Formation and Decay of Equilibrated Spectator Nuclei at Relativistic Bombarding Energies

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ABSTRACT

In recent experiments with the ALADIN forward-spectrometer multifragment decays of heavy nuclei were studied for a wide range of projectiles and targets and for bombarding energies between 100 and 1000 MeV per nucleon. The systematics available from these data exhibit a pronounced universality for the fragmentation of excited spectators after peripheral collisions of heavy symmetric systems or after more central collisions of mass asymmetric systems.

In order to permit a statistical interpretation of the spectator decay the masses and the deposited excitation energies prior to the decay were determined from balance equations. The experimental input to these equations included the number and kinetic energies of free neutrons measured with the large-area neutron detector LAND. Results from the analysis for ^{197}Au on ^{197}Au at a bombarding energy of 600 MeV per nucleon will be presented.

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1 Introduction

Heavy-ion reactions at relativistic bombarding energies offer a wide range of possibilities for studying multi-fragment decays of highly excited atomic nuclei. The largest fragment multiplicities measured so far were observed in central ^{197}Au on ^{197}Au collisions at a bombarding energy of 100 MeV per nucleon [1]. In these collisions the system of nearly 400 nucleons disintegrates completely into nuclear fragments and light particles. The analysis of the kinetic energy spectra in these reactions has revealed a considerable collective outward motion superimposed on the random motion of the constituents at the breakup stage (radial flow) which represents up to one-half of the incident kinetic energy in the center-of-mass frame [2]. This feature prevails, with monotonously increasing flow values, over the range of bombarding energies up to 1000 MeV per nucleon [3]. It demonstrates the strong dynamical coupling of entrance and exit channels in central collisions of heavy systems.

The process of fragment formation is found to be sensitive to the flow dynamics. The measured relative element yields are systematically correlated with the magnitude of the observed radial flow [3, 4]. Within a coalescence picture, the suppression of heavier fragments for larger flow values may be caused by the reduction of the density in momentum space associated with the collective expansion [4]. The interplay of dynamical and statistical effects in these violent collisions is a matter of high current interest [5].

Multi-fragment decays are also observed in more peripheral nucleus-nucleus collisions at high energies. The spectator systems formed during the initial stages of the reaction may be excited to an extent that complete breakups can occur. Here, in contrast to central collisions, no obvious dependence on the entrance channel is observed. The decay patterns were found to be mainly governed by the energy transfer to the spectator, as evident from the Z_{bound} scaling of the fragment charges and their correlations [6, 7]. The quantity Z_{bound} is defined as the sum of the charges of all product nuclei with $Z \geq 2$ and is related to the energy deposit. When plotted as a function of this quantity the fragment multiplicities and correlations exhibit a universal behaviour. It was first observed as an invariance with respect to the chosen target in the decays of ^{197}Au projectiles at 600 MeV per nucleon [6, 8].

In this report we will concentrate on the latter type of multifragmentation. Its invariant features are consistent with equilibration of the excited systems prior to their decay. Equilibration, on the other hand, will facilitate interpretations in statistical or thermodynamical terms. Multifragmentation has been considered a manifestation of the liquid-gas phase transition in finite systems. The pursuit of this challenging question will profit from the study of equilibrated systems that may be characterized by a few global variables such as mass, excitation energy, or temperature. Clearly, the aim must be to determine these quantities experimentally. The present status of our efforts in this direction is summarized

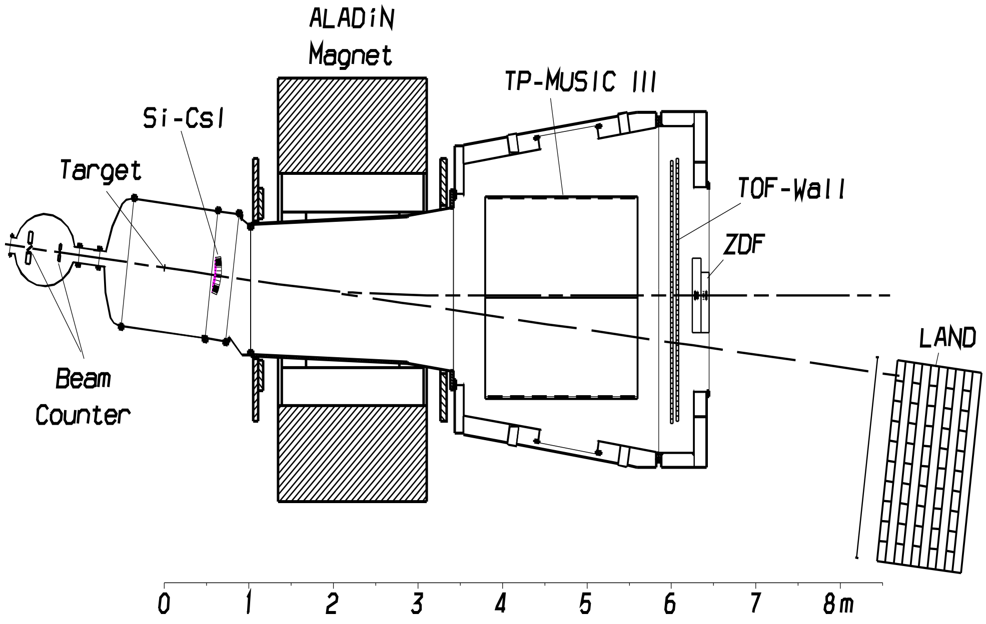

Figure 1: Cross-sectional view of the ALADIN facility. The beam enters from the left and is monitored by the beam counters before reaching the target. The entrance to the dipol magnet is surrounded by the Si-CsI(Tl) array. Projectile fragments are tracked and identified in the TP-MUSIC III detector and in the time-of-flight wall. Coincident neutrons emitted approximately in the direction of the incident beam (dashed line) are detected with the large-area neutron detector (LAND). The dash-dotted line represents the trajectory of beam particles after they were deflected by an angle of 8°.

in this report. The connections of the obtained results with possible phase transitions in nuclear matter will be discussed in the following contributions by Th. Möhlenkamp [9] and by W.F.J. Müller [10].

2 Experimental

The experimental setup (Fig. 1) resembles that used in earlier experiments but was modified in several respects: The solid angle adjacent to the acceptance of the ALADIN magnet was covered by the Catania hodoscope which consists of 84 Si-CsI(Tl) telescopes in closely packed geometry and which extends to angles up to $\Theta_{lab} \approx 16°$. The TP-MUSIC III served as the tracking detector. The multiple sampling of the ionization charges resulted in a resolution of $\Delta Z = 0.4$ (FWHM) for fragments with atomic number $Z \geq 8$. Lighter

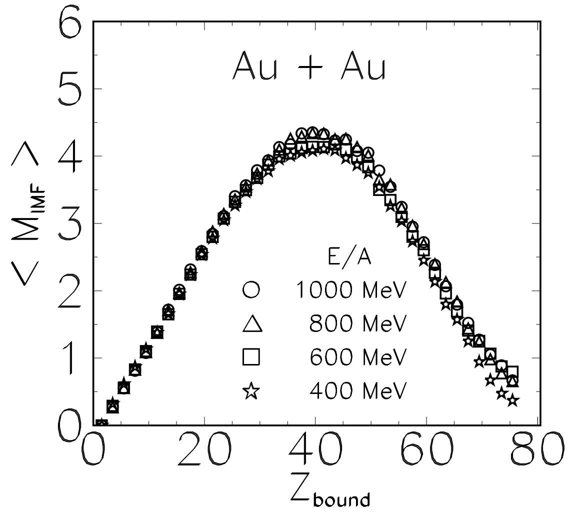

Figure 2: Mean IMF multiplicity $\langle M_{IMF} \rangle$ as a function of Z_{bound} for the reaction of ^{197}Au on ^{197}Au at E/A = 400, 600, 800, and 1000 MeV.

fragments were tracked and identified by collecting and amplifying their ionization charges with proportional counters mounted in three positions at the anode plane of the drift volume. The two-layered time-of-flight wall extended over a horizontal range of 2 m. The primary beam and projectile fragments emitted along directions close to that of the beam were detected with a plastic detector with light-fiber readout (denoted ZDF in Fig. 1). The large-area neutron detector LAND was positioned close to zero degrees with respect to the incident beam direction and operated in a calorimetric mode.

3 Dependence on Projectile Energy and Mass

The ALADIN spectrometer has been designed for optimum acceptance of projectile fragments which are focussed in forward directions. The focussing effect, however, is a function of the projectile velocity and changes with changing bombarding energy. We have therefore studied the extension of the projectile-spectator source in rapidity y and transverse momentum p_t both with experimental data and with model calculations. Guided by these analyses we define the spectator source in rapidity by the condition $y \geq 0.75 \cdot y_{proj}$, where y_{proj} is the projectile rapidity, and by upper limits in the laboratory angle. The angular cuts were chosen inversely proportional to the projectile momentum. This was motivated by the observation that the widths of the transverse momentum distributions are independent of the bombarding energy. At the lower bombarding energies these angular cuts include some of the detectors of the Si-CsI(Tl) telescope array.

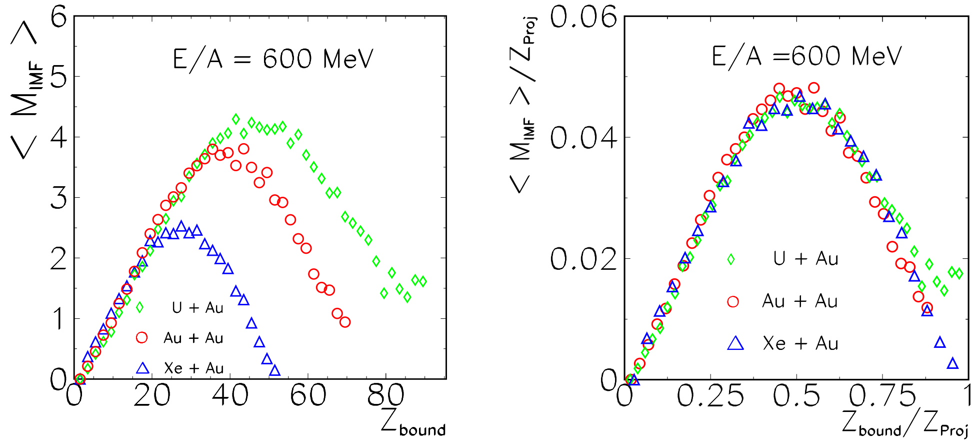

Figure 3: Correlation between the mean multiplicity of intermediate-mass fragments $\langle M_{imf} \rangle$ and Z_{bound} for the reactions ^{238}U on ^{197}Au (diamonds), ^{197}Au on ^{197}Au (circles), and ^{129}Xe on ^{197}Au (triangles) at $E/A = 600$ MeV, as measured with the TOF-Wall (left-hand-side). The same correlation but normalized with respect to the projectile atomic number Z_{proj} (right-hand-side).

In Fig. 2 the mean number of intermediate-mass fragments (IMF's, $3 \leq Z \leq 30$) is shown as a function of Z_{bound} for the reaction of ^{197}Au on ^{197}Au at four bombarding energies. With the definition of the projectile spectator given above the correlation between the two quantities is seen to be independent of the projectile energy within the experimental accuracy. The maximum multiplicity of 4 to 4.5 fragments is reached at $Z_{bound} \approx 40$.

The M_{IMF} versus Z_{bound} correlation depends on the mass of the projectile (Fig. 3, left-hand-side). More fragments are to be expected from heavier projectiles. However, this relation turns out to be almost perfectly proportional to the projectile mass viz. charge (Fig. 3, right-hand-side). For this comparison the upper limit of the IMF definition was changed from $Z \leq 30$ to $Z \leq Z_{proj}/3$. Since the element yields decrease rapidly with Z the upper limit is not crucial. The observed invariance with respect to the entrance channel is not restricted to the multiplicity of intermediate-mass fragments but appears to be a very general feature also of the relative asymmetries and other correlations between the abundancies and the atomic numbers of the fragmentation products [7].

4 Limits of the Universality of Spectator Decay

The observed universality gives rise to the question as to where its limits may lie. Our data for collisions with rather light targets such as beryllium or carbon indicate that, in these cases, beam energies considerably above 400 MeV per nucleon are required in order to reach the maximum IMF production. This is illustrated in Fig. 4 where the fragment multiplicities are plotted as a function of the relative impact parameter b/b_{max}. The impact parameter b was deduced by assuming a monotonous relation between b and Z_{bound}. The data for the Au target exhibit energy independent maxima consistent with the invariance discussed in the last section. At 1000 MeV per nucleon, the maximum shifts to smaller impact parameters with decreasing target mass but always assumes the same value, again consistent with the Z_{bound} universality. At 400 MeV per nucleon, in contrast, the maxima of the multiplicity distributions are considerably reduced already for the carbon target.

The lower part of Fig. 4 gives the normalized multiplicities $\langle M_{IMF}/Z_{bound} \rangle$. In first order, they are independent of the size of the decaying system and may thus reflect the relative degree of spectator excitation. The data for the beryllium target, in particular, illustrate that, at energies below 1000 MeV per nucleon, the spectators formed even in the most central collisions are not sufficiently excited in order to undergo a complete breakup.

On the high-energy side, there is no limit known at present. Limiting fragmentation, i.e. a saturation of the production cross sections for intermediate mass fragments at bombarding energies in excess of several GeV, has been observed [11]. It suggests that the formation of spectator nuclei with high excitation energies may be common to heavy-ion

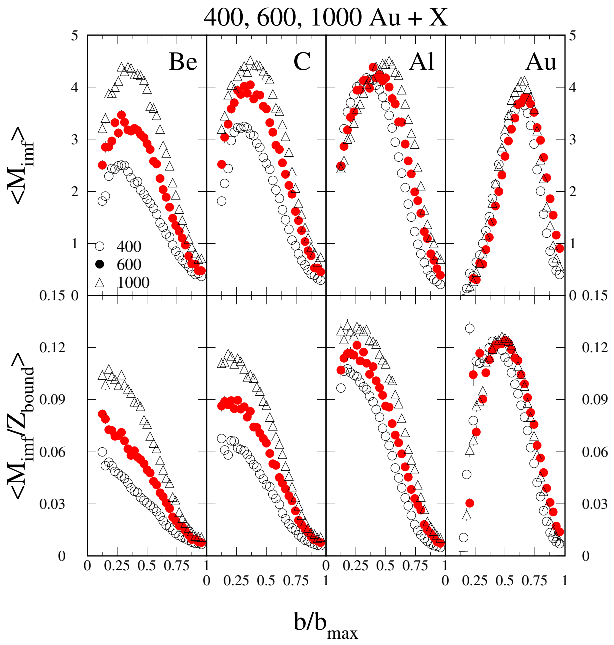

Figure 4: Mean multiplicity of intermediate-mass fragments $\langle M_{imf} \rangle$ (top) and normalized multiplicity $\langle M_{imf}/Z_{bound} \rangle$ (bottom) as a function of the deduced relative impact parameter b/b_{max} for the reactions of ^{197}Au projectiles with Be, C, Al, and Au targets at bombarding energies of 400, 600, and 1000 MeV per nucleon.

collisions in the GeV range. A recent study performed with ^{197}Au beams of 10.6 GeV per nucleon, available from the AGS at Brookhaven, and emulsion targets [12] reports nearly quantitative agreement with the fragmentation patterns of ^{197}Au on Cu collisions at 600 MeV per nucleon [6].

5 Neutrons from Spectator Decays

Neutrons from the decay of the excited spectator sources were detected with the large-area neutron detector LAND which was positioned close to zero degrees at about 9 m downstream from the target. The thickness of 1 m of the calorimeter-type detector permits the detection of fast neutrons with high efficiency.

Fig. 5 shows the rapidity distribution of neutron hits in LAND for central, semi-central, and peripheral collisions. The distributions are well described by a sum of two gaussian

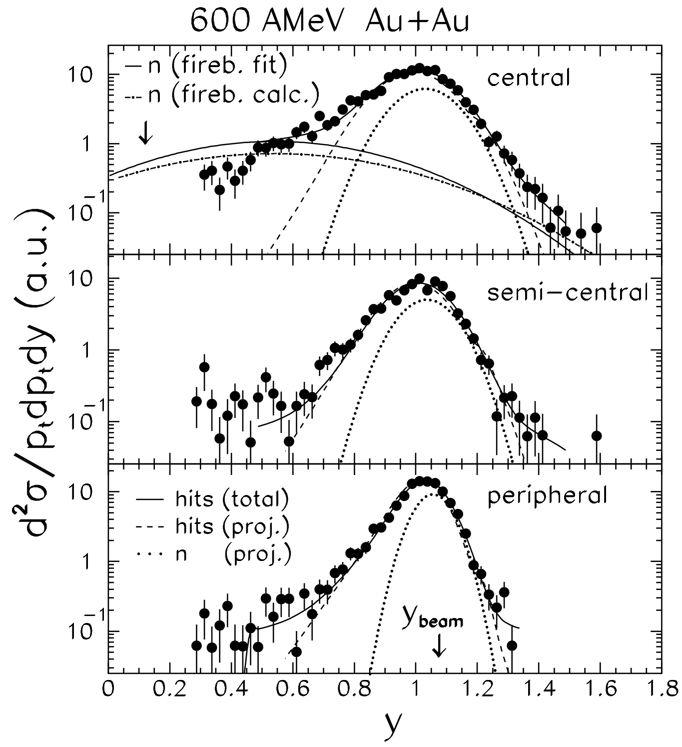

Figure 5: Rapidity distributions of neutron hits in LAND for the transverse momentum bin 20 MeV/c $\leq p_t \leq$ 25 MeV/c (points). The dotted lines represent the fit results for neutrons emitted by the projectile-spectator source. The contribution from the mid-rapidity source is shown for central collisions (top panel).

distributions, folded with the detector response (full line). The detector response was determined by using monoenergetic neutrons from deuteron break-up. The two gaussian distributions represent neutron emission from the fireball and from the projectile spectator or its fragments. The spectator source of neutrons moves with a rapidity very close to the beam rapidity of $y_{beam} = 1.07$ (after traversing one-half of the target).

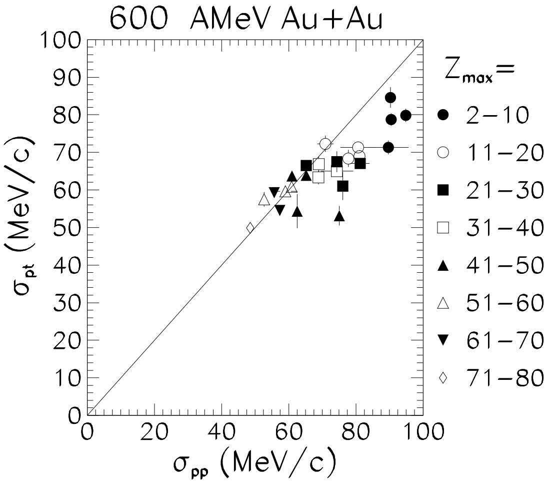

Figure 6: Transverse versus parallel widths of the neutron-momentum distributions for 10-unit wide bins in Z_{max} and Z_{bound} (not indicated) for the reaction of ^{197}Au on ^{197}Au at $E/A = 600$ MeV.

The widths of the transverse distributions of neutron momenta have been determined from fits to the observed parts of the distributions within the covered range of neutron transversal momenta (Fig. 6). The widths increase for the bins of smaller Z_{max} which indicates a larger temperature of the emitting source in the most central collisions. Figure 6, in particular, shows that the perpendicular and transverse widths are nearly identical. The neutron momentum distributions thus support the idea of equilibration at an early reaction stage.

6 Excitation Energy prior to Fragment Decay

The procedure used to determine the mass and excitation energy prior to the spectator decay is very similar to that used by Campi et al. [13]. However, besides the multiplicities and kinetic energies of charged particles and fragments also those of free neutrons were included in the analysis.

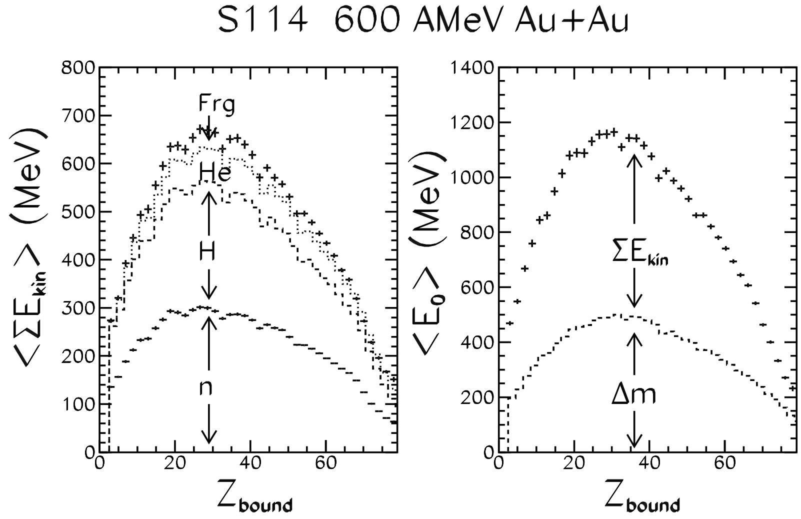

Figure 7: Individual contributions to the total kinetic energy (left-hand-side) and contributions by the total Q-value Δm and by the sum of the kinetic energies to the total energy of the spectator (right-hand-side).

The basic idea is to determine the atomic number Z_0, the mass number A_0, and the excitation energy E_0 of the excited spectator from balance equations. Since the hydrogen isotopes were not detected assumptions concerning the overall N/Z ratio of the spectator, the intensity ratio of protons, deuterons, and tritons, and the kinetic energies of hydrogen isotopes had to be made. In addition, the EPAX parameterization [14, 15] was used for deriving masses from the atomic numbers of the detected fragments. The uncertainties resulting from the variation of these quantities within reasonable limits are included in the adopted errors.

It is found that light particles and, in particular, the neutrons contribute considerably to the energy balance (Fig. 7). Independent of Z_{bound}, the Q value amounts to about 40% of the total spectator energy E_0.

The results for the mass A_0 and for the specific excitation energy E_0/A_0 are given in Fig. 8. The data points represent the results for individual bins in the Z_{max}-versus-Z_{bound} event representation. The mass A_0 decreases with decreasing Z_{bound} but, apparently, independent of Z_{max}. The smallest mean spectator mass in the bin of $Z_{bound} \leq 10$ is $\langle A_0 \rangle \approx 50$. The excitation energy E_0 appears to be a function of both Z_{bound} and Z_{max}; the higher values correspond to the smaller Z_{max} values, i.e. to more complete disintegrations of a system of given mass. The maximum number of fragments, observed at $Z_{bound} \approx 40$, is associated with initial excitation energies of $\langle E_0 \rangle / \langle A_0 \rangle \approx 8$ MeV. With decreasing Z_{bound} the deduced excitation energies reach up to $\langle E_0 \rangle / \langle A_0 \rangle \approx 15$ MeV. These energy deposits for the range

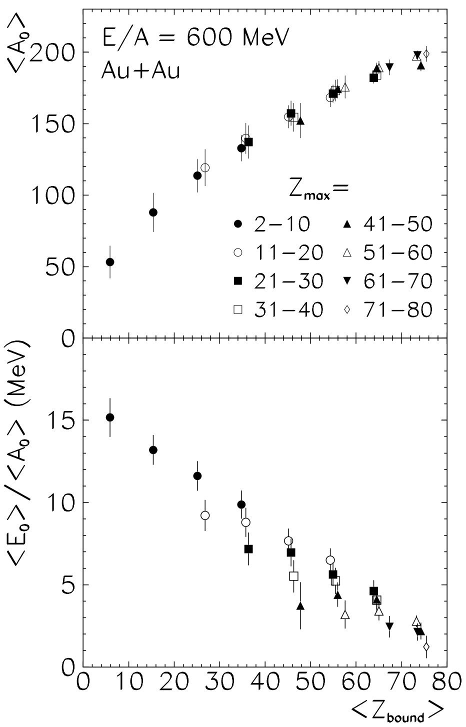

Figure 8: Mass $\langle A_0 \rangle$ (top) and specific excitation energy $\langle E_0 \rangle / \langle A_0 \rangle$ (bottom) of the spectator as a function of Z_{max} and Z_{bound} for the reaction of ^{197}Au on ^{197}Au at $E/A = 600$ MeV.

of small Z_{bound} are considerably larger than those obtained from the statistical analysis of the charge correlations of intermediate mass fragments ($Z \geq 3$) for ^{197}Au + Cu collisions at 600 MeV per nucleon [15].

7 Summary

The available systematics reveal a universal behavior of multifragment decays of excited spectator nuclei for the range of bombarding energies $E/A = 400$ to 1000 MeV, and possibly to higher energies. This suggests that the mechanism of thermally driven decay remains the same and, furthermore, that the relation of excitation energy and mass for the produced spectators is virtually unchanged over this range of bombarding energies. In reactions with the lighter targets higher bombarding energies are needed in order to reach maximum fragment multiplicities and to achieve a complete disintegration of the projectile spectator. The corresponding lower limits are about 600 MeV and 1000 MeV per nucleon for the carbon and beryllium targets, respectively.

The momentum distributions of free neutrons measured with LAND are dominated by emission from a spectator source with approximately beam rapidity. Balance equations were used in order to determine the mass and excitation energy of the spectator system prior to its decay. The masses decrease and the excitation energies increase monotonously with decreasing Z_{bound}. The maximum excitation energies obtained from this analysis reach a value of 15 MeV per nucleon for the bin of smallest Z_{bound}.

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