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Hot nuclei in 475 MeV, 2 GeV proton and 2 GeV ^{3}He induced reactions

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ABSTRACT

By using light projectiles instead of heavy ones in order to heat up nuclei, one can strongly minimize the excitation of collective modes such as compression, rotation and deformation. The sole effects of thermal energy in a nucleus can thus be studied more readily. The measurement of several observables such as neutron multiplicity, the light charged particles energy spectra and multiplicities, and fission probability have been performed at the Saturne facility using 475 MeV p, 2 GeV p and 2 GeV ^{3}He beams on several targets. We show that the reaction process is well described by a two step model (an intranuclear cascade and an evaporation phase). Temperatures higher than 5 MeV are evidenced for about 15% of the events. Binary fission plays an important role even for these highest temperatures.

The formation of highly excited nuclei and their decay have become topics of great interest. Indeed, one expects to learn about the properties of nuclei close to the limit of stability. The interesting issue concerning the maximum temperature that a nucleus can sustain has been addressed for a long time by theorists [SUR 87]. However this question has not yet received any satisfactory answer from experimental data.

The common way to excite nuclei is to induce violent collisions between heavy nuclei. This process is very effective in heating up nuclei but at the same time it introduces strong rotations, shape distorsions and nuclear compression. It seems difficult to disentangle all these effects when studying the decay of heated nuclei. These ambiguities can be avoided by using light particles such as protons or ^{3}He nuclei as projectiles instead of heavy nuclei. However for a light projectile, the efficiency of depositing energy in a nucleus must be evaluated. Early calculations [ABU 86] predicted that the cross sections decrease exponentially as a function of excitation energy. In contrast, certain experiments [NAK 83] have shown that a large fraction of events can be interpreted as a stopping of the projectile in the target nucleus. In order to investigate in greater detail the amount of energy left in heavy nuclei by light projectiles, we studied 475 MeV, 2 GeV proton induced reactions as well as 2 GeV ^{3}He induced reactions on a number of targets. The experiment was carried out at the SATURNE facility at Saclay.

Before undertaking such a study one needs to know what are the best observables regarding the heat deposited in a nucleus. The answer is given by an evaporation calculation. The results obtained with the code GEMINI [CHA 88] for a gold nucleus are presented on fig. 1 [LOT 93]. It shows that the most abundantly emitted particles are neutrons whatever the excitation energy. Because of their low emitting cost (no Coulomb barrier to overcome), neutrons are the only particles to be emitted at low E*, while at E*=1 GeV they still represent more than 2/3 of all emitted

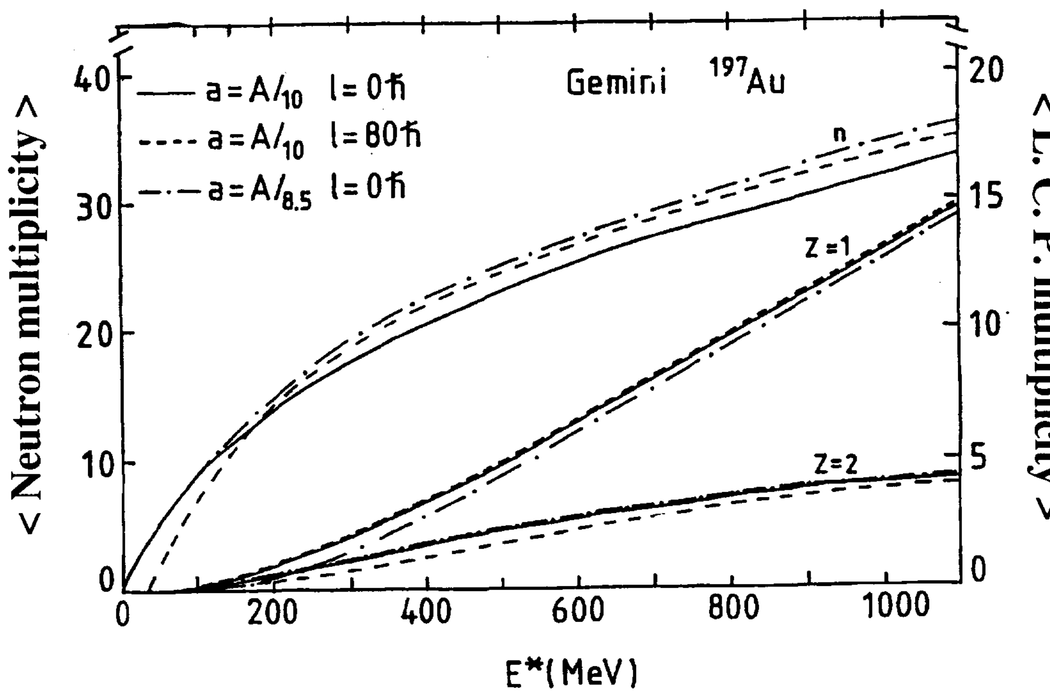

Fig 1: GEMINI calculations for average multiplicities of neutrons, Z=1 and Z=2 particles as a function of excitation energy of a gold nucleus [LOT 93].

particles. It is shown that the spin value and the chosen level density parameter do not influence substantially this conclusion. Hence, the choice was made to use a 4π-neutron multiplicity detector as the leading piece of detection. In coincidence with neutrons, charged particles (light charged particles, LCP and intermediate mass fragments, IMF) were measured by 10 evenly spaced silicon telescopes (placed at 15 to 165 deg.) and coincident fission fragments (FF) were detected by two parallel plate avalanche counters (PPAC) (fig. 2).

The ORION 4π neutron multiplicity detector was used consisting of a 4 m^3 tank of liquid scintillator doped with gadolinium. A detailed description of this detector can be found in the reference [GAL 94]. For the present experiment it is important to know that low-energy neutrons (those evaporated by thermalised nucleus) are detected with an efficiency of roughly 80%, whereas the high-energy neutrons emitted in the initial nucleon-nucleon collisions are poorly registered (e. g. the detection efficiency of a 60 MeV neutron is 20% only). A full Monte Carlo simulation [POI 74] of the neutron detection process was done as a function of initial neutron emission angle and kinetic energy in order to estimate the detection efficiency (coefficients) needed to make meaningful comparisons between measured data and modeled data. As a consequence, all multiplicity data presented thereafter will be measured data or data from models folded with the detection efficiency.

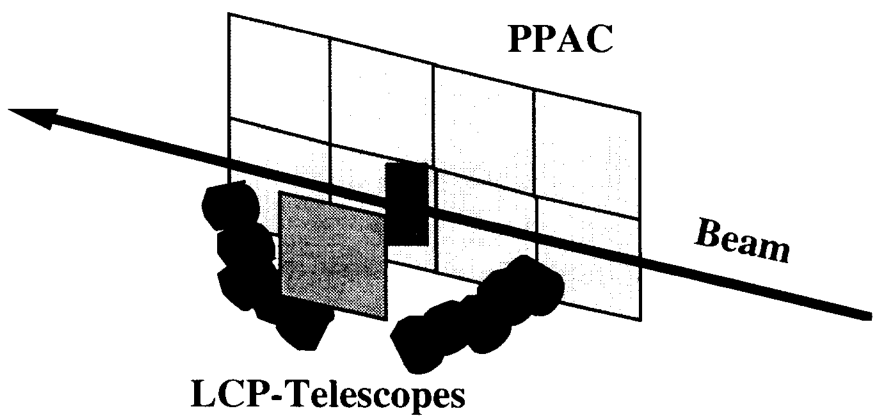

***Fig 2**: Experimental setup inside the reaction chamber placed at the center of the detector ORION whose detailed describtion can be found in ref [GAL 94].*

The reactions induced by high-energy light particles on heavy nuclei can be described by a two step model. The proton or ^{3}He induced reaction is treated as a succession of independent nucleon-nucleon collisions as given by the Intra Nuclear Cascade model (INC) of J.Cugnon [CUG 87]. In such an approach, the system is followed as a function of time and one is able to look at all characteristics of the system at any time. In particular, it is possible to determine at what moment the system behaves like a thermally equilibrated system by looking at the characteristics of the emitted particles as a function of time. It appears that after **30 fm/c** (i.e. about 10^{-22} s) the particles have Maxwell-Boltzmann-like energy distributions and are emitted isotropically. The INC calculation can then be stopped and the decay of the hot nuclei followed by an evaporation code. For this purpose, the GEMINI code which was used has the advantage of treating the evaporation of LCP, IMF and the fission process in a consistent way [CHA 88]. As mentioned before, the neutron multiplicity having been chosen as our best observable, all other observables will be presented as a function of the neutron multiplicity for both measured and simulated data. It must reminded once more that all the computed neutron data presented have already been folded by ORION efficiency.

The neutron multiplicity distributions are shown in fig. 3 as measured for 475 MeV and 2 GeV proton and 2 GeV ^{3}He on a series of targets [PIE 94]. All spectra exhibit the same pattern with a broad bump at relatively high multiplicity corresponding to rather central collisions and a pronounced maximum at very low multiplicity due to peripheral collisions. The influence of bombarding energy is well shown in p induced reactions: on the average a 2 GeV proton interaction is able to generate much more heat in a nucleus and thus allow for more neutrons to be evaporated than a 475 MeV projectile. It would be of great interest to pursue this excitation function further but this was not possible at SATURNE. On the other hand, it is shown that both p and ^{3}He beams lead to very similar neutron multiplicity

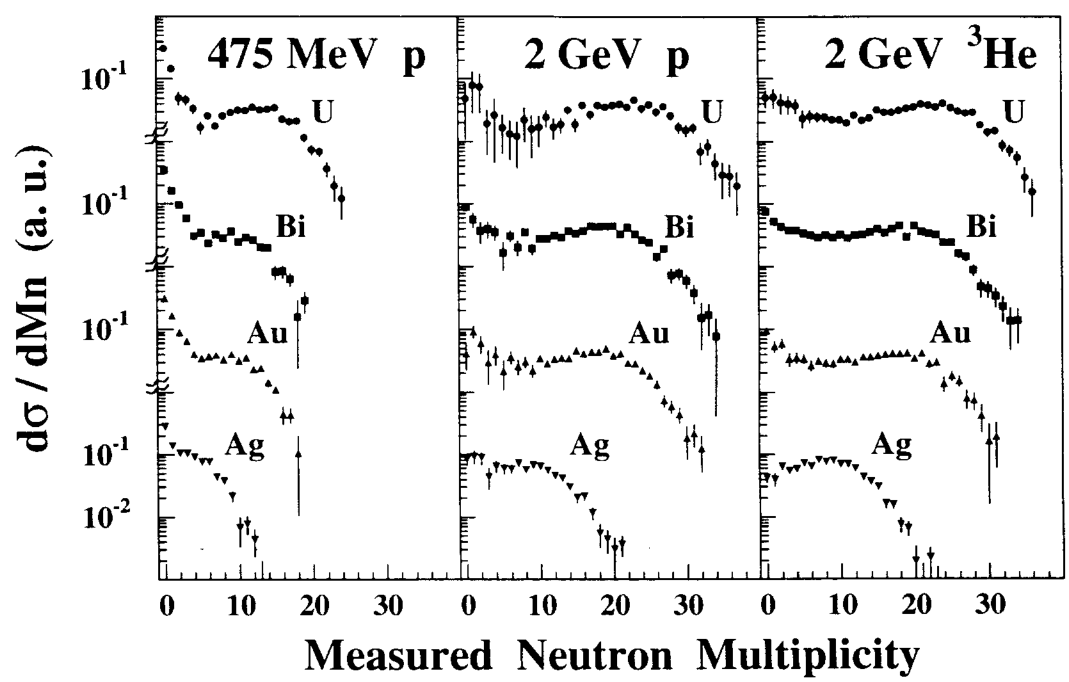

Fig 3: Experimental neutron multiplicity distributions for (475 MeV) proton, (2 GeV) proton and (2 GeV) ^{3}He beams on silver, gold, bismuth and uranium targets.

distributions pointing at similar energy depositions. Such behavior has been known for some time from radiochemical measurements [RUD 66]. The projectile energy for light projectiles appears to be a better scaling parameter than the energy per nucleon. It is also worth noting that the 2 GeV data, shown here, resemble very much the neutron multiplicity data for Ar reactions induced at similar bombarding energies [SOK 93].

The neutron multiplicity distribution for 2 GeV proton on gold was compared to model calculations. The calculated data are shown with the components from the two assumed reaction steps (fig. 4-a) as well as their sum (fig. 4-b). It is shown that the INC neutron component which is detected with a low efficiency contributes rather weakly to the total number of neutrons as they are registered by the detector. This indicates that the measured neutrons are essentially evaporated ones and that their multiplicity is strongly related to the thermal energy. Moreover, the agreement between experimental and calculated data is very satisfactory. The 2 to 3 neutrons difference

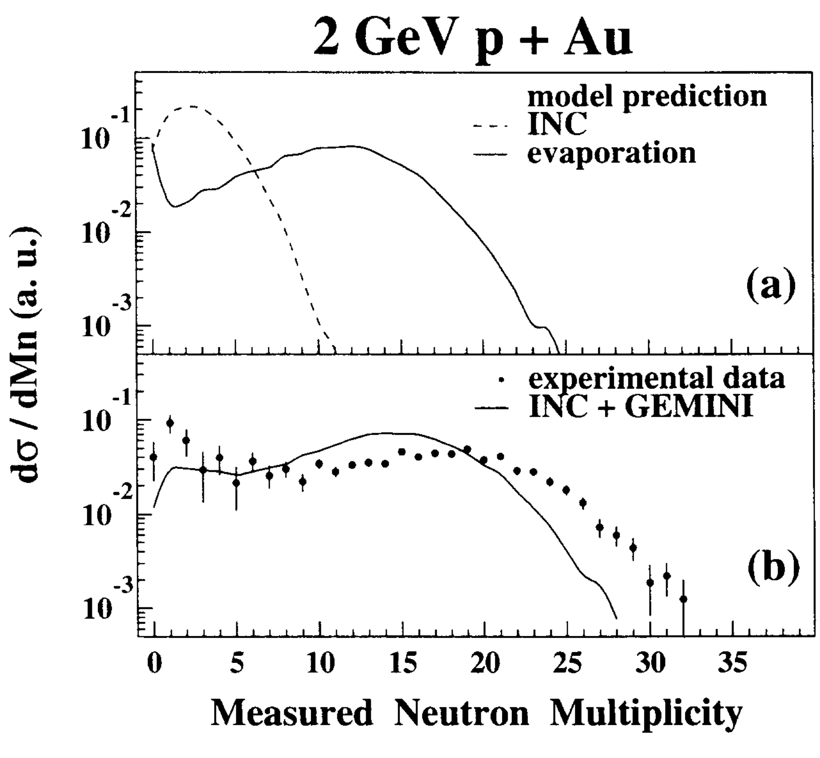

Fig 4: Theoretical (lines) and experimental (dots) neutron multiplicity distributions
a- The solid line represents evaporated neutrons, the dashed line for those emitted during the first step of the reaction
b- The solid line represents the sum of the two previous components, the dots the experimental distribution

observed on average can be essentially accounted for by secondary reactions. Calculations with the computer code GEANT [BRU 82] have shown that the high energy nucleons released in the INC step can induce secondary nuclear reactions in the surrounding target material (reaction chamber, scintillator, concrete...), giving rise to additional neutrons, on average one or two of which are detected by ORION. Taking this spurious effect into account, one can consider that the agreement between experimental and calculated data is even better than suggested in fig. 4-b where such an effect is not taken into consideration. One can then deduce from the calculation, the distribution of excitation energy in the nuclei after 30 fm/c and take it as a thermal energy distribution. It is shown in fig. 5 that the distribution does not decay exponentially as predicted by some models [ABU 86] but instead, is rather broad. For 15% of the events the thermal energy exceeds 500 MeV. Using the Fermi gas model and a level density parameter a=A/10, one calculates that 15% of the thus excited nuclei have a nuclear temperature exceeding T=5 MeV.

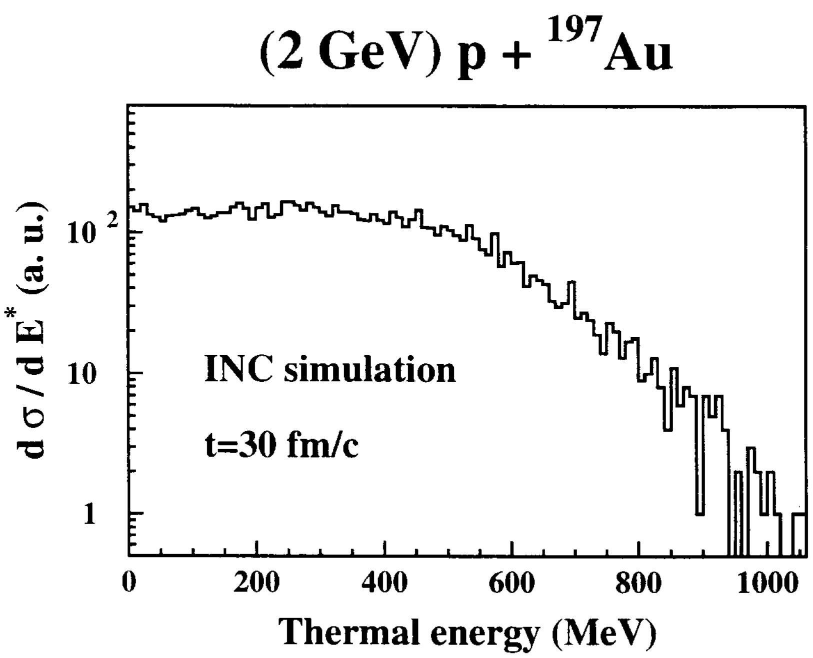

***Fig 5**: Thermal energy distribution of nuclei as predicted by an INC [CUG 87] code after a thermalisation time of 30 fm/c.*

In order to check these results further, other variables sensitive to temperature have been investigated. As an example, LCP have been considered. Alpha-particle energy spectra are shown to depend upon their emission angle. Two components can be distinguished (fig. 6) which are supposed to correspond to the two steps of the reaction process. In the backward direction the high energy component is comparatively weak (about one or two per cent of the total yield) and several methods have been applied to subtract this component by using different assumptions. After evaluation of the slope of the high energy part and its subtraction the fit of the resulting spectra leads to average temperatures of 4.5 MeV for those events characterised by high neutron multiplicity. Therefore there is satisfactory agreement between the two different approaches aimed both at inferring the nuclear temperature.

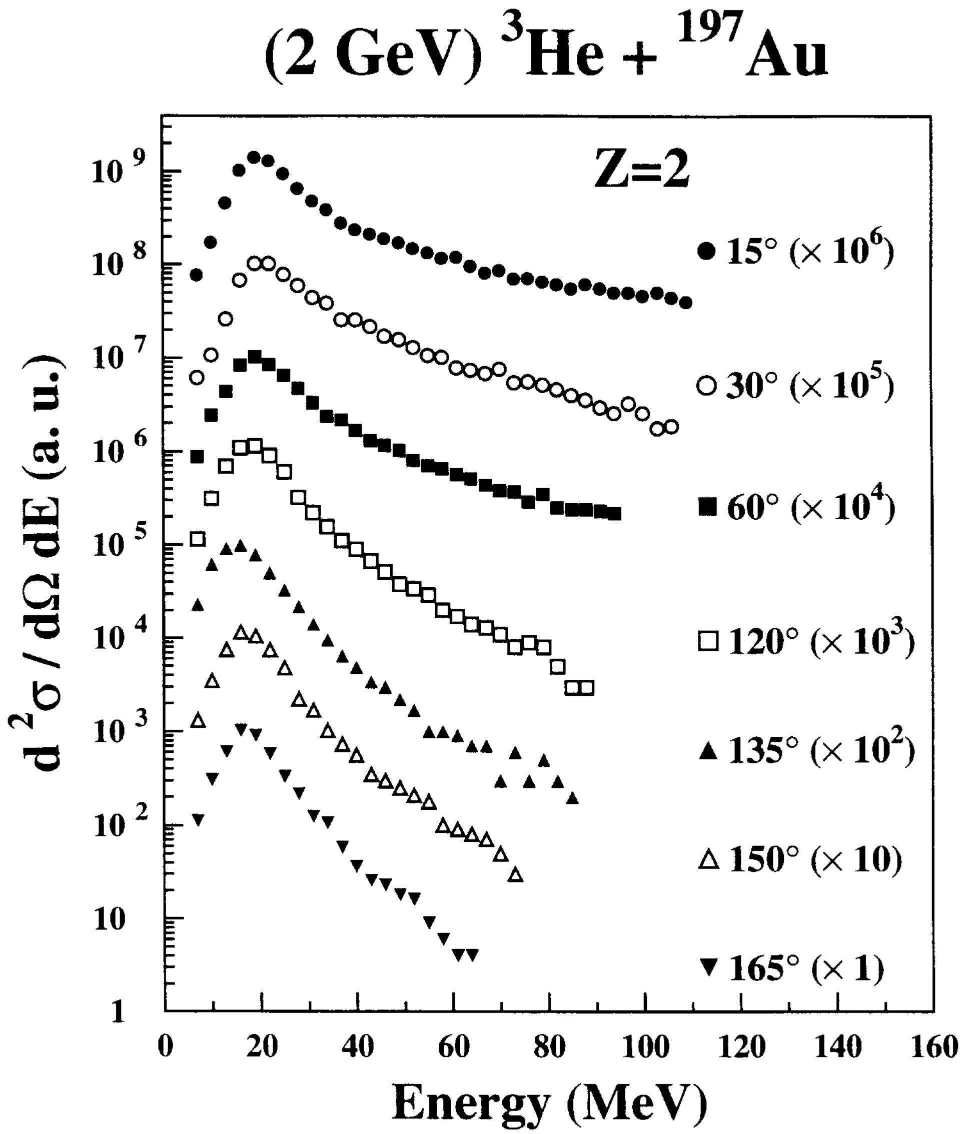

***Fig 6**: Energy spectra of alpha particles at angles of 15° to 165°*

The multiplicities of evaporated-like charged particles (those emitted backwards have been used for normalization assuming isotropical emission for integration over 4π) have been estimated as a function of neutron multiplicity (fig. 7). These multiplicity distributions have also been computed from GEMINI and an overall good agreement with the experimental data is found. This gives additional confidence in the model and in the thermal energies which have been deduced from the model. It can be noted that within the statistical uncertainties the experimental IMF multiplicities (not shown here) are also accounted for by the model. Latter results appears to be a distinctive character of light particle induced reactions, contrary to heavy-ion induced reactions whose measured IMF cross sections are often exceeding those given by standard evaporative calculations.

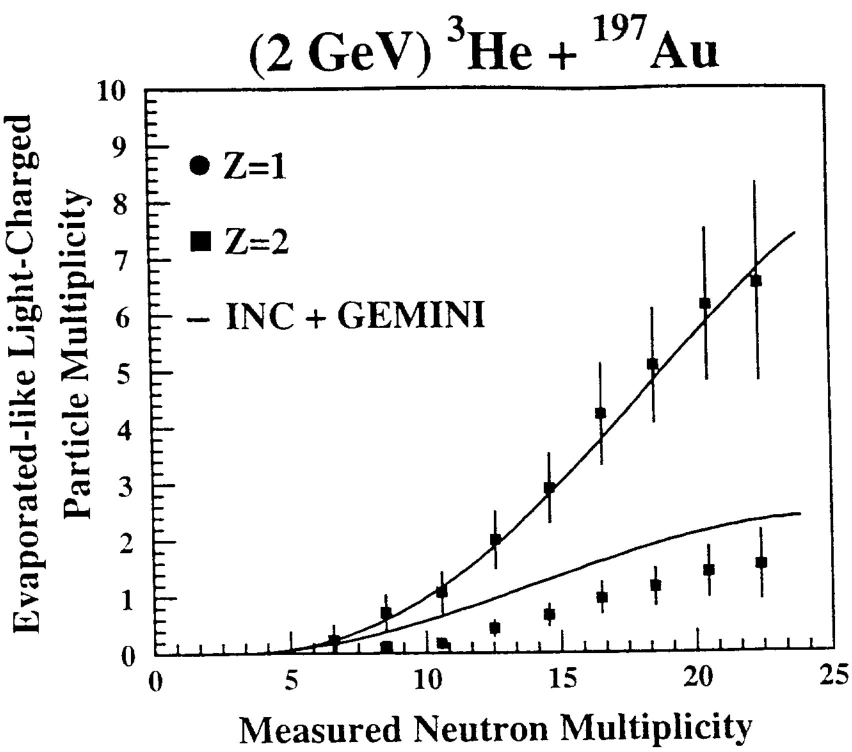

Fig 7: Multiplicity distributions of light charged particles as a function of neutron multiplicity (symbols represent experimental data and the lines the theoretical data).

Last but not least, fission has been investigated as a function of neutron multiplicity. The fission process is of special interest since fission occurs on a rather long time scale [HIL 92]. Observing fission can thus be used as a proof of the collective character of the decay of a hot nucleus and thus as a proof that the considered nucleus has not reached the maximum limiting temperature that a nucleus can sustain [GAL 94].

The measured fission probabilities are shown in fig. 8-a and 8-b together with the calculated probabilities. A good agreement is found in 475 MeV proton induced reactions or at relatively low neutron multiplicity with the 2 GeV ^{3}He beam. At high multiplicity the calculated data overpredict measured data. This result is not surprising since in the utilized GEMINI code the fission probability is based on phase space arguments and dynamical effects are not taken into account. Those effects allow numerous evaporated particles to be emitted in a short time scale thus, resulting in an enhancement of the fission barrier. As a consequence it is expected that fission is suppressed and numerous nuclei will end up as evaporation residues. Unfortunately such an assumption could not be experimentally checked since the corresponding nuclei carry too little recoil energy in order to leave the target. Only a characterisation of the residues by their emitted gamma rays would give an unambiguous signature.

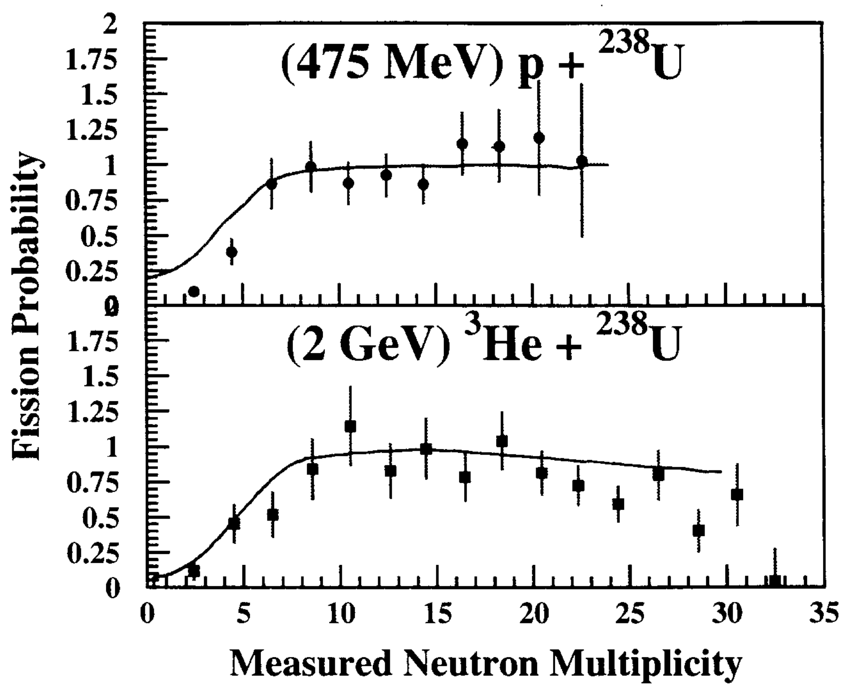

***Fig 8**: Fission probabilities as a function of measured neutron multiplicity. The dots represent experimental data and the lines INC + GEMINI calculations.*

The possibility of a competition between fission and a multifragmentation process could not be fully investigated because of the lack of 4π coverage for charged particles. However the weak rate of IMF emission measured on average rules out multifragmentation as an important exit channel.

To summarize, it has been shown that light particles can be used in order to heat up a nucleus without the complication of collective excitations brought in by heavy projectiles. By measuring both, neutron multiplicities, energy spectra and average multiplicities of charged particles, strong constraints are put in the comparison of experimental data and model calculations. At 2 GeV bombarding energy 15% of the target-like nuclei are excited to temperatures larger than T=5 MeV. At such temperatures the nuclei have not yet reached their limit of stability with respect to the stored thermal energy and they decay in a rather conventional way, evaporating particles (essentially light nuclei and very few IMF), undergoing binary fission or ending up as evaporation residues.

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