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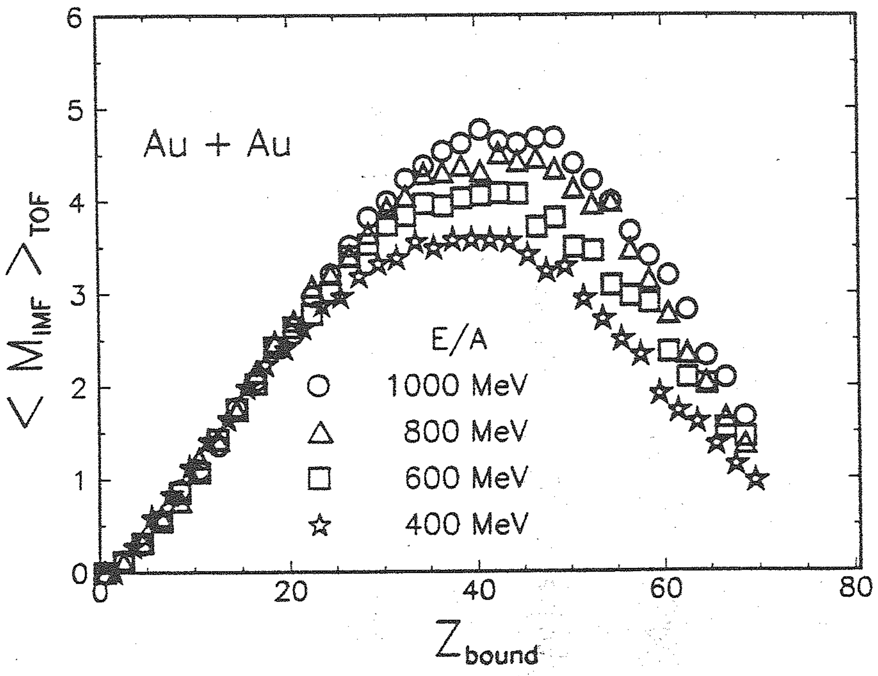

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Determination of Thermal Excitation Energies Produced in High-Energy p, ^{3}He, and ^{84}Kr Induced Reactions via Neutron Multiplicity Measurements

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ABSTRACT

Multiplicity distributions of neutrons were measured inclusively with the large-volume neutron calorimeter ORION for proton and ^{3}He induced reactions at an incident energy of 2 GeV. The experimental distributions are found to be in qualitative agreement with model calculations assuming an intranuclear cascade as first reaction stage and, following, statistical emission from a thermalized nucleus. Angular and atomic-number distributions of projectile-like "spectator" fragments from the reaction ^{84}Kr+^{197}Au were measured at E/A=150 MeV using an annular multi-strip ΔE-ΔE Si-detector. The observed correlations between multiplicity of neutrons and projectile-like fragment atomic numbers indicate large deposits of excitation energy in these fragments.

1. Introduction

For many years now, production of hot nuclei[1] and study of their decay have been in the focus of interest of intermediate-energy heavy-ion studies. The fact that large amounts of kinetic energy can be dissipated in heavy-ion collisions and the prospect of being able to study thermal limits of stability of nuclei strongly motivated such studies. For this high excitation-energy regime new decay processes are predicted[2-7], e.g. multi-fragmentation, vaporization, and explosion-like reactions, which, if confirmed, are of great interest to the study of properties of nuclear matter. The use of heavy projectiles, however, does complicate the interpretation of experimental data because of large dynamical effects and the excitation of not only intrinsic degrees of freedom but collective ones as well, e.g. compression, rotation. In this work, first results of an experimental study will be presented using two different approaches to examine separately, purely thermal decay and, by comparison, collective ones.

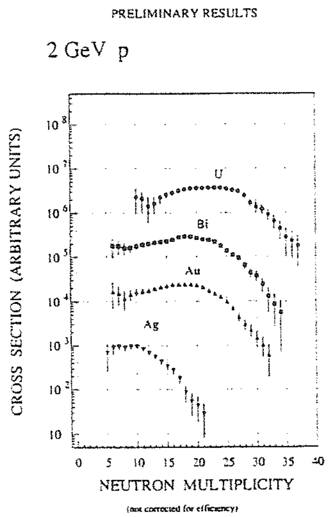
2. Experimental Setup

First series of experiments have been performed at SATURNE accelerator facility at Saclay, France, using either 475 MeV ^1H, 2 GeV ^1H, 2GeV ^3He, or ^{84}Kr at E/A=150 MeV and 400 MeV impinging on a variety of targets (C,Ag,Ho,Au,Bi,U). For all projectile-target combinations inclusive and exclusive neutron multiplicities were measured using the 4π liquid scintillator detector ORION. This detector is well suited to measure essentially thermal energy deposition in the target nucleus close to rest, because of its high efficiency for low-energy neutrons (ϵ =0.7-0.8) and small sensitivity to high-energy neutrons. In addition, a variety of detectors were employed to measure charged reaction products. Light-charged particles (LCP) and intermediate-mass fragments (IMF) were detected with 10 silicon detector telescopes (9 telescopes in the Kr experiments). Fission fragments of the target-like nucleus were measured in coincidence using two parallel-plate avalanche counters. For reactions involving Krypton projectiles, angular and atomic number distributions of projectile-like ("spectator") fragments were measured with an annular multi-strip ΔE-ΔE Si-detector.

3. Reactions With Light Projectiles

Fig. 1 displays inclusively measured neutron multiplicity distributions for 2 GeV p+(U, Bi, Au, Ag) reactions. The distributions shown in this figure are

Fig. 1 Cross-sections for multiplicities of neutrons measured inclusively for 2 GeV p+(Ag,Au,Bi,U) reactions.



corrected for background contributions but not for the finite detection efficiency of the detector. Cross sections for low neutron multiplicities are not shown because of their large experimental errors. The neutron multiplicity distributions exhibit for all target nuclei a broad maximum whose position shifts with increasing target mass from ca. m_n=8 for Ag to m_n=23 for Uranium. It is interesting to note that these distributions are strikingly similar to those typically observed for reactions between heavy ions at lower bombarding energies, e.g. $^{40}Ar+^{197}Au$ at E/A=44 MeV[8]. In order to estimate the multiplicity of directly emitted particles and the amount of energy thermalized in the system, theoretical calculations have been performed using an intranuclear cascade (INC) model [9] together with a statistical decay model[10]. The first stage of the reaction was simulated within the INC-model allowing to calculate the multiplicity and velocity distribution of neutrons emitted during the cascade. A thermalization time of 30 fm/c, after which an evaporation stage was assumed to set in, was estimated. The assumption of thermalization is justified by the fact, that at times larger than 30 fm/c the number of particles emitted in the cascade, their total kinetic energy and the decrease of excitation energy in the residual nucleus exhibit an exponential dependence on time similar to a statistical emission process observed for a thermalized system. To allow a further comparison between simulation and experimental data, the response of the experimental setup to the theoretically calculated neutron distributions was simulated with the Monte-Carlo code DENIS [11].

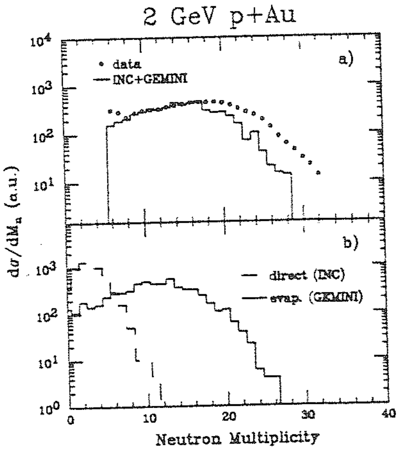


Fig. 2 Upper panel: Theoretical and experimental neutron multiplicity distributions. Results of theoretical calculations combining an intranuclear cascade (INC) model with a statistical decay model (GEMINI) for 2 GeV p+Au collisions are plotted in form of a histogram. The experimental data are represented by circles. Lower panel: Theoretical multiplicity distributions for directly emitted and evaporated neutrons.

Results of the simulation calculation folded with detector efficiency for 2 GeV p+Au reactions are plotted in form of a histogram in the upper panel of Fig. 2. The experimentally measured neutron multiplicity distribution is represented by circles. A good qualitative description is achieved except for the highest multiplicities. The lower panel of Fig. 2 shows separately the calculated multiplicity distributions folded with detector efficiency for evaporated and directly emitted neutrons. The simulations predict that most of the detected neutrons are emitted from a thermalized residual nucleus, indicating that measuring the neutron multiplicity is a good approach to measure the amount of energy thermalized even at such high bombarding energies. From these simulations a broad distribution of thermal energy is predicted with an average value of $\langle E^* \rangle$ = 280 MeV and sizable cross sections even for excitation energies as large as 600 MeV ($T > 5$MeV). These values are found to be in agreement with LCP-multiplicities and spectral temperatures deduced from coincident light charged particle spectra associated with large neutron multiplicities.

4. Reactions With Heavy Projectiles

The second series of experiments using Kr-projectiles was intended to determine the temperature of "spectator" nuclei for peripheral collisions from the associated multiplicity of evaporated neutrons. The influence of angular momentum was to be measured by the correlation between fission-fragment plane and reaction plane, defined by the deflection direction of the coincident projectile-like fragment. Fig. 3 shows double differential cross sections of fragments, produced in Kr+Au collisions at E/A = 150 MeV, detected in the forward-angle multi-strip ΔE-ΔE Si-detector for 6 scattering angle bins. The distribution of fragments detected between $\Theta = 0.5 - 1°$, close to the grazing angle for this reaction ($\Theta_{graz} \approx 0.9°$), is displayed in the upper-left panel. Most prominent feature of this distribution is a group of elastically and quasielastically scattered projectiles, centered at atomic number Z=36 and neutron multiplicity $m_n = 0$, from which a continuous band of cross section evolves with increasing average neutron multiplicity for decreasing Z. This pattern is quite similar to the one already observed for the same system at a much smaller bombarding energy of E/A=32 MeV[12]. No qualitative change of the average correlation between atomic number of the projectile-like fragment and average neutron multiplicity as function of scattering angle is observed. However, a strong change in the production cross-sections is seen. Large Z are strongly suppressed for larger scattering angles whereas low Zs are distributed more evenly in the angular range between $\Theta = 0.5°$ and 5°. The correlation between Z of the projectile-like fragment and neutron multiplicity reflects the strong dependence of the size of the projectile-like fragment and dissipated energy on impact parameter. Thus, neutron multiplicity appears to be a good observable to select an impact parameter or a degree of dissipation as it was shown at much smaller bombarding energies[13]. Because of electronic detection thresholds, fragments with atomic numbers of less than ca. 5 were not measured. For these lightest fragments average multiplicities of $m_n \approx 37$ are observed. Results of simulation calculations using the intranuclear cascade code ISABEL[14] are represented by a solid line in the middle left panel of Fig. 3. As seen from this figure the functional dependence of the average neutron multiplicity on Z is reproduced but the absolute values of $\langle m_n \rangle$ are underpredicted by almost a factor of 1.5. Because of the early stage of the analysis no definite answer can be given to why the model calculation cannot reproduce the experimental data even on the average. Possible reasons may be that the model simply fails to describe correctly the collision process, the detection efficiency of energetic neutrons is underestimated, or additional neutrons might be generated in secondary interactions of reaction products with the detector itself and its surrounding. However, despite the lack of a quantitative understanding, the thermal excitation energies produced in Kr+Au collisions at E/A=150 Mev are likely to be much larger than the amount that can be explained by a change in surface energy of the nuclei, as already pointed out by [15]. Further work is in progress to obtain a more quantitative understanding of the experimentally observed correlations.

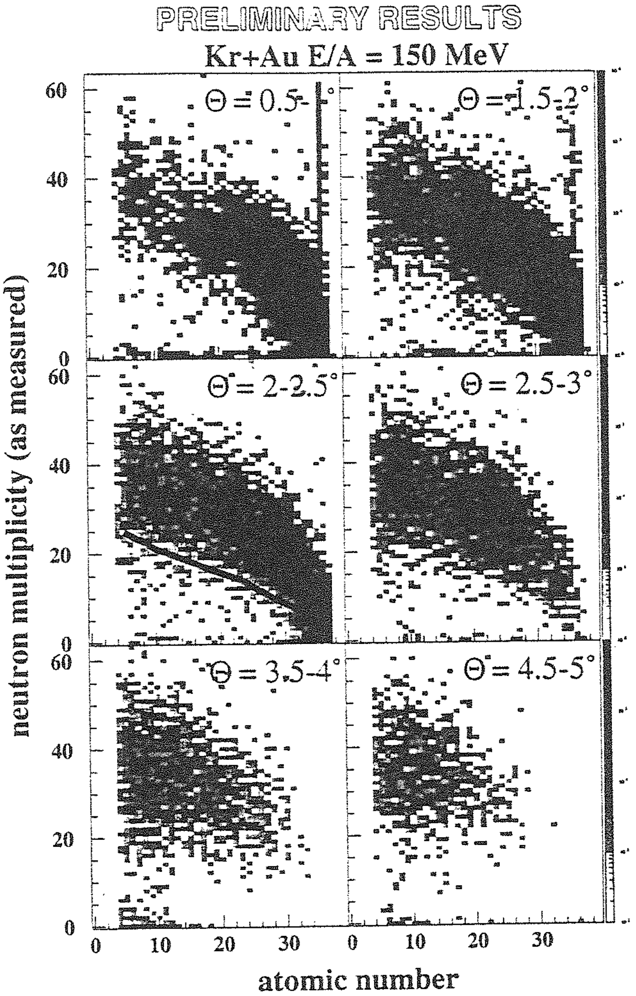


Fig. 3 Distributions of double-differential cross-sections for fragments produced in Kr+Au collisions at E/A = 150 MeV for six bins of scattering-angle. The logarithmic intensity scale is the same for all distributions and defined by gray-levels. The intense line structure at Z=36 is a result of pile-up of reaction events with elastic scattering. The solid line in the middle-left panel represents results of theoretical calculations combining an intranuclear cascade model with a statistical decay model.

5. Summary

For the first time, excitation energy distributions were determined from neutron multiplicity measurements for light-ion induced reactions at relativistic bombarding energies. The results for 2 GeV p+Au reactions are described qualitatively by calculations assuming an intranuclear cascade and evaporation from thermalized residual nuclei. The experimental distributions show that large amounts of thermal energies can be deposited in such collisions. Average neutron multiplicities measured in coincidence with projectile-like "spectator" fragments produced in Kr+Au reaction at E/A= 150 MeV show a smooth evolution with atomic number and scattering angle. The observed correlations between multiplicity of neutrons and projectile-like fragments indicate large deposits of excitation energy in these fragments.

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