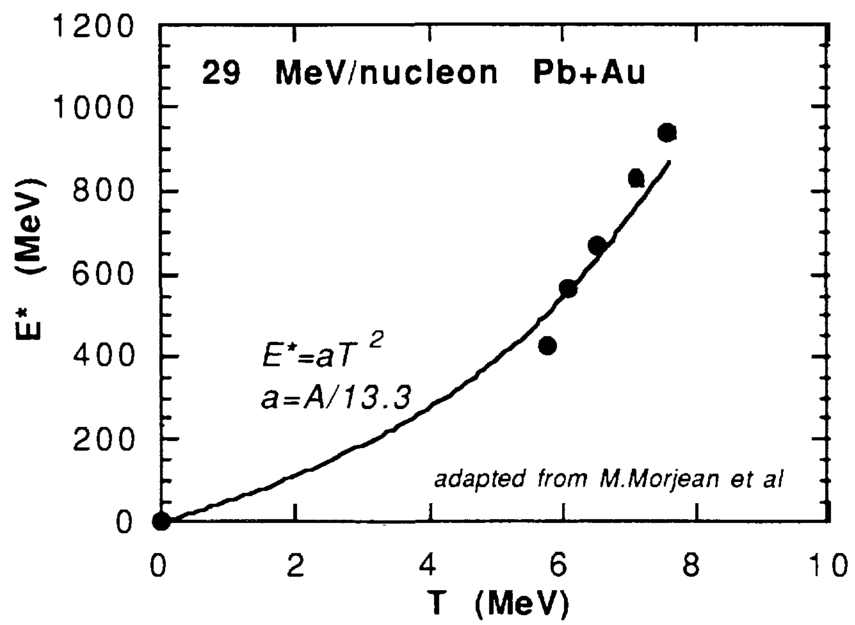

Fig.3 Correlation between dissipated energy and temperature as deduced from the Pb+Au reactions (Morjean 1995).

2.2 Strong Excitation of the Collective Modes in Nucleus-Nucleus Collisions (Example of the 29 MeV/nucleon Pb+Au Reactions).

The study of the dynamics of a nucleus-nucleus collision is a necessary step in order to know how the initial energy is dissipated and in what degrees of freedom this energy is finally tied up. The kinetic equations were thus solved in the frame of the Landau-Vlasov approach for the Pb+Au system considered before (Bresson 1993). The results are qualitatively illustrated in Fig.4 for different impact parameters using snapshots of the projection on the reaction plane of the one body distribution function. It is shown that the heated nuclei are strongly deformed as the impact parameter decreases, that all the fragments cannot be attributed to projectile- or target-like nuclei as it has been observed also in the experimental data (Lecolley 1995) and that the fragments are initially compressed. Moreover -and this is not apparent in the cartoon but it can be derived quantitatively from the computed data- the nuclei are spinning after the interaction. Spins up to 60-80 hbars units have been estimated for the fissioning tprojectile-like nuclei in rather peripheral collisions (Bresson et al 1993).

It is thus seen that the sharing between intrinsic and collective excitation depends strongly on the impact parameter and that the heated nuclei are left with all their degrees of freedom excited (Bresson 1993). Because of the sensitivity of the sharing to the equation of state (Xu et al 1991), there is certainly extremely rich physics to be studied there, but the experimentalist faces an extraordinary complex problem when all degrees of freedom are varying simultaneously. It is difficult to disentangle thermal from collective effects.This has motivated us (Galin 1988) to complement the nucleus-nucleus investigations by alternative approaches in order to excite nuclei without compression, spin, shape distorsions (or at least to minimize these collective excitations as much as possible).

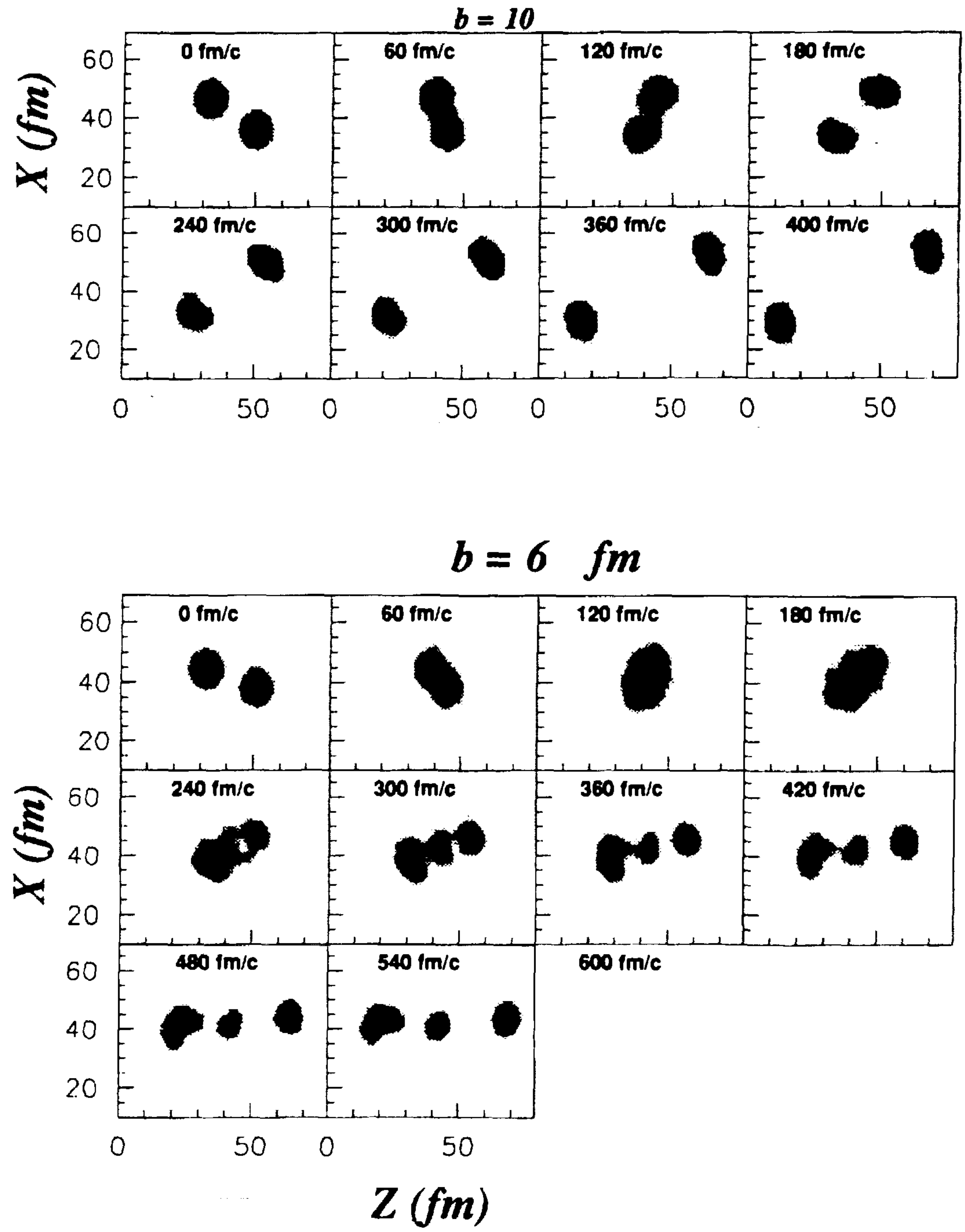

Fig.4: Snapshots, as a function of time, of the projection on the reaction plane of the one-body distribution function for the 29 MeV/nucleon Pb+Au collisions for impact parameters of 10 and 6 fm (Bresson 1993).

3. Protons and Antiprotons as Efficient Heaters of the Nucleus.

Proton and antiproton induced reactions are interesting alternatives for a "soft heating" of a nucleus. Such reactions present the decisive advantage of undergoing weak collective excitations (Cugnon 1993). To first approximation, both the rotation, compression and deformation energies can be simply neglected as shown in Intra Nuclear Cascade calculations (Cugnon et al 1985, 1987, 1988, Golubeva 1988). These projectiles are thus ideally suited to complement the data obtained in nucleus-nucleus collisions. The thermal effects can be investigated without beeing distorded or even masked by the collective ones. In the following, we would like to give the status of such investigations which have taken advantage of the 4π detectors developped for nucleus-nucleus studies. We will try to show that not only very high thermal energies can be reached but that some of the decay channels appear clearly different from what has been observed in nucleus-nucleus collisions for similar deposited thermal energies.

The interaction of pions and protons with a nucleus has been usually treated as a succession, or cascade, of independent pion(nucleon)-nucleon collisions. As for the antinucleon-nucleus collisions, one deals first with the annihilation, most of the time on a single nucleon and taking place on the surface of the nucleus (T. von Egidy 1987). With antiprotons at rest, five pions are emitted with only some of then interacting with the nucleus. One can thus consider the antinucleon-nucleus interaction as a multi-pion-nucleus interaction, making it more efficient -in terms of energy dissipation- than a single pion-nucleus interaction (Polster 1995).

Annihilations with accelerated antiprotons are expected to bring more excitation energy into the nucleus than those proceeding with antiprotons at rest. In the last case the annihilation takes place after formation of an antiprotonic atom in the outer tail of the density distribution of the nucleons in the nucleus. With accelerated antiprotons and due to the decrease of the antinucleon-nucleon cross section with energy, the mean free path of the antinucleon increases slightly with energy, making the annihilation closer to the center of the nucleus. This gives the emitted pions a higher probability to interact with the nucleus and thus to deposit their energy in the nucleus. In addition, the boost in energy of the pions provided by the accelerated projectile makes their interaction with the nucleus more probable (Cugnon 1993).

3.1. Comparison Between Protonic and Antiprotonic Heating on the basis of INC calculations.

The first question raised when using proton or antiproton projectiles relates to their ability to heat up a nucleus as efficiently as it can be in a nucleus-nucleus interaction. Calculations developed by J.Cugnon (1993) show that both with energetic antiprotons and protons thermal energies of the order of or higher than 1 GeV should be reached for a nucleus of mass 200 (there are broad fluctuations and the predictions shown on Fig.5 are only mean values). It is also clear from the model calculations that at any given bombarding energy the antiproton takes the lead over the proton in terms of deposited energy into the nucleus (Fig.5). This is due the extra energy which is released in the annihilation and which contributes efficiently to the heating. With antiprotons at rest, annihilation is obviously the only source of energy. Recent calculations for antideuterons (Cugnon 1992) demonstrate the great benefit that could be taken from a double annihilation. It can be mentioned that a different type of INC calculations performed for p-nucleus (Botvina) lead to larger excitation energies whereas for pbar-nucleus (Golubeva) they lead to similar energies than shown in Fig.5.

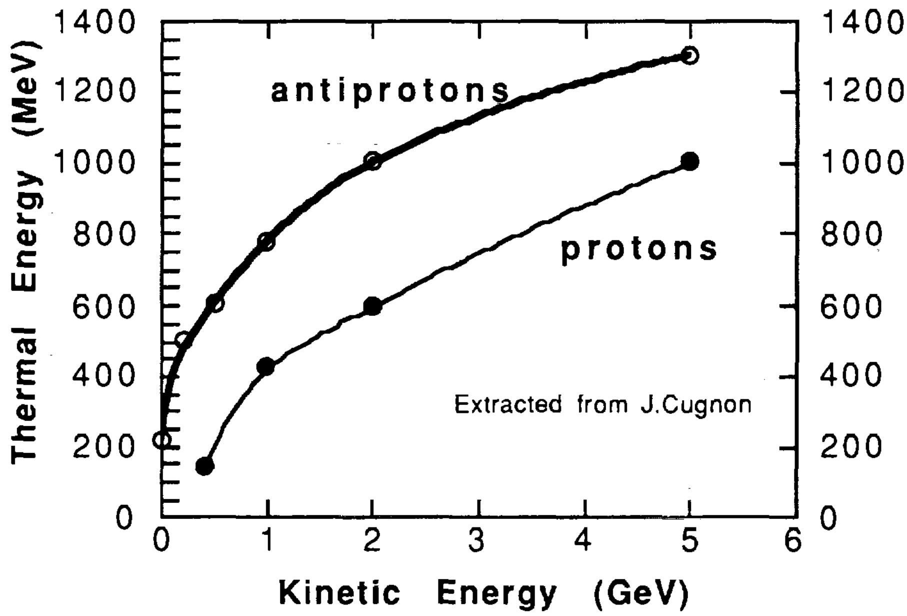

Fig.5 Protonic and Antiprotonic Heating of Nuclei with mass 200 in central collisions (Cugnon 1993).

To check these theoretical predictions an experimental program has been initiated with both the proton beams of SATURNE (Saclay) and the antiproton beams of LEAR (CERN-Geneva). In both cases the main observable considered is the multiplicity of emitted neutrons. It is well known that for heavy nuclei this quantity is strongly connected with thermal energy. The absence of barrier makes the evaporation of neutrons strongly favored over charged particles. For a nucleus of mass 200 with E*=1 GeV, evaporation calculations and experimental data show that the ratio of emitted neutrons to all emitted particles is close to 70% (Lott 1993). Counting the neutrons with an efficient 4π Gd-loaded, liquid scintillator detector provides a good picture of the heat distribution as a function of the nature of the projectile and its bombarding energy. Moreover this kind of detector is weakly sensitive to high energy neutrons emitted during the first stages of the cascade thus making it a reliable thermometer.

3.2. Protonic Heating as Deduced from Experiment (2 GeV p and ^{3}He induced reactions at SATURNE)

The data, both with p and ^{3}He as projectiles, exhibit a broad neutron multiplicity (Mn) distribution with two maxima: the first one peaked at low Mn stems from peripheral collisions whereas the second one, much broader, originates from an extended range of more central collisions (Fig.6, Ledoux 1995). These distributions resemble very much those measured in heavy nucleus induced collisions, both in shape and by the number of neutrons, readily indicating large amounts of thermal energy (Schwinn 1994). Such distributions can be fairly well reproduced by a two-step model, an Intra Nuclear Cascade followed by a sequential evaporation. Such calculations are also able to reproduce correlated observables such as the multiplicity of evaporated H and He particles as a function of neutron multiplicity. This gives good confidence in the thermal energy distribution which can be carried out from such calculations. It is thus shown that a 2GeV proton interaction with Au leads for more than 15% of the events to energy depositions (thermal energy) larger than 500 MeV (i.e. temperatures larger than 5 MeV in a Fermi model with a level density parameter a=A/10). Energies as high as 800 MeV are even reached in the tail of the distribution (Fig.7, Pienkowski 1994).

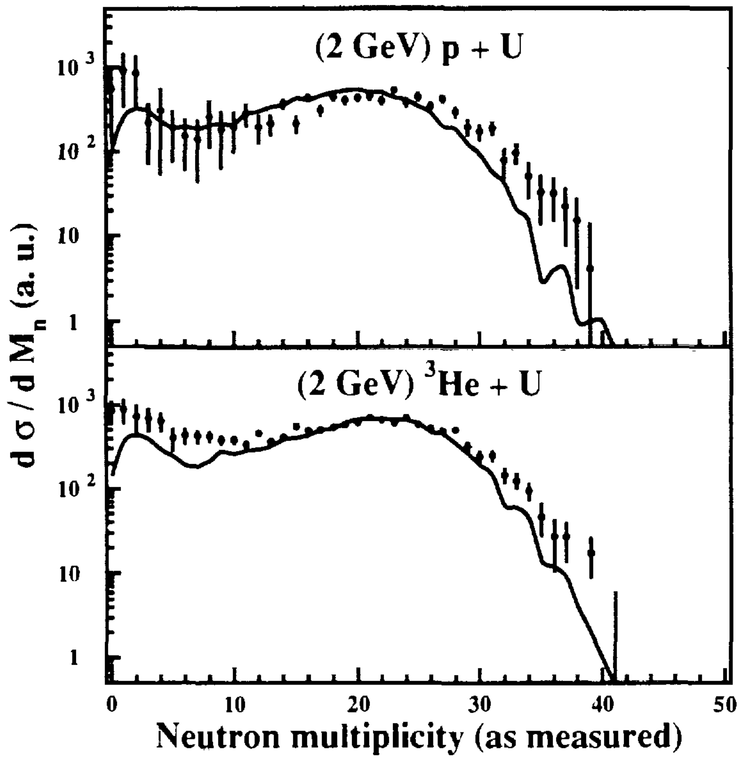

Fig.6 Neutron multiplicity distributions as measured (dots) and compared with model calculations folded by detection efficiency (solid line) for 2 GeV proton and ^{3}He induced reactions (adopted from Ledoux 1995).

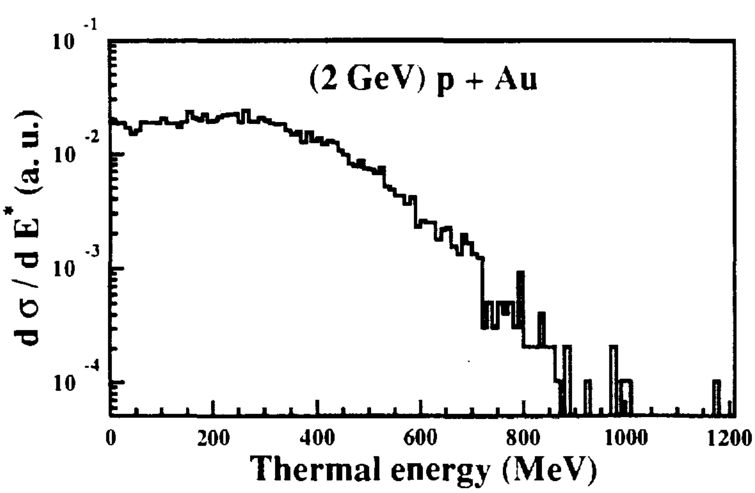

Fig.7 Thermal energy distribution as computed after interaction of a 2 GeV proton with a Au nucleus (Ledoux 1995).

3.3. Antiprotonic Heating as Deduced from Experiment (PS208-LEAR-CERN experiment)

Preliminary neutron multiplicity data from antiproton experiments have shown a different pattern from those observed for proton experiments with a strongly pronounced maximum at high multiplicity and hardly any contribution at low Mn (Fig.8 from experiment PS208). This is due to the annihilation process which always leads to a rather large energy deposition.

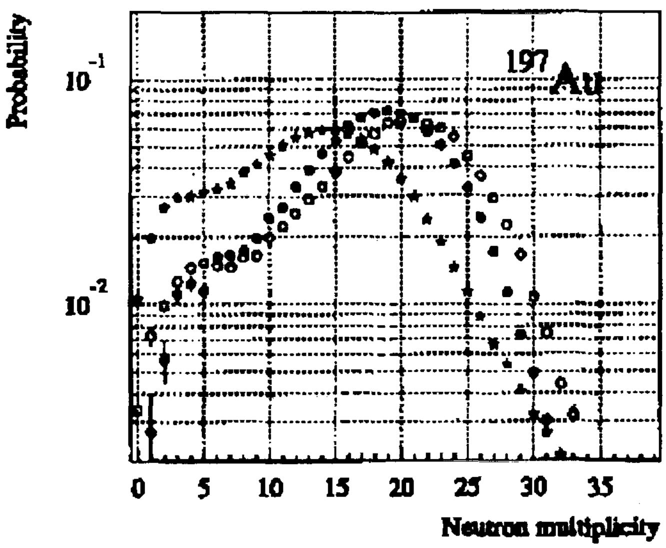

Fig.8 Neutron multiplicity distributions as measured in antiproton reactions induced on a Au target at 0, 585 and 1217 MeV (star, full and open symbols, respectively). (Hilscher 1994).

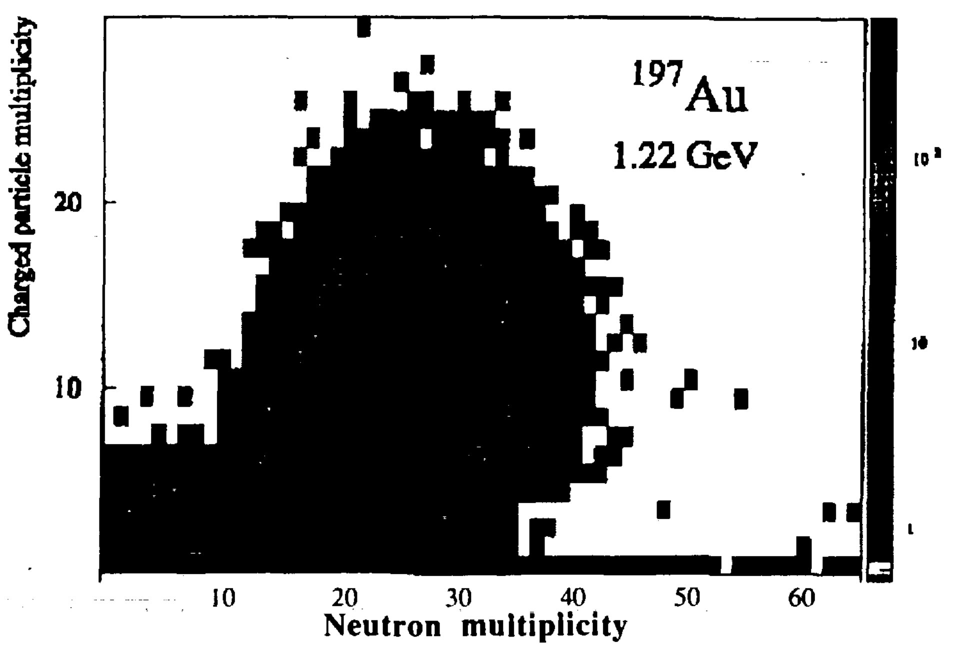

Fig.9 Distribution of correlated neutron and charged particle multiplicities (as measured) in the interaction of 1.217 GeV antiproton with a Au target (on line data PS208, Hilscher 1994))

Preliminary estimates of the dissipated energy distribution have been made by summing up event by event the estimated energy removed by all evaporated-like particles (neutral and charged) from data as shown in Fig.9 (Hilscher 1994). For nuclei with mass 200, energies as high as 1 GeV can be carried out for 1.217 GeV antiproton induced reactions, thus demonstrating the great benifit when using projectiles of antimatter.

The data from PS208 have also been tentatively compared with classical evaporation calculations. Using the GEMINI evaporation code one computes as a function of thermal energy the total number of evaporated particles and their distribution as neutrons, H, He and IMF (Lott 1993). These quantities are shown as continuous lines in Fig.10. The total measured multiplicity of evaporated-like particles in the 1.217 GeV antiproton induced reaction was normalized on the calculated ones. It is verified that the distribution of the different kinds of evaporated particles, n, H, He, IMF, scales rather well with the model predictions giving confidence that the multiplicity of all emitted particles provides a rather good indication of the excitation energy. It is thus demonstrated that thermal energies of about 1 GeV are reached with 1.217 GeV antiprotons which could not be attained with protons of higher energy (2 GeV protons in the SATURNE experiment).

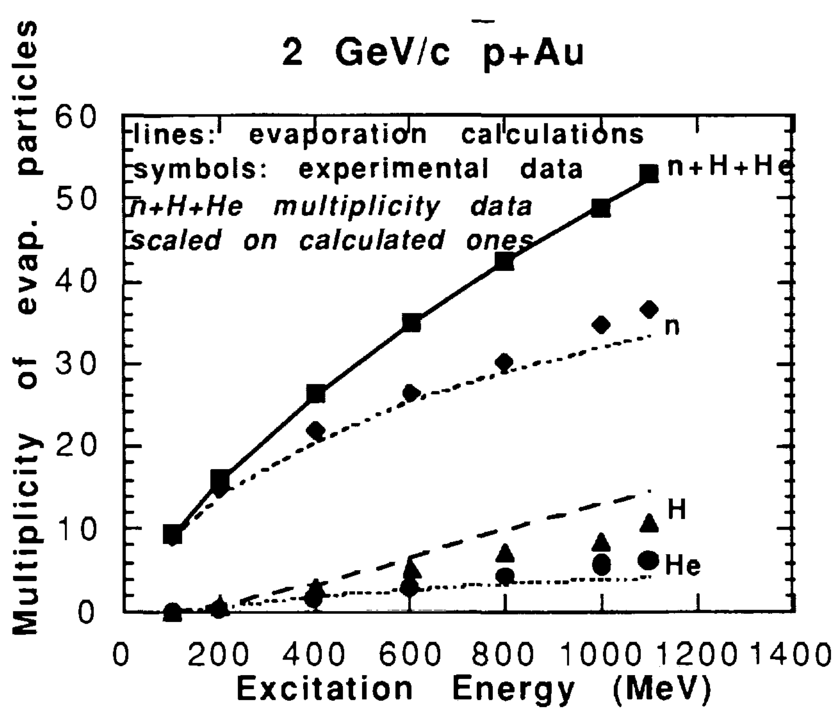

Fig.10: Expected multiplicity of evaporated particles (n, H, He and n+H+He) as a function of excitation nergy as obtained from GEMINI (short-dashed, long-dahed, dotted, and solid lines respectively) and comparison with experimental data (diamonds, triangles, dots and squares, respectively)

A similar conclusion has been pointed out considering the target residue distribution as it is obtained in radiochemical measurements. It has been shown that the stopped antiproton data scale reasonably well with the 1 GeV proton data on one hand and that the 1.217 GeV antiproton data scale with the 6 GeV proton data on the other hand. Such features verify qualitatively the theoretical predictions given in Fig.5 showing that antiprotons are definitely much more efficient heaters than protons at the same energy (J.Jaztrzebski 1995).

3.4. Compared Decay of Hot Nuclei after Antiproton and Nucleus-Nucleus Reactions

As already shown, the simultaneous detection of neutrons and charged particles by 4π devices makes possible a detailed investigation of the different decay channels. With the data analysis still in progress, one can only present some highlights and stress the main differences in the decay properties of nuclei heated with antiprotons on one hand and those obtained in heavy-ion induced collisions on the other hand.

The vaporization of the nucleus into nucleons and small composite particles (essentially n and H, He) has been observed for medium size nuclei (Cu) with a probability of about 1% in antiproton-induced reactions at 1.217 GeV. Most of the emitted particles are isotropically emitted reflecting an equilibrium and evaporative origin. On the average the distribution of the products in the exit channel is given as follows after efficiency corections: 11.6 detected neutrons, 10.3 hydrogen isotopes, 5.5 helium isotopes and 1.0 Intermediate Mass Fragment (essentially Li, Be nuclei), making altogether an average total Z=27 and a total A=56. The difference of charge and mass with those of the interacting projectile and target (Z=28 and A=64-66) is due to the finite efficiency of both 4π detectors and to the undetected escaping pions.

Vaporization phenomena have also been observed for both projectile and target nuclei by the INDRA collaboration in ^{36}Ar+58Ni reactions between 32 and 95 MeV/nucleon bombararding energies (Bacri 1995). At best, in the collisions at 95 MeV/nucleon the vaporization channel exhausts about 10^{-4} of the reaction cross section i.e. two orders of magnitude less than in the antiproton induced reaction. The latter reaction appears thus more efficient than the former one to bring a nucleus at the vaporization stage but it is not yet clear whether the two phenomena have a common origin. Indeed there is a build up of collective excitation in the nucleus-nucleus collision which does not exist in the antiproton-induced reaction. In particular spin effects could be responsible for the much more probable He emission in the nucleus-nucleus collision. More detailed comparisons still need to be performed in order to track down other possible differences in the exit channels.

The behavior of heavy easily fissionable target nuclei raised at high excitation energy is also a topic of current interest. These heavy nuclei have a propensity for undergoing multifragmentation in nucleus-nucleus collisions as illustrated in Fig.1. Such a behavior seems quite unlikely in antiproton induced reactions leading to similar energy depositions. Multifragment events are comparatively scarce and when they are observed the fragments are rather light (from Li to C essentially). Fraction of these events can be essentially accounted for by an evaporation code which treats IMF emission on the same footing as light particle evaporation. This is a marked difference with what has been observed in nucleus-nucleus collisions where the calculated IMF abundancy always underestimates the data by a large amount. This gives a strong hint that compression effects followed by an expansion of the nuclear system are responsible for multifragmentation in nucleus-nucleus collisions and that such a phenomenon has very little to do with thermal effects.

At the same thermal energy and for different targets, binary fission is observed in antiproton induced reactions with considerably larger probabilities than after a nucleus-nucleus collision (preliminary data with 1.217 GeV antiproton on U give as much as 30%

fission probability at about 1 GeV excitation energy). Clearly the much lower multifragmentation probability is responsible for such a difference. To our knowledge it is the first time that fission of a nucleus can be investigated at the level of 1 GeV excitation energy in absence of spin and for better defined initial nuclei. All previous studies of fission at such energies were performed after a nucleus-nucleus collision and thus were complicated by the presence of spin. The observation of fission is of particular interest since it can be used as a signal for collectivity in the sense that if we observe fission in the exit channel (or an evaporation residue) at very high initial temperature it is a proof that the nucleus as such as survived.

These antinucleon induced reactions shed new light on the fission process itself. It has been argued in the recent years (Hilscher and Rossner 1992) that the competition between evaporation and fission could not be treated considering only available phase space as done in a classical deexcitation model. Indeed the fission process, a highly collective decay mode, is slow as compared to the evaporation of light particles and this dynamical effect should be taken into account properly. This allows for many particle to be emitted prior to fission and indeed many particles have been measured prior to scission (Hilscher and Rossner 1992). Experimentally it is rather easy to distinguish particles emitted prior to scission from those after scission but it is more difficult to distinguish those emitted prior or post the saddle-point, the irreversible point towards fission. With these new data one can expect to learn something new on the rate of evaporation before and after saddle. Indeed, if all evaporated particles detected in coincidence with the fission fragments in the antiproton experiment were emitted first, then a large fission barrier would build up and the depleted nucleus would have no chance to undergo fission anymore. Only if a limited number of particles of presaddle origin are evaporated can the chance to undergo fission remain sizeable. A detailed analysis of these fission probability data (not yet performed) is thus expected to provide new insights into the fission process at high excitation energy.

4. Summary and prospects

The first attempts to a detailed study of hot nuclei produced with light projectiles (protons and antiprotons) have been successful and very encouraging. First it has been shown that energy depositions as thermal energy of the order of 1 GeV were feasible and that detailed analysis of such events have been made possible by coupling a 4π neutron detector of high efficiency with a 4π detector of large dynamics for charged particles.

Marked difference have been observed in the decay of such nuclei with what has been measured in nucleus-nucleus collisions for similar temperatures. Multifragmentation has essentially disappeared in antiproton induced reactions stressing the role of compression in such a phenomenon when it is observed after a nucleus-nucleus collision. In contrast binary fission becomes a widely opened channel giving a unique opportunity to study the dynamics of fission in absence of spin.

For medium size nuclei, vaporization has been observed as in nucleus-nucleus collisions but with a much larger probability. Much work has still to be done for comparing in detail the characteristics of such pocesses and see what can be learnt from the dissociation. Is it a signature that the maximum temperature has been reached in such nuclei? So far such a vaporization has not been observed in more massive nuclei.

Model calculations indicate that the use of more energetic protons and antiprotons would allow higher excitation energies to be reached. Gains of more than 50% are expected from both types of beams going from the presently employed energy up to 5 GeV. Also reasonably intense beams ($I>10^4$ pps) of antideuterons would be of considerable interest giving the opportunity to probe the limit of stability with respect to temperature for the heaviest nuclei.

Our understanding of hot nuclei properties is expected to benefit from the comparison of light (anti)particle induced reactions with heavy nuclei induced reactions. As much effort should be devoted to the study of the former than has been done for the latter. Unfortunately there are fewer and fewer light particle accelerators available in the world to complete such a program. A premature shutdown of the excellent antiproton beams from LEAR at CERN would be a great handicap.

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References

Bacri C.O. et al, *Phys. Lett.* **B353** (1995) 27
Baldo M. et al, *Phys. Lett.* **B340** (1994) 13
Bonche P., Levit S and Vautherin D, *Nucl. Phys.* **A427** (1984) 278
Bonche P., Levit S and Vautherin D, *Nucl. Phys.* **A436** (1985) 265
Botvina et al, to be published
Bresson S., PhD Thesis Caen University*GANIL Preprint* **T-93-02** (1993)
Bresson S. et al, *Phys. Lett.* **294B** (1992) 33
Cugnon J. and Vandermeulen J., *Nucl. Phys.* **A445** (1985) 717
Cugnon J. et al, *Nucl. Phys.* **A470** (1987) 558
Cugnon J. et al, *Nucl. Phys.* **A484** (1988) 542

Cugnon J., *Second Biennal Workshop on Nucleon-Antinucleon Physics Moscow Sept* (1993), *Preprint* **ULG-PNT-93-1-G**
Cugnon J.,.*Nucl. Phys.* **A542** (1992) 559.........
Von Egidy T., *Nature* **328** (1987) 773
Galin (1988) *Nucl. Phys.* **A488** (1988) 297c
Galin J., Jahnke U. *J. Phys. G: Nucl. Part. Phys.* **20** (1994) 1105
Gelbke C.K., *these Proceedings* (1995)
Golubeva Y.S. et al, *Nucl. Phys.* **A483** (1988) 539
Golubeva Y.S. et al, to be published
Hilscher D. and Rossner H., *Ann. Phys., Paris* **17** (1992) 471
Hilscher D. for PS208, contribution to LEAP'94, *Proceedings of the third biennal conference on low-energy antiproton physics*, Bled (Slovenia) Sept. 1994, edited by M.Mikuz (World Scientific, Singapore, 1995).
Jastrzebski J. et al , Proceedings of XXIX Zakopane School of Physics, Trends in Nuclear Physics, *Acta Polonica* **B26** (1995) 527
Lecolley J.F. et al, *Phys. Lett.* **325B** (1994) 317
Lecolley J.F. et al, *Phys. Lett.* **354B** (1995) 202
Ledoux X, PhD thesis GANIL (1995) and to be published
Levit S. and Bonche P., *Nucl. Phys.* **A437** (1985) 426
Lopez et al, Contribution to the XXXIIIrd Int. Winter Meeting on Nucl. Phys. Bormio (1995) to be published
Lott B. et al, *Z. Phys.* **A346** (1993) 201
Moretto L.G. and Wozniak G.J., *Annual Rev. of Nucl. and Part. Science* **43** (1993) 379 and references therein
Morjean et al , *Nucl. Phys.* (1995) in press
Piasecki E. et al, *Phys. Rev. Lett.* **66** (1991) 1291
Piasecki E. et al, *Phys. Lett.* **B351** (1995) 412
Pienkowski L et al , *Phys. Lett.* **336B** (1994) 147
Pochodzalla J. et al, *GSI Preprint* **GSI-95-13** (1995)
Polster et al, *Phys. Rev.* **C51** (1995) 51
Song H.Q. and Su R.K., *Phys. Rev.* **C44** (1991) 2505
Suraud E., *Nucl. Phys.* **A462** (1987) 109
Quednau B. et al, *Phys. Lett.* **309B** (1993) 10
Schwinn et al, *Nucl. Phys.* **A568** (1994) 169
Töke et al, *Nucl. Phys.* **A583** (1995) 519
Trautmann W., *these Proceedings* (1995)
Xu H.M. et al , *Phys. Lett.* **261B** (1991) 240