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THERMAL EXCITATION ENERGY DISTRIBUTION OF 475 MeV AND 2 GeV PROTON AND ^{3}He INDUCED REACTIONS IN HEAVY NUCLEI*

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The 4π neutron detector ORION was installed at SATURNE laboratory to perform experiments with high energy light- and heavy- ion beams. The first preliminary results are now available. The thermal excitation energy distribution of nuclei produced in high energy proton induced reactions was measured using almost direct approach. Comparison of the experimental results and predictions of the intranuclear cascade (INC) model is presented. The experimentally observed distributions are in fair agreement with the results of the INC model.

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1. Introduction

Heavy ions of intermediate energies (*i.e.* with kinetic energy per incident nucleon close to the intrinsic Fermi energy) are currently recognized as being the most efficient projectiles when used to heat up nuclei to high temperatures [1]. Also, and because of their large masses, such projectiles are able to bring to the heated nuclei sizeable amounts of collective energy in the rotation, compression and deformation modes [2]. Indeed, in recent experiments involving Pb projectiles at 29 MeV/nucleon on Au target, high spin values have been reached [3]. The study and understanding of the decay of such heated species are difficult when, in addition to the temperature T which is usually determined experimentally, other degrees of freedom are also excited that are not well under control. One would like to know first the influence of T, and T only, on the decay of heated nuclei and on the limit of stability of these nuclei. This latter problem has been investigated theoretically [4, 5], but in our opinion, data derived from heavy-ion collisions are too intricate to check unambiguously the model predictions. One needs hot nuclei produced by light projectiles.

In order to generate large amounts of heat in nuclei, without depositing sizeable amounts of collective energy one essentially has a choice of two approaches: either use protons (or alternatively neutrons or pions) or, probably even better, antiprotons of a few GeV [6, 7]. Here we report on the first truly exclusive proton (^{3}He)-nucleus experiments carried out at SATURNE (Saclay) with proton beams of 0.475-2 GeV and ^{3}He beams at 2 GeV on heavy targets. Previous experiments at KEK [8] aiming at determining stopping powers of protons and pions in nuclei did not allow to obtain the heat information we want to extract.

For each event the neutron multiplicity has been measured. In addition, several decay channels of these nuclei such as light charged-particle emission, intermediate-mass fragment emission and fission have been investigated in detail. In the present contribution, we would like to focus on the excitation energy measurements. As far as we know, it is the first time that the neutron multiplicity technique is applied to assess heat in proton (^{3}He)-induced reactions. Such a method has proved to be very successful in the context of heavy-ion induced reactions [1] and it is worth demonstrating its effectiveness in the novel context of high-energy proton (^{3}He) induced reactions.

2. Experiment

2.1. Experimental setup and experimental procedure

The target was located at the center of a scattering chamber, surrounded by a $4m^3$ tank of liquid scintillator loaded with Gadolinium (ORION detector). The evaporative neutrons of several MeV emitted in a nuclear reaction are slowed down in the tank by elastic scattering on the nuclei of the liquid (essentially H and C) till thermalization, before being captured by the Gd nuclei. Resultant emitted gamma-rays are detected by a set of phototubes surrounding the tank. The diffusion process preceding the radiative capture is slow enough (several microseconds) to permit that many neutrons, which can be emitted in a single event within a few 10^{-18}s, are eventually captured at well separated time intervals, thus allowing their counting [9]. Such an apparatus has efficiency better than 80% for neutrons below 10 MeV. In contrast, the detection efficiency is as low as 20% for 100 MeV neutrons. Higher energy neutrons released at the first steps of the nucleon-nucleon cascade escape and thus cannot be recorded at all. In brief, ORION records neutrons of evaporative origin -those of interest for temperature determination- with a good efficiency and disregards most of the knocked-out neutrons. This detector acts as a genuine thermometer of the nucleus once the measured neutron multiplicity is corrected for detection efficiency and converted into temperature by using an evaporation code [1]. The efficiency for low-energy neutrons is checked using a Cf source.

The neutron multiplicity measurements were performed in two different ways. In the exclusive mode, *i.e.* when triggered by any charged reaction product, the target was thin (about half a milligram/cm^2) and the beam intensity was about 107 pps. In the inclusive mode, the target was about 1000 times thicker and the beam intensity reduced by the same factor. In the latter case, the incident particles were first tagged by a thin plastic scintillator (START detector) located 30 meters upstream from the target. This signal was used in coincidence with the prompt ORION signal (the one generated by both the prompt gamma-rays and recoiling protons also used as a STOP signal) to open the gate for counting the radiative captures. Moreover, the time elapsed between these two signals was used off-line to distinguish good events from random events.

2.2. Experimental data

Three standard types of corrections have to be applied on these raw data [1]. First one has to take into account the background counted during the gate opening of nearly 100 microseconds. This contribution (essentially gamma-rays from the concrete and, with a much weaker intensity, cosmic rays) is monitored between the bursts of beam particles. It represents less than one neutron equivalent in terms of multiplicity and is taken away from the raw data by a classical unfolding procedure. The second correction deals with events which were triggered on background (less than 10%) and which can be essentially removed using the time information. This correction is also pretty small. Finally, a significant number of events at low neutron multiplicity are due to spurious reactions on light materials which are present in the target environment (frame or/and holder). They represent as much as 20 to 60% of good events at low neutron multiplicity. They can be subtracted using data from measurements performed in absence of target foil, with the same target environment. Considering the possible large errors generated by subtraction of two large numbers, the data at very low multiplicity are not presented.

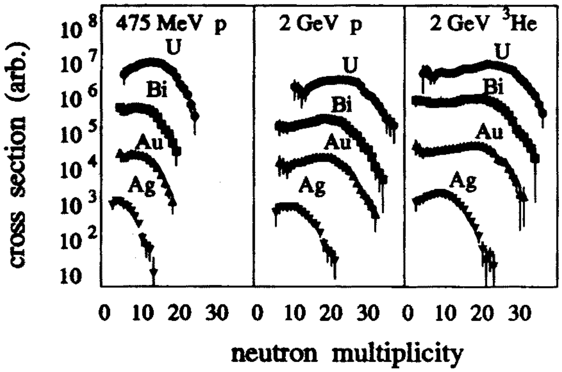

Fig. 1. Neutron multiplicity distributions corrected for background and random reactions effect.

The data are shown in Fig. 1 for three bombarding conditions and four different targets. It is striking to observe similarities both in patterns and absolute neutron multiplicity values in data from heavy-ion induced reactions at close total bombarding energies (for instance 1.760 GeV Ar or 2.690 GeV Kr in previously studied reactions [1]). This tells immediately that there must be some impact parameter dependence as in heavy ion induced reaction and that despite the different processes of energy dissipation the net outcome in terms of generated heat must not be strongly different. Clearly, it would be interesting to explore higher bombarding energies to investigate further the proton capability of producing even hotter nuclei.

The influence of the target Z on neutron multiplicity Mn is the same as the one observed with heavy-ion projectiles: the heavier the target, the stronger the stopping power but also the larger the capability of evaporating neutrons instead of charged particles. The influence of bombarding energy for proton induced reactions is clearly shown, and it would be of great interest to complement this excitation function at larger bombarding energies. The similarities between the data for p and ^{3}He induced reactions at the same total bombarding energy are also worth noticing.

3. Intranuclear cascade predictions

There exist several models which can simulate the fate of light-particle induced reactions. Unfortunately none of them can describe the whole process in a consistent way *i.e.* from the impact of the projectile onto the target nucleus, to the cooling down of the resulting heated nucleus. Usually, a dynamical model, based on a sequence of elementary Intra Nuclear Cascades (INC) treats the first violent stages of the collision and the subsequent stages are described by models based on statistical approaches. The dynamical model is run as long as the nucleus cannot be considered in statistical equilibrium; the evaporation code takes over once thermalization is achieved. The chosen INC model and evaporation code GEMINI have been developed by Cugnon [10] and Charity [11], respectively.

A somewhat crucial parameter is the time at which the INC has to be stopped to give way to evaporation. Several observables have been considered to best determine the change of regime. These observables are the number of ejected nucleons, the number of nucleons involved in the cascade process, the total kinetic energy of the emitted nucleons and the excitation energy of the nucleus. It was found that, after time t = 30 fm/c (10^{-22}s), all these quantities exhibit an exponential dependence as functions of time and this can be considered as a signature of a statistical decay.

The INC model predicts that on the average 7.5 and 9 neutrons are emitted prior to equilibrium for the central reactions induced by the p and ^{3}He projectiles, respectively. Most of these neutrons being highly energetic it is estimated that only about 40% of them should be detected by ORION. It can thus be confirmed that the neutron multiplicity measurement probes mostly the thermal properties of the nuclei and is almost insensitive to the dynamical process through which the hot nuclei are formed.

The excitation energy distribution at time t = 30 fm/c is given in Fig. 2 for 2 GeV protons and ^{3}He on Au. As expected, the smaller the impact parameter, the larger the average thermal energy. The similarity of the patterns of computed energy data of Fig. 2 and measured neutron multiplicity data of Fig. 1 is apparent. Both of them first show a rather flat behavior followed by exponential fall off.

The full evaporation calculations starting from the computed data of Fig. 2 and folded by detector efficiency is still in progress but nevertheless useful comparisons can already be made. The maximum that one can see

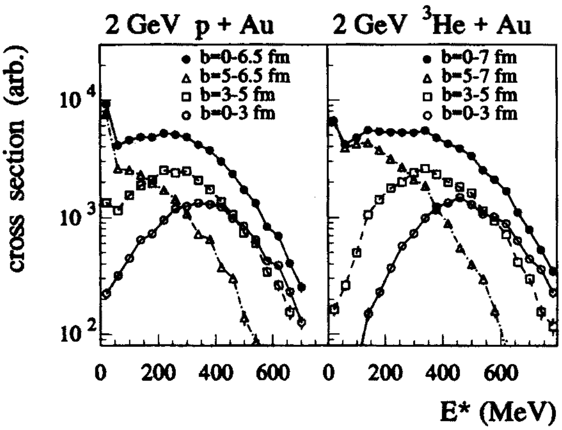

Fig. 2. Excitation energy spectra for 2 GeV p+Au and ^{3}He+Au reaction. Intranuclear cascade prediction calculated at thermalization time, $t = 30$ fm/c. The results for several impact parameter bins.

for p+Au between $E^* = 200$, and 300 MeV in Fig. 2 would translate into 17–23 evaporated neutrons using GEMINI [1] or 14–18 neutrons once folded by ORION efficiency. Thus there is fair agreement with experimental data if one takes into account the few knocked-out neutrons from the cascade which can also be detected by ORION.

The thorough calculation accounting for all the previously mentioned effects on the whole excitation energy distribution and not only on the most probable value is expected to shed more light on the comparison between measured data and simulated ones. At the present stage of the data analysis one has strong hints that Au-like nuclei left with thermal energy $E^* =$ 500 MeV (or $T = 5$ MeV, using a level density parameter $a = A/10$) are formed in 2 GeV proton-induced reactions. The corresponding cross section (a few percent of the reaction cross section) should be sufficient for the decay properties of these hot nuclei to be investigated in some detail. The analysis of fission data, light charged particle and intermediate-mass fragment data is in progress. The use of the neutron multiplicity is crucial in the latter analysis, since this observable provides a strong selection in temperature of the studied nuclei.

4. Summary and prospects

A fairly direct experimental approach — a 4π neutron measurement — has been applied for the first time to the study of thermal energy generation in reactions induced by GeV-range light particles. Inclusive neutron multiplicity data have been presented for different projectiles and targets.

INC calculations were performed to determine thermal energy distributions, which in turn can be converted into neutron distributions using a standard evaporation code. The first results show a fair agreement between experimental data and model calculations. Events associated with high thermal energy ($T = 5$ MeV) are observed with sizeable cross sections, thus giving a unique opportunity to study the decay properties of such hot nuclei formed without appreciable spin or initial compression. Such conditions are impossible to meet in heavy ion induced reactions.

It should be recalled that, according to static model predictions of Suraud [4] or Bonche *et al.* [5] one should reach the limit of the heat that a nucleus of mass 200 can sustain at such high temperatures. The presence (or absence) of binary fission — a well known slow nuclear process — should constitute a stringent test for these models. As long as fission is observed the considered initial mother nucleus can be safely considered as being able to sustain the heat it was initially given since it survived a long time.

At last, one would like to stress the relevance of the elementary data we have obtained for the issue of nuclear waste transmutation with high-intensity proton accelerators. In such an approach, the high flux of neutrons required for efficient transmutation would be generated in proton-induced reactions of 1.5-2 GeV typically, impinging on heavy (Pb for instance) and very thick targets (typically half a meter thick). Thin target data are certainly very valuable to allow prediction of neutron production in thick targets [12].

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