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Abstract:

Inclusive neutron multiplicity distributions have been measured for 475 MeV, 2 GeV proton- and 2 GeV ^{3}He-induced reactions on Ag, Au, Bi, U targets. There is good agreement beetween these multiplicity data and results of Intra Nuclear Cascade calculations. The results indicate a broad distribution of excitation energies and the formation of thermalized nuclei with temperatures exceeding 5 MeV with a 10% probability.

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Neutron experiments with a large variety of heavy-ion beams (Ne[1], Ar[2], Kr[3], Xe[4], Pb[5] and U[6]) have enabled the study of the formation and decay of hot nuclei over a broad range of systems and bombarding energies. Thermalized systems with temperatures as high as 7 MeV were observed in the Pb+Au reaction[7]. It was also found in these studies that a thorough understanding of the reaction mechanisms is necessary for successfully addressing the issue of the decay of hot nuclei and of their limit of stability with respect to temperature[8-9].

Furthermore, collective excitation modes, such as compression or rotation, are likely to be excited strongly in the hot nuclear systems formed in nucleus-nucleus collisions, thus making it difficult to disentangle the pure thermal effects from those due to collective modes. It thus is interesting to alternatively explore the production of hot nuclei with energetic light projectiles like ^{1}H and ^{3}He instead of heavy ions. For the description of these reactions two successive phases are usually assumed. In the first, the impinging nucleon, or nucleons in the case of a composite projectile, interact(s) with individual nucleons of the target nucleus in a series of incoherent scatterings, expelling some of the struck nucleons. Then, once thermalization is achieved in the residual nucleus, a standard evaporation process takes place. The first step is the foundation of Intra Nuclear Cascade (INC) models[10], that have been quite successful in reproducing selected data in this energy domain. Owing to the different characteristics of the particles released in the two steps, two contributions can be identified in the experimental data[11].

Most of the light-particle induced reactions studied thus far have been analyzed on event averaged data because of the lack of sufficient information on an event-by-event basis[12-16]. Other experiments were semi-exclusive[17-18]. In the present experiment a 4π neutron multiplicity measurement was carried out for the first time on an event-by-event basis, thus allowing to probe the excitation energy distribution. Unexpectedly large excitation energies were found even with the very light projectiles employed in the present investigation.

In the present letter, the emphasis will be on the neutron data. For the ^{1}H-induced reactions on Au at 2 GeV we present an extensive comparison with model calculations, from which the distribution of the thermal excitation energies that can be reached in such reactions can be deduced. In a forthcoming paper, fission data, complementary to the neutron data, will be considered in detail[19].

The GANIL 4π neutron multiplicity detector, ORION[20], consisting of a Gadolinium-loaded liquid scintillator, was mounted at SATURNE. A thin plastic start detector was inserted about 30 meters upstream of the reaction chamber, allowing to tag the incoming beam particles. A coincidence between the signal provided by this plastic counter and the prompt signal of ORION was assumed to occur after any nuclear reaction and required to trigger the counting of the neutrons thermalized in ORION. Because of the low stopping power of the light beam particles, rather thick targets (0.449g/cm^2, 0.575g/cm^2, 0.784g/cm^2, 0.284g/cm^2, for natural Ag, Au, Bi, U respectively) could be used with a beam intensity of several tens of thousands of particles per second. The measured inclusive neutron multiplicity distributions were corrected for background and details on such an analysis can be found elsewhere[21].

Fig.1 displays the measured neutron multiplicity data (M_n) for the three projectiles and four targets (Ag, Au, Bi, U), corrected for background contributions and pile-up but not for the detector efficiency. The differential cross-sections were normalized relative to the measured total cross-sections. It could be checked, when the incident particles were properly tagged by the start detector, that the thus measured absolute cross sections agree with independently estimated inelastic cross sections[22-23] within 20%. The data exhibit a broad bump at large multiplicities and a maximum at very low multiplicity as observed in heavy-ion induced reactions[24]. The average number of neutrons is seen to depend critically upon the target mass whatever the projectile and bombarding energy. This reflects the capability of a projectile to dissipate more energy in a heavy nucleus than in a

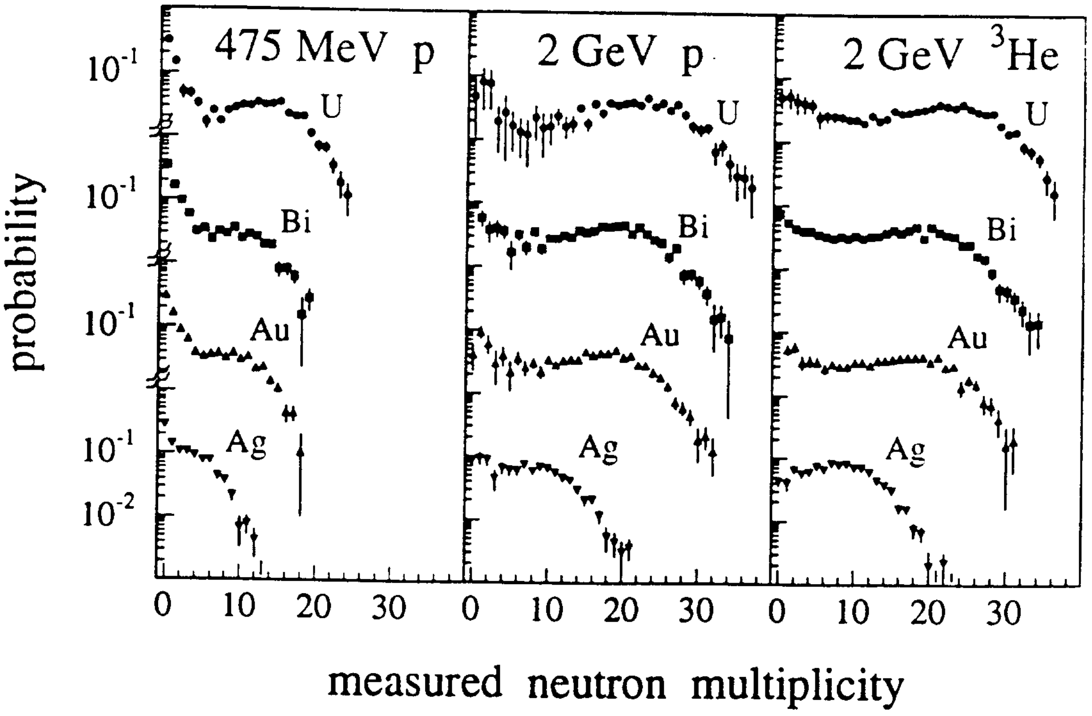

Fig.1 Neutron multiplicity distributions, uncorrected for detector efficiency, for 475 MeV, 2 GeV proton- and ^{3}He-induced reactions. The integrated measured distributions have been normalized to unity.

lighter one, simply because of the larger number of successive N-N interactions in the heavier nucleus. Moreover, it is well known that a massive nucleus will evaporate many more neutrons than charged particles because of the Coulomb barrier hindrance. Both effects contribute to the emission of more neutrons from heavy nuclei than from light ones. Most interesting are the observed "horse's back-and-tail" shapes of the neutron multiplicity distributions which were not expected on the basis of early model calculations[10, 25] which predicted exponentially decreasing E* distributions. Also, fission probabilities measured as a function of linear momentum transfer[26] could rather suggest monotonically decreasing energy deposits.

The effect of the bombarding energy on the energy dissipation is well demontrated by the data obtained with 475 MeV and 2 GeV ^{1}H, respectively. For every target, mean multiplicities for the bumps are roughly twice as large at the higher incident energy. This is in agreement with previous experimental results from which it was concluded that a saturation in the excitation energy deposition should not show up for proton beam energies below 2 to 4 GeV[27]. The neutron multiplicity distributions are amazingly similar for 2 GeV ^{1}H and ^{3}He induced reactions on a given target. A similar result was found for the ^{1}H and ^{4}He-induced reactions at 5 GeV[28] for which many observables look alike. For light projectiles the total bombarding energy rather than the energy per incident nucleon appears to be the relevant scaling parameter as long as energy dissipation is considered. It is also worth noting that 1.76 GeV Ar-induced reactions on Au[24] lead to neutron multiplicity distributions very similar to those obtained with either 2GeV ^{1}H or ^{3}He beams on the same target. This however might be accidental since the dissipation mechanisms are expected to be very different for 2GeV/nucleon protons and for 44MeV/nucleon (Ar).

In the following we focus on the 2GeV ^{1}H+Au experiment. Calculations were performed in the framework of the INC model of Cugnon[10] followed by evaporation. The evaporation stage was assumed to set in after 30 fm/c. Indeed, it was only after such a time delay that a clear change of behavior was observed as a function of time for the calculated quantities such as the integrated number of emitted particles, their total kinetic energy or the excitation energy of the residual nucleus. This is suggestive of a system in thermal equilibrium. The time of 30 fm/c allows approximately five successive nucleon-nucleon interactions to occur on the average, which is usually considered as being large enough for the nucleus to reach thermal equilibrium[29].

In order to compare the model calculations with the experimental data, the probability for detecting neutrons from the INC with the present experimental setup was folded with the detector efficiency using an extended version of the code DENIS[30]. It is shown in Fig.2b that the average number of INC neutrons emitted before 30fm/c and detected by ORION is small. Therefore mostly low energy neutrons of evaporative origin are being measured. The evaporative neutrons have been calculated with the statistical model code GEMINI[31], using as initial conditions (A,Z,E*) for the emitting nuclei those given event by event by the INC calculations after a time of 30fm/c. The multiplicity distribution of the evaporated neutrons, after folding with the detector efficiency, is given in Fig.2b. It is clearly seen that the evaporative neutrons are much more abundant than those from the INC. This gives confidence that the measured overall neutron multiplicity remains a good observable of the initial thermal excitation energy even for reactions with light projectiles and high beam energies.

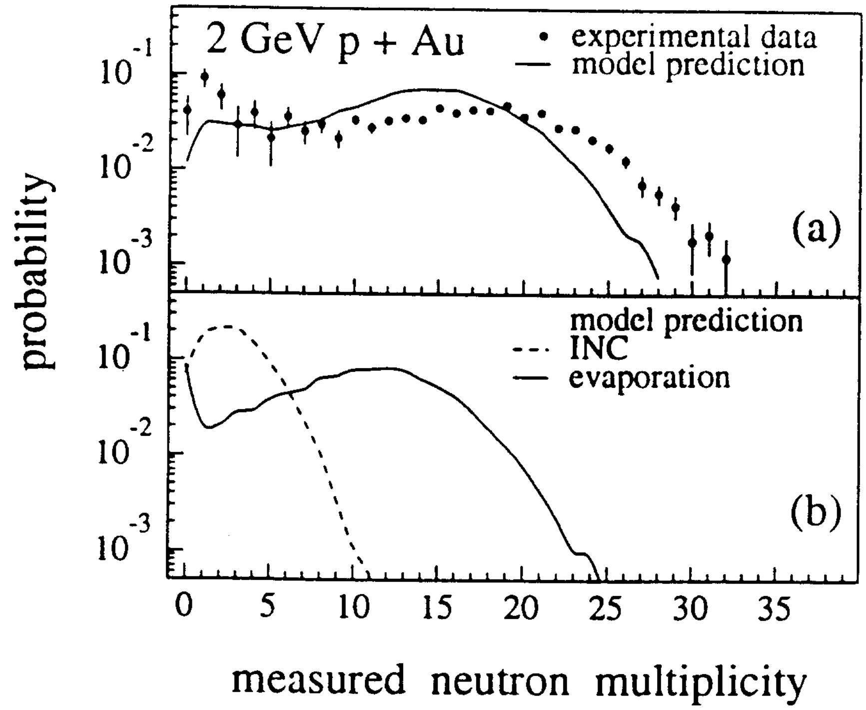

Fig.2 Calculated neutron multiplicity distributions folded with the detector efficiency for 2 GeV proton induced reactions on Au.

Bottom (B): The INC and evaporative contributions shown individually.

Top (A): Their sum and the experimental data.

After adding event by event the two calculated neutron contributions, the predicted multiplicities, corrected for the detection efficiencies, can be directly compared in Fig.2a with the experimental data. There is a fair overall agreement in the shapes of the distributions, with the experimental data shifted upward in neutron multiplicity by about 20% as compared to the calculated ones. However, the spurious neutron contributions resulting from secondary reactions induced by INC-type particles in the neutron tank, scattering chamber walls and the surrounding concrete walls have not been included in the calculations. A rough estimate of these contributions, performed with the computer code GEANT[32], leads to an effect of 10 to 20%, depending on the assumed elementary cross sections and on the actual composition of the concrete material. Including these spurious neutron sources, the agreement between the experimental data and the computed data is even better than suggested in Fig.2. It should be stressed that not only the 4π integrated neutron multiplicity distribution is well reproduced, but also the differential ones in the 5 forward-to-backward sectors of the ORION detector, showing that the angular neutron distribution is also accounted for. This gives additional confidence in the capability of the INC plus evaporation model to very satisfactorily account for the data.

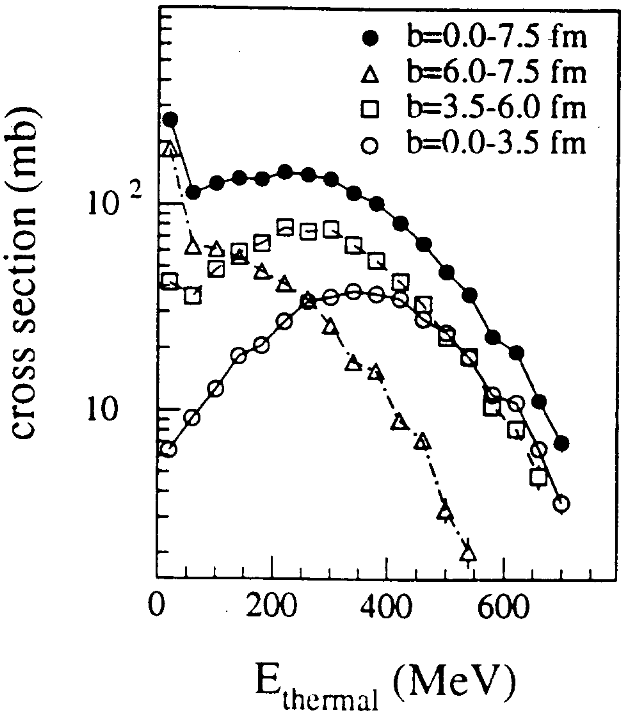

Fig.3 Thermal energy distribution as obtained from INC calculations after 30fm/c for different impact parameter ranges and their sum, for 2 GeV protons on Au.

The influence of the impact parameter on the thermal energy production is well exemplified in Fig.3. The energy distribution, summed over all impact parameters, is very broad. Very strikingly, events with more than 500 MeV thermal energy (or T>5 MeV assuming a level density parameter a=A/10) still represent a sizeable fraction (more than 10%) of the total cross section. This unexpected result has prompted us to undertake more detailed investigations on the decay of these hot nuclei. It has been found for instance that the measured evaporated-like alpha-particles, associated with large neutron multiplicities, exhibit both multiplicities and spectral temperatures compatible with those of nuclei of T>5 MeV, thus corroborating the data deduced from the neutrons.

To summarize, it has been shown that in light particle-induced reactions at incident beam energy of up to 2 GeV the neutron multiplicity is still an excellent observable of the energy dissipation. A broad distribution of thermal energies is observed after the INC step. Strikingly similar neutron multiplicity distribution patterns are seen in ^{1}H and ^{3}He-induced reactions at the same bombarding energy of 2 GeV. This indicates that similar thermal energy distributions are obtained with both projectiles at the same bombarding energy. Finally it was shown that as much as 10% of the reaction cross-section, i.e. roughly 200mb, are found in nuclei with temperatures of more than 5 MeV. This offers an excellent opportunity to study further and in more detail the decay of such hot nuclei with low angular momenta, which, to our knowledge, has never been done before under such favorable experimental conditions.

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