Heavy Residues with A<90 from the Asymmetric Reaction of 20 AMeV $^{124}$Sn+$^{27}$Al as a Sensitive Probe of the Onset of Multifragmentation

M. Veselsky$^{a,b}$, G.A. Souliotis$^b$, G. Chubarian$^b$, L. Trache$^b$, A. Keksis$^b$, E. Martin$^b$, A. Ruangma$^b$, E. Winchester$^b$, and S. J. Yennello$^b$.

$^a$Institute of Physics, Slovak Academy of Sciences, Dubravska 9, 84228 Bratislava, Slovakia
$^b$Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA

Abstract

The cross sections and velocity distributions of heavy residues from the reaction of 20 AMeV $^{124}$Sn + $^{27}$Al have been measured at forward angles using the MARS recoil separator at Texas A&M in a wide mass range. A consistent overall description of the measured cross sections and velocity distributions was achieved using a model calculation employing the concept of deep-inelastic transfer for the primary stage of peripheral collisions, pre-equilibrium emission and incomplete fusion for the primary stage of more violent central collisions and the statistical model of multifragmentation (SMM code) for the deexcitation stage. An alternative calculation employing the sequential binary decay (GEMINI code) could not reproduce the observed yields of the residues from violent collisions (A<90) due to different kinematic properties. The success of SMM demonstrates that the heavy residues originate from events where a competition of thermally equilibrated fragment partitions takes place rather than a sequence of binary decays.

Key words: Nuclear reactions, intermediate energy, peripheral collisions, violent collisions, sequential binary decay, simultaneous multifragmentation.

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$^1$ E-mail address: fyzimarv@savba.sk (M. Veselsky).
1 Introduction

The yields of the heavy residues, the large remnants of the heavy member of an asymmetric reacting pair of nuclei, are known to comprise a large fraction of the reaction cross section for intermediate energy nuclear collisions. The studies carried out in inverse kinematics at projectile energies of several tens of AMeV by Bazin et al. [1], Faure-Ramstein et al. [2], Pfaff et al. [3], Hanold et al. [4] and Souliotis et al. [5,6,7] have shown the utility of the fragment separator approach in studying the heavy reaction products from Kr+X, Xe+X and Au+X mass asymmetric collisions at intermediate energies. Compared to asymmetric reactions in normal kinematics [8,9], where the low energies of residues (~0.015 AMeV) cause the loss of substantial portions (50%) of the product distributions, due to experimental thresholds [8], the studies in inverse kinematics using a high resolution spectrometer/detector system allow the observation of a wide range of nuclei including the projectile-like fragments (PLFs) and the heavy remnants of the hot nuclei originating from violent collisions. From such inclusive measurement, one can gain important information about the reaction mechanism, complementary to that obtained in exclusive studies, where only the light reaction partners are observed with high isotopic resolution.

For asymmetric reactions of a heavy beam with a light target nucleus (typically C, Al) the momentum transfer data obtained (see e.g. [2,4,5]) demonstrate the presence of reaction mechanisms ranging from quasi-elastic peripheral collisions to processes analogous to the complete fusion and incomplete fusion observed at low energies. However, since asymmetric reactions at several tens of AMeV are complex processes, the description of the data by the simple low energy concepts such as massive-transfer hypothesis or the high-energy geometric abrasion model have shown to be, despite qualitative agreement, far from quantitative.

With increasing target mass, the reactions become more symmetric and the observed yields of heavy residues are dominated by peripheral processes such as deep-inelastic transfer as, for instance, shown in detail in our recent work [10] in the reaction of 25 AMeV $^{86}$Kr $+^{64}$Ni. As it follows from the model analysis (for details see the original work), the projectile-like fragments observed in this reaction are heated by intense exchange of nucleons with the target. The excitation energy is sufficient for emission of complex fragments. Previous studies [1,11,12,13,14,15,16,17,18,19] of the collisions of heavy nuclei at intermediate energies have also shown that such reactions are predominantly binary. Evidence has been presented [19] for a sequential decay of one of the initial binary fragments leading to a three (or more) body final state. In some of the binary encounters the projectile-like fragments have been found [15,18] to have very high temperatures (T~7 MeV).
The focus of the present work is the formation of heavy residues in the reaction of 20 AMeV $^{124}$Sn on $^{27}$Al. The main motivation was the observation of heavy remnants of hot nuclei created in violent collisions at low impact parameters where a single hot source is created. In particular, it is of importance to establish in detail to what extent the observed properties of such heavy residues are influenced by the dynamics of the entrance channel (pre-equilibrium emission, incomplete fusion) and/or by the process of de-excitation (emission of complex fragments, multifragmentation). In the reaction $^{124}$Sn + $^{27}$Al one can assume that the residues with masses much lower than that of the beam originate from violent collisions. Such an assumption is supported by the work presented in [20], where it was shown that for the damped peripheral collisions $^{28}$Si + $^{112,124}$Sn at energies 30 – 50 AMeV the heavy target-like fragment remains rather cold, while the light projectile-like fragment is hot enough to undergo multifragmentation. This is caused by approximately equal sharing of the excitation energy imparted to the reaction partners due to nucleon exchange. In order to heat the heavy fragment to higher excitation energies, part of the lighter partner should fuse with the heavier one, thus converting the kinetic energy of the relative motion into heat. The recoil spectrometer MARS at the Cyclotron Institute of Texas A&M University offers the possibility to carry out this study with an appropriate angular and momentum acceptance, under high-resolution conditions and in the appropriate region of nuclei.

2 Experimental Method and Data Analysis

The present study was performed at the Cyclotron Institute of Texas A&M University. A 20 AMeV $^{124}$Sn$^{27+}$ beam from the K500 superconducting cyclotron, with a typical current of $\sim$0.5 pnA, interacted with a $^{27}$Al target of thickness 2.0 mg/cm$^2$. The reaction products were analyzed with the MARS recoil separator [21]. The primary beam struck the target at 0° relative to the optical axis of the spectrometer. The direct beam was collected in a small square Faraday cup approx. 30 cm after the target, blocking the angular range 0.0–1.0°. The fragments were accepted in the remaining angular opening of MARS: 1.0–2.7° (the angular acceptance of MARS is 9 msr [21]). This angular range encompasses the grazing angle of 2.1° [22] for the present reaction. MARS optics [21] provides one intermediate dispersive image and a final achromatic image (focal plane) and offers a momentum acceptance of 4%.

At the focal plane, the fragments were collected in a large area (5×5 cm) three-element ($\Delta E_1$, $\Delta E_2$, E) Si detector telescope. The $\Delta E_1$ detector was a position-sensitive Si strip detector of 63 µm thickness, whereas the $\Delta E_2$ and the E detector were single-element Si detectors of 150 and 950 µm, respectively. The position information from the $\Delta E_1$ strips provided a continuous monitoring of the focusing and collection of the fragments at the various settings of the
separator. Time of flight was measured between two parallel plate avalanche counters (PPACs) \cite{23} positioned at the dispersive image and at the focal plane, respectively, and separated by a distance of 13.2 m. The PPAC at the dispersive image was also X–Y position sensitive and used to record the position of the reaction products. The horizontal position, along with NMR measurements of the field of the MARS first dipole, was used to determine the magnetic rigidity $B\rho$ of the particles. Thus, the reaction products were characterized by an event-by-event measurement of the energy loss, residual energy, time of flight, and magnetic rigidity. The response of the spectrometer and detector system to ions of known atomic number $Z$, mass number $A$, ionic charge $q$ and velocity was calibrated using low intensity primary beams of $^{124}$Sn at 20 AMeV and $^{40}$Ar, $^{44}$Ca and $^{86}$Kr at 25 AMeV. To cover the N/Z and velocity range of the fragments, a series of measurements was performed at overlapping magnetic rigidity settings in the range 1.3–1.6 Tesla-meters.

The determination of the atomic number $Z$ was based on the energy loss of the particles in the first $\Delta E$ detector \cite{24} and their velocity, with a resulting resolution (FWHM) of 1.0 $Z$ units for near-projectile fragments and 0.6 $Z$ units for $A<90$. The ionic charge $q$ of the particles entering the spectrometer after the Al stripper, was obtained from the total energy $E_{\text{tot}}=\Delta E_1+\Delta E_2+E$, the velocity and the magnetic rigidity according to the expression:

$$q = \frac{3.107}{931.5} \frac{E_{\text{tot}}}{B\rho(\gamma - 1)} \beta \gamma$$

(1)

where $E_{\text{tot}}$ is in MeV, $B\rho$ in Tm, $\beta = v/c$ and $\gamma = 1/(1-\beta^2)^{1/2}$. The measurement of the ionic charge $q$ had a resolution of 0.8 $Q$ units (FWHM) for near-projectile fragments and 0.5 $Q$ units for $A<90$. Since the ionic charge must be an integer, we assigned integer values of $q$ for each event by putting appropriate windows on each peak of the $q$ spectrum at each magnetic rigidity setting of the spectrometer. Using the magnetic rigidity and velocity measurement, the mass-to-charge $A/q$ ratio of each ion was obtained from the expression:

$$A/q = \frac{B\rho}{3.107 \beta \gamma}$$

(2)

Combining the $q$ determination with the $A/q$ measurement, the mass $A$ was obtained as:

$$A = q_{\text{int}} \times A/q$$

(3)

($q_{\text{int}}$ is the integer ionic charge determined as above) with an overall resolution (FWHM) of 1.0 $A$ units for near-projectile fragments and about 0.6 $A$ units for $A < 90$. We refer to our previous work in ref. \cite{10}, carried out using
the same experimental setup within the same run, for more details. The reconstruction of the Z, q and A and the gating procedure were applied to the calibration beam data to ensure the reproduction of the expected Z, q and A values and the elimination of spurious yield contributions from neighboring Z and q values. For the heavier products with masses $A > 90$ the experimental resolutions did not allow the mass to be resolved unambiguously. However, the gross features for such products can still be obtained. Close to the beam, part of the yield could not be detected due to background from the quasi-elastically scattered beam.

Combination and appropriate normalization of the data at various magnetic rigidity settings of the spectrometer provided fragment distributions with respect to Z, A, q and velocity. Correction of missing yields caused by charge changing at the PPAC (positioned at the dispersive image) was performed based on the equilibrium charge state prescriptions of Leon et. al. [25]. The overall data reduction procedure was similar to that followed in earlier work on $^{197}$Au fragmentation [6] and $^{238}$U projectile fission [26] at 20 AMeV. The isotope distributions were subsequently summed over all values of q. It should be pointed out that the resulting distributions in Z, A and velocity are the fragment yield distributions measured in the angle interval $1.0–2.7^\circ$ and in the magnetic rigidity range 1.3–1.6 T m.

3 Results and Discussion

The gross features of the measured data from the reaction of 20 AMeV $^{124}$Sn + $^{27}$Al are displayed in Figs. 1,2. In Fig. 1 isotopic yields (contour plot) are presented as a function of mass and atomic number. The masses of observed products cover the range from the projectile-like fragments to the border of the intermediate mass fragment domain at $Z=20$. The yields of projectile-like nuclei peak around the nuclide $^{116}$Te. The position of this peak is caused by missing yield from the region close to the beam where the reaction products cannot be resolved using the existing detector set-up due to significant background from quasi-elastic processes. At masses below $A=90$ the distribution becomes rather flat and follows approximately the corridor of stable isotopes (thick dashed line). These are the reaction products which are expected to originate from the hot excited systems. Fig. 2 presents the velocity distributions of residues with selected atomic numbers. In the region close to beam the velocity distributions appear to be convolutions of multiple contributions from different reaction channels ranging from quasielastic products close to the beam velocity to various incomplete fusion channels where the velocity decreases with the amount of mass transferred from the target. With decreasing mass of the reaction product, the velocity distributions develop toward a single contribution of a Gaussian shape with a low velocity tail. The centroids
of these distributions shift with decreasing mass toward higher velocity. Such a trend is caused by the kinematic selection of the spectrometer.

The experimental heavy residue data presented in Figs. 1,2 contain useful information on the production mechanism. The properties of the final products are the result of a complex process including an early stage dominated by the dynamics of the entrance channel which is governed by the impact parameter and a de-excitation stage where the final partitions of the reaction products are generated. In such a case, a viable method of reaction mechanism analysis appears to be the use of various model frameworks for both the initial stage of the collision and the de-excitation. The model which eventually proves superior to the others can be considered as reflecting the physical process in most detail.

As a first choice for the description of the initial stage we use the model framework described in [27]. The basic features of the reaction mechanism model for violent collisions are the pre-equilibrium emission and the incomplete fusion (ICF). The pre-equilibrium emission is treated using a simplified variant of the exciton model employing a phenomenological parametrization of emission probability as a function of exciton number and angular momentum. The incomplete fusion model is based on the concept of geometrical fragmentation refined for the Fermi energy domain where incomplete fusion occurs by fusion of the participant zone with one of the spectators. It is applied to the reconstructed projectile-like and target-like prefragments formed in the pre-equilibrium stage. For the dissipative peripheral collisions the model of deep inelastic transfer (DIT) is used as implemented by Tassan-Got and Stefan [28]. The DIT scenario is employed for events where the overlap of projectile and target nuclei does not exceed 3 fm. Again the DIT stage is preceded by the pre-equilibrium stage. Such a hybrid framework proved rather successful [27] in the description of a wide range of data obtained in experiments ranging from inclusive measurements to highly exclusive ones in 4π geometry and can be considered appropriate for the reaction investigated in the present work, with a capability of quantitative description. Throughout the paper, this calculation will be named for simplicity as DIT+ICF. Nevertheless, one has to keep in mind that pre-equilibrium emission is an essential part of this model.

In order to describe the de-excitation stage of hot nuclei, there exist several concepts implemented in various codes. The statistical de-excitation code GEMINI [29] uses Monte Carlo techniques and the Hauser-Feshbach formalism to calculate the probabilities for fragment emission with \( Z \leq 2 \). Heavier fragment emission probabilities are calculated using the transition state formalism of Moretto [30]. Within such a model, the final partition of products is generated by a succession of fragment emissions (binary decays). Alternative to this scenario is the model of statistical multifragmentation, where the fragment partition is generated at once in the so-called freeze-out configuration.
In this work, we use the code SMM [31] as a representative implementation of the concept of prompt multifragmentation. Thermally equilibrated partitions of hot fragments are generated in the hot stage, which is followed by propagation of fragments in their mutual Coulomb field and secondary de-excitation of hot fragments flying in their asymptotic directions.

The results of the DIT+ICF/GEMINI calculation, compared to experimental observables are given in Fig. 3. In the GEMINI calculations, we used essentially the parameter set recommended by the author, featuring Lestone’s temperature dependent level density parameter [32], a fading of shell corrections with excitation energy and enabled IMF emission. This parameter set proved successful in our recent work [10] on the reaction \(^{86}\text{Kr} + ^{64}\text{Ni}\) at 25 AMeV.

In Fig. 3a the mass yield curve is presented. The measured data, normalized for beam current and target thickness are given in mb and presented as solid circles. The result of the DIT+ICF/GEMINI calculation, filtered by the spectrometer angular and momentum acceptance is given by the full line, whereas the dashed line gives the total (unfiltered) yield. A comparison of the measured yields to the calculated filtered yields shows reasonable agreement for the heavier projectile-like fragments (A>90). The missing experimental cross section at the masses close to the beam is caused by the limitations of the experimental set-up as explained in the discussion of Fig. 1. The yields of residues with A<90 are increasingly underestimated by the calculation despite the fact that the unfiltered calculated yields are rather flat in this region, which appears to reflect the trend of the experimental data. Since, according to Fig. 3a, the yield of unfiltered residues with A<90 is rather flat, the missing filtered yield below A=90 in the calculation appears to be caused by the fact that the kinematic properties of the simulated residues with A<90 increasingly miss the spectrometer acceptance with decreasing mass, leading to increasing losses in the filtering procedure.

In Fig. 3b, the calculated and measured yield distributions as a function of Z (relative to the line of \(\beta\)-stability, \(Z_\beta\)) and A are presented. The line of stability is calculated as: \(Z_\beta = A/(1.98 + 0.0155A^{2/3})\) [33]. The calculated average values from DIT+ICF/GEMINI are shown as a thick dashed line (without acceptance cut) and as a thick full line (with spectrometer acceptance cut). The measured yield distribution is represented by a contour plot. The DIT+ICF/GEMINI calculation describes reasonably well the centroids of the experimental data.

Finally, in Fig. 3c, the velocity vs. mass distributions are given. The data are again shown as contours. The thick dashed line is from the DIT+ICF/GEMINI calculation without acceptance cut and the full line is with acceptance cut. In this case the filtered calculated data appear to follow the experimental trend at masses above A=90, while they exhibit slight increase of the mean velocity
with decreasing masses below A=90.

An alternative calculation was carried out, where the SMM code was used for the de-excitation of the hot nuclei produced by the DIT+ICF simulation. In the SMM calculation, a freeze-out configuration with hot primary fragments was assumed. Hot fragments are propagated in the Coulomb field and de-excited by secondary emission. Only thermal excitation energy is used as input while the rotational energy (typically not exceeding 10 MeV) is subtracted. The results are presented in Fig. 4 in a fashion analogous to Fig. 3. As one can see in all panels of Fig. 4, the DIT+ICF/SMM calculation provides very consistent description of experimental observables for A<105 (the discrepancies in the region close to the beam are analogous to previous cases).

Using the ratio of filtered to unfiltered calculated yield for each mass, correction factors (whose magnitude are inferred from Fig. 4a) for the acceptance of the spectrometer can be obtained as a function of mass. When applied to the measured yield data, an estimate of the total yield, shown by the open circles in Fig. 4a, could be obtained.

Thus, implementation of the prompt multifragmentation scenario appears to lead to production of heavy residues with proper kinematics. Compared to light particles or intermediate mass fragments (IMFs) used for imaging of the emitting source via particle-particle correlations, the experimentally detected heavy residues possess direct information on the properties of hot multifragment partitions. The process of secondary emission, as can be concluded from the simulations, does not influence significantly the kinematic properties of the heavy residues with masses A=40–90, since emission of nucleons is a dominant channel of secondary de-excitation.

Detailed insight into the different kinematic properties of residues simulated using GEMINI and SMM codes can be obtained from Figs. 5, 6 and 7. In Fig. 5 the calculated angular distributions as a function of residue mass for GEMINI (a) and SMM (b) are presented. Two horizontal lines mark the angular acceptance of the MARS separator. It is remarkable to notice that, in fact, the gross features of both distributions are very similar and the experimental effect appears to be caused by the distant tail of the distribution, which extends much further toward zero angle in the scenario where the hot nucleus disintegrates at once into more pieces. Nevertheless, the essential feature of the zero angle region is that it is highly selective toward products from incomplete or complete fusion channel since the hot source is flying essentially along the beam direction and the final angular distribution is determined by the de-excitation process. In the case when the hot nucleus disintegrates by sequential binary decay, the recoil from emitted fragments causes a shift of the residue angle away from the zero angle. In Figs. 6, 7 the calculated velocity distributions as a function of mass obtained using the GEMINI and SMM codes are given, respectively. In both cases, unfiltered yields are presented in panel (a), while
the filtered yields are given in panel (b). As one can observe in panel (a), the SMM calculation leads to a much wider velocity distribution for A<90 which corresponds to a flatter angular distribution extending further toward zero angle. In the GEMINI calculation, the velocity distribution is concentrated close to the center of the distribution for a given mass, while the tails toward higher/lower velocities are suppressed since such residues, due to kinematics, can be produced only close to zero angle. On the other hand, when comparing the fastest residues for a given mass at A<90, which are emitted close to zero angle, the GEMINI calculation leads to higher maximum velocities, due to a larger recoil caused by the scenario of sequential binary decay. Nevertheless, due to the momentum coverage of the whole measurement which is close to 20 %, such a difference does not have a strong influence on the filtered yield. The effect of angular acceptance of MARS is dominant and determines the filtered yields which are much higher in the SMM simulation than in the GEMINI simulation.

In Fig. 8 the normalized unfiltered residue mass distributions at various impact parameters are given for both calculations. For DIT+ICF/SMM, one can notice a rather strong dependence of the production rate for residues with A<90 on impact parameter. For the DIT+ICF/GEMINI calculation, the dependence is rather weak. Significant contribution of A<90 residues is produced already at b=8 fm and toward lower impact parameters the shape of the distribution changes only moderately. As one can see in Fig. 9a, the average excitation energy of the hot source obtained using DIT+ICF model changes with impact parameter rather strongly. At b=8 fm, the average excitation energy amounts only to 80 MeV, which translates into relative excitation below 1 AMeV. At such excitation energy, the emission of IMFs is rather improbable and the simulated residues with A<90 can be expected to be fission fragments in the traditional sense. However, the mass distribution of such residues is virtually flat due to a weak asymmetry dependence of fission barriers of nuclei with fissility $x = 0.4 - 0.5$, as suggested by theory [34]. In the GEMINI calculation, such fission fragments are produced with a probability of about two orders of magnitude larger than in the SMM calculation. This rather large difference in yield reflects a different treatment of fission in each code. The code GEMINI uses the asymmetry-dependent fission barriers [34] normalized to angular momentum dependent finite range fission barriers of Sierk [35]. On the other hand, the SMM code, where fission and multifragmentation are treated separately, uses the fission barriers of Barashenkov [36] without explicit angular momentum dependence (the mass distributions in the SMM are generated according to the parametrization of Adeev [37]). For example, the nucleus $^{124}$Sn at angular momentum $J=0$ is supposed to have the fission barrier of 41.5 MeV in GEMINI and 44.8 MeV in SMM. At $J=25$, which is a typical value of angular momentum at b=8 fm (see Fig. 9b), the fission barrier of Sierk drops further to 36.9 MeV. Assuming a level density parameter $a=A/10$, the difference of level density indeed amounts to slightly less than two orders of
magnitude, consistent with Fig. 8. Thus the production rates of residues with \(A<90\) at \(b=8\) fm are consistent with the production rates of fission fragments. An analogous conclusion applies to impact parameter \(b=6\) fm. At central impact parameters \(b=4\) fm and \(b=2\) fm, where the average relative excitation energy approaches and exceeds 2 AMeV, the production rate of residues with \(A<90\) increases dramatically in the SMM calculation and exceeds the production rate of GEMINI calculation, since the multifragmentation threshold is exceeded by an increasing part of the excitation energy distributions at central impact parameters \(b=4\) fm and \(b=2\) fm, as one can deduce from Fig. 10.

For the heavier asymmetric system \(^{136}\text{Xe}+^{48}\text{Ti}\) at 18.5 AMeV, where, due to higher fissility, the fission mass distribution is dominated by symmetric mass splits, the experimental investigation of 3-body events carried out by Gui et al. [38] revealed that the sequential fission mode with symmetric mass distribution dominates at lower excitation energies, while at higher excitation energies the de-excitation mode with wider asymmetry range and short emission time was observed. The asymmetric de-excitation mode with short timescale can, in principle, be related to the onset of multifragmentation. The decrease of the emission time with increasing mass asymmetry was observed also for 3-body events in the symmetric reactions \(^{100}\text{Mo}+^{100}\text{Mo}\) and \(^{120}\text{Sn}+^{120}\text{Sn}\) around 20 AMeV [39], where, on the other hand, the typical spatial configuration with the small fragment located between the two large fragments suggests the occurrence of dynamical effects specific to emission from the symmetric binary configuration.

At excitation energies above the multifragmentation threshold, the SMM scenario leads to competition of the hot multifragment partitions with the single hot thermally equilibrated fragment (practically identical to the compound nucleus in traditional sense). Within the sequential binary decay scenario with finite range fragment emission barriers, as implemented in GEMINI, the onset of multifragment channels is much smoother. Apart from the reduction of the fission barrier, the angular momentum of the hot residue leads to a reduction of the thermal excitation energy due to the energy of rotational motion. However, the values of angular momentum in Fig. 9b imply that in the present work the rotational energy typically does not exceed 5 MeV and thus does not influence the results, especially at mid-central to central collisions which lead to production of heavy residues with \(A<90\). An interesting aspect of the excitation energy versus mass distributions, shown in Fig. 10, is the gradual change of the governing pattern from the essentially Wilczynski plots at peripheral impact parameters to the pattern typical for incomplete fusion scenario at central impact parameters. Thus, the success of SMM implies that the residues with \(A<90\) observed at forward angles originate from incomplete fusion.
For further comparison, the calculations using only the model of deep inelastic transfer combined with both GEMINI and SMM, analogous to DIT/GEMINI simulation used in our recent work [10], have been carried out. In the case of the nearly symmetric reaction $^{86}\text{Kr} + ^{64}\text{Ni}$ at 25 AMeV [10], the DIT/GEMINI simulations proved to be rather successful. Similar success was achieved in the reaction of 20 AMeV $^{124}\text{Sn} + ^{27}\text{Al}$ at 20 AMeV, the yields of residues with $A < 90$ can not be reproduced by taking into account peripheral processes only, independent of which de-excitation code was used. For instance, in the DIT/GEMINI simulations, the total unfiltered yields are roughly analogous to the simulation presented in Fig. 3 and the filtered yields again do not reproduce the observed yields of residues with $A < 90$. In this case, the filtered distribution exhibits similar decrease in the $A < 90$ region but extends further than in DIT+ICF/GEMINI case, due to higher excitation energy and different angular and momentum distribution of the generated hot nuclei. The difference can be attributed mostly to the absence of cooling via pre-equilibrium emission, since the products of violent collisions are not included in the DIT/GEMINI simulation and do not pass the filter procedure in the latter case. On the other hand, the DIT/SMM simulation, when compared to DIT+ICF/SMM simulation shown in Fig. 4, significantly underpredicts the yields of the residues with $A < 90$ ( both unfiltered and filtered ), due to the fact that for peripheral collisions, the excitation energy of projectile-like fragments exceeds the value of 2 AMeV, where the multifragmentation threshold can be anticipated, only very rarely, and due to orbiting, such sources move typically at angles away from zero.

Furthermore, a backtracing procedure was used for the DIT+ICF/SMM simulation. In Fig. 11a,b,c the mass, charge, excitation energy distributions of hot heavy sources contributing to filtered yield of residues with $A = 65-75$ are shown. Fig. 11d shows the distribution of contributing impact parameters. On average, a typical contributing hot source can be characterized as a nucleus $^{144}\text{Nd}$ with excitation energy about 310 MeV ( 2.2 AMeV ). The average impact parameter is about 2 fm ( $l = 44$ ) and the average spin of the hot source is $J = 30$. Thus the results of the backtracing procedure are in good agreement with the results of the analysis presented above. The observed ( symbols ) and filtered ( solid histograms ) velocity and N/Z-distributions of residues with $A = 65-75$ along with the velocity and N/Z-distributions of contributing hot heavy sources ( dashed histograms ) are compared in Fig. 12. The simulated velocity and N/Z-distributions reproduce in high detail the experimental ones, thus further demonstrating the appropriate description of reaction mechanism within the DIT+ICF/SMM simulation and the appropriate treatment of the spectrometer in the filtering procedure. The comparison of the observed and filtered velocity distribution with the backtraced velocity distributions shows that indeed the observed residues correspond to the
forward kinematic solution, selected by the spectrometer angular acceptance. The momentum acceptance of the measurement does not appear to play a role in the filtering procedure. The width of the backtraced velocity distribution is rather small and corresponds to the incomplete fusion scenario. The comparison of the observed and filtered N/Z-distribution with the backtraced N/Z-distributions shows a strong shift of the N/Z-ratio towards the $\beta$-stability line which is typical for hot heavy sources where N/Z-equilibration is achieved during de-excitation. The widths of the distributions differ only slightly and the narrow N/Z-distributions correspond to the incomplete fusion scenario.

Since the experimental effect is determined by residues originating from violent collisions it is interesting to assess to what extent the description of incomplete/complete fusion can be considered adequate. As already mentioned above, the ICF calculation [27] proved rather successful in quantitative description of the available data on properties of hot sources created in the mid-central to central collisions. Thus, we believe that the description of the entrance channel does not bring uncertainties influencing the conclusions of the present study and that the experimental data provide information about the details of the de-excitation stage, allowing to distinguish between different scenarios based on quantitative observables, such as the yields of heavy residues.

In order to illustrate in detail the difference in the de-excitation scenarios of sequential binary decay and statistical multifragmentation, we carried out simplified calculations. In agreement with the results of backtracing procedure, the hot nucleus $^{144}$Nd with excitation energy 310 MeV flying along the beam direction with velocity $\beta=0.17$ was de-excited by both GEMINI and SMM. The spin of the hot nucleus was chosen $J=30$, in accord with backtracing procedure. The resulting angle versus mass contour plots are presented in Fig. 13 in a fashion analogous to Fig. 5. The behavior observed in Fig. 5 is essentially reproduced. Again, the SMM leads to larger yields of residues with $A<90$ at angles corresponding to the MARS acceptance. The effect of MARS angular acceptance is demonstrated in Fig. 14 where the velocity versus mass contour plots are shown for the simulated residues with $\theta=1-3$ deg acceptance. Again the results for the heavy residues corresponding to the forward kinematic solution (upper arm in Fig. 14) are analogous to the results of full simulations as shown in Figs. 6,7. The heavy residues corresponding to the backward kinematic solution (lower arm) were not detected in the experiment and thus are rejected by the full MARS filtering procedure for the current experiment. As suggested above, the selection caused by the angular acceptance of MARS indeed seems to be the most crucial criterion of the filtering procedure for the heavy residues investigated in the present work. In Fig. 15 both unfiltered yields and yields filtered by the MARS angular acceptance (upper and lower panels, respectively) for GEMINI and SMM simulations are shown. As one can see, the unfiltered yield of heavy residues with $A<90$ is
higher in the SMM simulation and this is essentially preserved after filtering by MARS angular acceptance. The essential difference between the results of SMM and GEMINI in the simplified calculation appears to be in the production rate of heavy residues with $A<90$, in good agreement with the conclusions set in the discussion of Fig. 8. Using a backtracing procedure of this simplified SMM simulation it was determined that the most probable hot fragment partition contributing to the filtered yield is essentially a ternary configuration resembling the ternary fission with two heavier fragments accompanied by a lighter third particle. The same conclusion applies to backtracing of the full simulation. In general, the simplified and full simulations lead essentially to the same results, which is even more convincing when taking into account that the source characteristics have been chosen using backtracing of SMM simulation but nevertheless the result is equivalent also for the simulations using GEMINI. Based on the simplified simulation, we assure that the reason for different production rates derives from the difference of physical scenarios used by the de-excitation codes.

In the particular case of the GEMINI code it is of importance to establish to what extent an adjustment of the parameter set could be justified in order to improve the agreement of the simulation with experiment. As already illustrated in the discussion of Fig. 8, the parameter essentially determining the decay rate of channels with heavy residues with $A<90$ is the fission barrier height. The comparison with the recent high-quality experimental data on asymmetric fission barriers [41] suggests that the finite range fission barriers used in the GEMINI code are in reasonable agreement with experiment. The asymmetry dependence of the experimental barriers is reproduced well, while the experimental values are typically higher by 1-2 MeV. Thus, there is no physical justification for an enhancement of the decay rate by lowering the fission barriers. In a similar fashion, the choice of the level density parameter of Lestone [32] is in agreement with the systematics of effective level density parameters obtained using the experimental data on particle emission spectra [32,42]. The value of the level density parameter in the saddle point configuration is typically larger (by 3-4%) than in the particle evaporation channels, due to the temperature dependence of the level density parameter of Lestone. Such a calculation is essentially equivalent to the calculation with temperature independent level density parameter and $a_f/a_n$ ratio according to models taking into account the surface area increase in the saddle configuration [43].

However, several experimental works [44] suggest that a value of $a_f/a_n=1$ is good approximation at excitation energies in the saddle configuration above 40 MeV, mostly based on statistical model analysis of evaporation residue cross sections and pre-fission neutron multiplicity. In any case, the further increase of $a_f/a_n$ ratio does not appear to be justified. Thus, the parameter set used can be considered appropriate as demonstrated in other works [10,40] where heavy residues originating from peripheral collisions have been investigated. In these deep-inelastic collisions, the details of de-excitation are overshadowed
by the broad excitation energy, angle and velocity distributions.

The insight into the difference between the sequential binary and simultaneous decay can be obtained using the conclusions of the paper of Lopez and Randrup [45], where a statistical model of sequential binary decay is compared to a more general statistical model where a transitional state formalism is extended to the multifragment partition with any number of fragments. The authors observe that the transitional state model of multifragmentation leads also to a more general expression for the decay rate of binary channels leading to additional enhancement at high temperatures due to additional available degrees of freedom when compared to the binary decay formula used in the GEMINI code. In a similar fashion we can conclude that the decay rate of channels with higher fragment multiplicities will be enhanced in the more general model of Lopez and Randrup when compared to the corresponding de-excitation chain with binary splits, due to still higher number of available degrees of freedom. When considering, as suggested by the authors, that the transitional state model of multifragmentation presented in [45] is an alternative formulation to the models of nuclear disassembly such as statistical multifragmentation model [31], on which the SMM code is based, we can attribute the success of the SMM simulation in describing the experimental yields to the proper treatment of the available degrees of freedom in de-excitation of hot sources with the highest excitation energies created in the most violent collisions.

From the comparison of the measured yields with the results of simulations, one can conclude that the heavy residues with $A<90$ observed in the experiment are produced in violent collisions at low impact parameters, where a single hot source is created by incomplete fusion which further de-excites via simultaneous multifragmentation. The production of such residues cannot be explained either by peripheral collisions or by fission and sequential decay of the hot source. The DIT+ICF/SMM simulation is shown to be a realistic model framework for the description of asymmetric nucleus-nucleus collisions at projectile energies around the Fermi energy, offering a quantitative description of the experimental data.

4 Summary and conclusions

In the present work, the cross sections and velocity distributions of heavy residues from the reaction of 20 AMeV $^{124}$Sn on $^{27}$Al have been measured at forward angles using the MARS recoil separator at Texas A&M. A consistent overall description of the measured cross sections and velocity distributions was achieved using a model calculation employing the concept of deep-inelastic transfer for the primary stage of the peripheral collisions, pre-equilibrium emission and incomplete fusion for the primary stage of the more violent central
collisions and the statistical model of multifragmentation for the deexcitation stage. An alternative calculation employing the model of the sequential binary decay could not reproduce the observed yields of the residues from violent collisions (A<90) since the angular distribution of the generated residues does not extend far enough toward zero angle. The success of the statistical multifragmentation model can be attributed to a better treatment of decay rates and kinematic properties of de-excitation channels, leading to heavy residues with A<90, at excitation energies around the multifragmentation threshold, within the scenario where various multifragment partitions compete according to their statistical decay widths. The decay widths for sequential binary decay exhibit restrictions inherent to the physical picture of the asymmetric binary fission. As demonstrated in the present work, a high resolution measurement using a kinematic separator is a sensitive method allowing to investigate the details of de-excitation of hot nuclei created in violent collisions.

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Fig. 1. Isotopic yields (contour plot) for the reaction 20 AMeV $^{124}$Sn + $^{27}$Al as a function of mass and atomic number. Successive contours correspond to a decrease of the yield by a factor of 10. The corridor of stable isotopes is given by a thick dashed line.
Fig. 2. Velocity distributions of residues with selected atomic numbers measured in the reaction 20 AMeV $^{124}$Sn + $^{27}$Al in the laboratory system. The vertical dotted line represents the beam velocity.
Fig. 3. Fragment distributions for the reaction 20 AMeV $^{124}$Sn + $^{27}$Al. (a) - isobaric yield distribution. The data are shown as solid circles. The dashed line is the result of DIT+ICF/GEMINI (see text). The full line is the result of the same calculation as the dashed line, but imposing a cut corresponding to the angular and momentum acceptance of the spectrometer. (b) - yield distributions as a function of Z (relative to the line of $\beta$ stability, $Z_\beta$) and A. Highest yield contours are plotted with thicker lines. Successive contours correspond to a decrease of the yield by a factor of 2. The calculated values from DIT+ICF/GEMINI are shown as i) thick dashed line: without acceptance cut and, ii) thick full line: with acceptance cut. (c) - velocity vs. mass distributions. Data are shown as contours as in (b). The thick lines are as in (b). The horizontal full line represents the beam velocity and the horizontal dashed line represents the velocity of compound nucleus in the case of complete fusion.
Fig. 4. Fragment distributions for the reaction 20 AMeV $^{124}$Sn + $^{27}$Al as in Fig. 3, except that the calculations are DIT+ICF/SMM. Open circles in (a) show estimated total cross sections (see text).
Fig. 5. Calculated angular distributions in the laboratory system for the reaction 20 AMeV $^{124}$Sn + $^{27}$Al as a function of residue mass for GEMINI (a) and SMM (b). Successive contours correspond to a decrease of the yield by a factor of 2. The two horizontal lines mark the angular acceptance of the MARS separator used in the present work.
Fig. 6. Calculated velocity distributions for the reaction 20 AMeV $^{124}$Sn + $^{27}$Al as a function of mass obtained using the DIT+ICF/GEMINI simulation. Unfiltered yields are presented in panel (a), while the filtered yields are given in panel (b). Successive contours correspond to a decrease of the yield by a factor of 2. The horizontal lines mark the beam velocity.
Fig. 7. Calculated velocity distributions for the reaction 20 AMeV $^{124}$Sn + $^{27}$Al as a function of mass obtained using the DIT+ICF/SMM simulation. Unfiltered yields are presented in panel (a), while the filtered yields are given in panel (b). Successive contours correspond to a decrease of the yield by a factor of 2. The horizontal lines mark the beam velocity.
Fig. 8. Normalized unfiltered residue mass distributions for the reaction 20 AMeV $^{124}$Sn + $^{27}$Al at various impact parameters obtained using (a) DIT+ICF/GEMINI, and (b) DIT+ICF/SMM simulations.
Fig. 9. Average excitation energy (a) and angular momentum (b) of the heavy source as a function of impact parameter obtained for the reaction 20 AMeV $^{124}$Sn + $^{27}$Al using the DIT+ICF model.
Fig. 10. Calculated excitation energy vs mass distribution of the heavy source at various impact parameters obtained for the reaction 20 AMeV $^{124}$Sn + $^{27}$Al using the DIT+ICF simulation. Successive contours correspond to a decrease of the yield by a factor of 2.
Fig. 11. Mass, charge, excitation energy distributions of hot heavy sources contributing to the filtered yield of residues with $A=65-75$ and the distribution of contributing impact parameters, as determined by backtracing the DIT+ICF/SMM simulation.
Fig. 12. The observed ( symbols ) and filtered ( solid histograms ) velocity and N/Z-distributions of residues with A=65-75 along with the velocity and N/Z-distributions of contributing hot heavy sources ( dashed histograms ), as determined by backtracing the DIT+ICF/SMM simulation. The observed distributions are normalized to the filtered distributions.
Fig. 13. Angle vs mass contour plots of heavy residues originating from decay of the hot nucleus $^{144}$Nd with excitation energy 310 MeV flying along the beam direction with velocity $\beta = 0.17$ de-excited by GEMINI (upper panel) and SMM (lower panel). Successive contours correspond to a decrease of the yield by a factor of 2. The two horizontal lines mark the angular acceptance of the MARS separator.
Fig. 14. Velocity vs mass contour plots for the simulated residues with $\theta=1.3$ deg originating from decay of the hot nucleus $^{144}$Nd with excitation energy 310 MeV flying along the beam direction with velocity $\beta=0.17$ de-excited by GEMINI (upper panel) and SMM (lower panel). Successive contours correspond to a decrease of the yield by a factor of 2.
Fig. 15. Unfiltered yields and yields filtered by MARS angular acceptance (upper and lower panels respectively) of heavy residues originating from the decay of the hot nucleus $^{144}$Nd with excitation energy 310 MeV flying along the beam direction with velocity $\beta=0.17$ de-excited by GEMINI (dashed line) and SMM (solid line).