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Dissipative Binary Mechanisms in Central ^{24}Mg + ^{12}C Collisions at 25A and 35A MeV *

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Abstract

A study of the most violent collisions in the ^{24}Mg+^{12}C reactions at 25A and 35A MeV has been carried out. Experimental data, for those events in which the total charge of the system has been detected, are compared to simulations based on statistical fragmentation codes. For violent events, a binary mechanism appears to be competing successfully with compound nucleus formation.

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In the investigation of multifragmentation [1–4] of hot nuclear matter produced by heavy ion collisions at intermediate energies (*i.e.* between 10 and 100 MeV/nucleon), central or violent collisions have been the subject of many studies [5–7], along with complementary topics, such as fusion and incomplete fusion [8–11]. The most violent collisions typically result in a large number of fragments and, until recently, only a fraction of those fragments could be detected and analyzed in any single event. The availability of innovative multi-detector arrays covering large solid angle [12–15] makes possible the detection of all charged particles (CP) produced in a reaction [16]. The present paper reports an analysis of the most central collisions for a light system of 36 nucleons. Since a determination of the source properties for these events is essential, detection of the entire system is a prerequisite for a proper event-shape analysis. Our analysis is limited to collisions in which the total charge of the system (projectile+target) has been detected in an array of charged-particle counters. We compare the anisotropy and velocity distributions of the data with those predicted by two excitation scenarios representing opposite, limiting cases, namely complete fusion and dissipative binary collisions. A general trend, favouring a competition between compound nucleus formation and a dissipative binary mechanism is observed for violent channels.

The experiment was performed at the TASCC facility of Chalk River Laboratories, with beams of ^{24}Mg at $25A$ and $35A$ MeV incident on a 2.4 mg/cm^2 C target. The inverse-kinematics experiment focussed reaction products into the 80-detector CRL-Laval Array. The array is comprised of three rings of 16 plastic phoswich detectors each, covering angles from 6^o to 24^o (for particles of Z=1 to 12) and two rings of 16 CsI(Tl) scintillators each, covering angles from 24^o to 46^o (for particles of Z=1 and 2). Each phoswich detector consists of a thick, slow-plastic E-detector and a 0.7 mm ΔE layer of fast plastic scintillator, heat-pressed to the front of the E detector [17]. Energy calibration data were obtained from elastically scattered ^{24}Mg ions and secondary beams of Z=1 through 11 scattered on ^{197}Au targets located at various positions along the beam trajectory. The phoswich detectors were calibrated according to the relation given in Ref. [18] and the CsI(Tl) detectors by the energy-light relation from Ref. [19]. The intrinsic resolution of the detectors was better than

5% and the precision of the energy-light relation was close to 5% for both types of detectors. The energy threshold varied from 7.5 to 19.6 MeV/nucleon for Z=1 to Z=12 for the phoswich detectors and was approximately 2 MeV/nucleon for Z=1 and Z=2 in the CsI(Tl) detectors. Isotopic identification for charge Z=1 was possible in the CsI(Tl) detectors in the 25A MeV experiment. For the other particles the mass given was that of the most abundant isotope.

Successive beam pulses from the cyclotron were separated by more than 25 ns; to minimize accidental coincidences, only particles arriving within one cyclotron period were included in an event. Events with two particles striking the same detector were largely eliminated by means of restrictive gates on the charge identification spectra for all the detectors and by a special gate on the α-particle double hit band, which was counted as two α-particles with identical energies, coming from the ground-state dissociation of ^{8}Be. The reconstructed velocity of the center of mass (CM) for the complete events provides a good test of whether pileup has been successfully excluded. Fig. 1 shows such a reconstruction for events with total detected charge ΣZ=18 and ΣZ=12, at 25A and 35A MeV, along with the calculated CM and beam velocity for both energies. Velocity reconstruction for detected events with ΣZ=12 demonstrates the bias that incomplete events would make on the analysis. As indicated by the vertical lines in the figure, complete events lying in the tails toward lower or higher velocities were excluded from the analysis. For exit channels with less ambiguity in the isotopic identification of the reaction products, further improvements in the reconstructed CM velocity may be achieved, as seen in Fig 8. of Ref. [19]. This fact is exploited in our analysis of the 9-He exit channel.

The experimental events in which the total system charge was detected (ΣZ=18) had charged-particle multiplicities between 5 and 12, and represented a wide variety of exit channels. Of the obseved events,63% combined one intermediate-mass fragment (IMF) of element number 3 to 11 with hydrogen and helium ions, 28% had two or three IMFs plus light ions, and the remaining 9% were completely disassembled into light ions.

A mid-rapidity charge parameter (Z_{mr}) [20] was used to evaluate the centrality of the events. The parameter represents an event-by-event sum of charges for particles with rapidity greater than 75% of target rapidity and less than 75% of projectile rapidity, with rapidity defined as

$$Y = \frac{1}{2} ln \frac{E_k + cP_{par}}{E_k - cP_{par}}, \quad (1)$$

where E_k is the kinetic energy of the particle in the CM in MeV and P_{par} its momentum parallel to the beam axis in the CM in MeV/c. At 25A MeV, 76% of the events had Z_{mr} greater than 15 and at 35A MeV the corresponding fraction was 62% , indicating the violent nature of the majority of the (ΣZ=18) events.

Possible reaction mechanisms for these violent events include dissipative binary collisions, which have been observed recently in heavier systems [21,22], as well as complete and incomplete fusion.

Incomplete fusion reactions are largely eliminated from our analysis by the ΣZ=18 requirement. It has been shown [8,23] that in incomplete fusion reactions viewed in reverse kinematics, the pre-equilibrum emission of target-like spectators is not forward-peaked in the laboratory frame. Since the probability is very low that all pre-equilibrium, target-like charged particles are emitted forward of 46^o and above detector threshold, we would not detect incomplete fusion reactions as complete events. Similarly, pre-equilibrum emission of projectile-like spectators, though rare in reverse kinematics reactions, would be very forward-peaked, and mostly lost in the beam-exit port of the array.

The events with complete charge detection were compared to simulations generated with the statistical code, GEMINI [24] and filtered by the detector acceptance. Two extreme excitation scenarios were considered: complete fusion in which the projectile and the target form a thermalized compound nucleus, and binary dissipative collisions in which a two-source system is produced, composed of a quasi-projectile and a quasi-target with different kinematic and energetic characteristics.

The angular momentum input to the GEMINI code was determined from a comparison between experimental data and simulations made for different values of angular momentum. For the complete fusion scenario, we examined the reaction-plane correlation spin observable

[25], which gives the angle between each particle velocity and the reaction plane normal (deduced from the trajectory of the heaviest fragment), for Ar* with angular momentum values of 0,8,17 or 25 $\hbar$. The spin observable showed that the best agreement with the data was obtained for the calculated maximum angular momentum that can be sustained by the nucleus (25 $\hbar$ for argon), as determined from the prescription of Ref. [26]. For the dissipative binary collision scenario, the value of angular momentum was taken as proportional to the excitation energy of the nucleus, without exceeding the maximum sustainable angular momenta (16 and 8 $\hbar$ for ^{24}Mg and ^{12}C, respectively).

The simulated disintegrations produced with GEMINI were transfomed into the laboratory frame and the complete events were then passed through the experimental filter reproducing the geometry and energy thresholds of the multi-detector array. The filtering also took into account isotopic variations and the position uncertainty due to the large solid angle of each detector. Only the filtered events with ΣZ=18 were retained for the comparison. The CP multiplicities of the filtered events in both excitation scenarios were consistent with, but slightly higher than, the experimental data.

The elongation of an event in momentum space is an important observable for distinguishing binary and fusion-like reaction mechanisms. Quantiatively, a global variable can be constructed from a comparison of the longitudinal and transverse momentum components of the event's constituent particles [27]. This anisotropy ratio, R , is defined as

$$R = \frac{2}{\pi} \frac{\sum_{i=1}^{M} |P_{iCM\perp}|}{\sum_{i=1}^{M} |P_{iCM\parallel}|} \tag{2}$$

where $\frac{2}{\pi}$ is a geometric normalisation constant, M is the CP multiplicity, and $P_{iCM\parallel}$, $P_{iCM\perp}$ are momenta of the i^{th} particle in the CM frame, perpendicular and parallel to the beam axis. Fig. 2 shows the anisotropy distribution as a function of charged-particle multiplicity for experimental events with ΣZ=15,16 or 17, and both experimental and simulated events with ΣZ=18 for both energies. The effect of the experimental acceptance on the anisotropy ratio distributions may be deduced from the horizontal lines representing the R distributions for primary or "unfiltered" simulations, averaged over all multiplicities. Isotropic events should have an R distribution centered at 1.0 for $M \rightarrow \infty$, but for the low multiplicities typical of these reactions, intrinsic fluctuations produce slightly different values of R [28] for nearly isotropic events, such as those expected from the complete fusion simulations. It is also important to note that the R distributions are not symmetric about their centroids and that the widths of the distributions vary. Consequently. the experimental acceptance may highlight the difference between two distributions having similar "unfiltered" centroids, as is the case in the $25A$ MeV simulations.

Simulated complete fusion events were obtained from the disintegration of an argon compound nucleus, recoiling at center-of-mass velocity, with the excitation energy set to the maximum available in the CM reference frame, *i.e.* 200 MeV for events from the $25A$ MeV reaction and 280 MeV for the $35A$ MeV reaction. In the simulation of dissipative binary collisions, the excitation energy and scattering angle of both the quasi-projectile and the quasi-target were provided by the semi-classical coupled-channels (nucleon exchange) code, TORINO [29]. The code requires the input of an impact parameter, from which it deduces the subsequent course of the reaction. For systems as light and energetic as ours, this should not necessarily be taken as the geometric trajectory of the entrance channel, but rather as a relative scale for the violence of the interaction. The impact parameter that best reproduces the anisotropy ratios at $25A$ MeV is 5.1 fm, which gives excitations of 95 and 81 MeV and velocities of 74% and 57% of the projectile velocity for the projectile-like and target-like sources, respectively. At $35A$ MeV, the best agreement is obtained with 4.1 fm, giving the corresponding excitation energies of 145 and 98 MeV, and velocities of 76% and 51% of the projectile velocity. The input impact parameter and the value of the simulated anisotropy ratio are closely related, an increase of 10% in the value of b at 35A MeV corresponding to a decrease of more than 20% in the average simulated R value.

At both energies, the anisotropies, measured as a function of multiplicity, are found to be similar for the incompletely detected (ΣZ=15, 16, or 17) and completely detected (ΣZ=18) events. Evidence for contributions from more peripheral collisions is seen at low multiplicity, where the anisotropy ratios fall significantly below 1.0. For the complete events, at both energies, the anisotropy ratios lie close to the values predicted by the dissipative binary simulation at all multiplicities. Of particular interest is the dependence of R upon beam energy. Clearly, at 35A MeV, the anisotropy values deviate more from the fusion predictions than at 25A MeV. This suggests that, as beam energy increases, the two sources become increasingly separated in velocity space. GEMINI simulations of complete fusion events with no angular momentum show no major shift in the anisotropy ratios.

The ΣZ=18, 9-He exit channel of this reaction was studied in somewhat greater detail, permitting an analysis with less isotopic ambiguity. We were able to treat this as a 9-α channel, since it has been shown for ^{24}Mg-induced reactions in this energy range [30] that 92% or more of Z=2 ions are indeed ^{4}He. A similar competition between fusion and binary mechanisms was observed. Here the simulations were done with the sequential part of the statistical code SOS [31], modified by its author to produce only n-α exit channels, thus reducing considerably the computing time necessary to produce a statistically significant number of 9-α events. The initial conditions for the complete fusion simulation were the same as those for the GEMINI calculations, but with no angular momentum consideration. As before, TORINO was used to produce the conditions for the binary simulations, with a small range of impact parameters, rather than a single value, for each energy. In order to get the best possible fit to the experimental data, impact parameters from 5.0 to 6.0 fm and from 4.0 to 5.0 fm were selected for the 25A MeV and 35A MeV reactions, respectively. Fig. 3 shows the ratio between the average velocity of the 6 fastest alpha-particles and the average velocity of the 3 slowest alpha-particles. This choice of variable is based on the products expected from the decay of a ^{24}Mg* quasi-projectile and a ^{12}C* quasi-target. Both simulated distributions resemble the data at 25A MeV, though the data may be somewhat closer to the dissipative binary collision case. At 35A MeV, the binary character of the 9-α channel is evident.

In conclusion, the reconstructed CM velocity distributions have demonstrated both the validity of the energy calibration and the value of total charge detection in the correct determination of source properties. We have compared the anisotropies (Fig. 2) and source-velocity ratios (Fig. 3) observed experimentally for complete (ΣZ=18) events with the results of simulations filtered by detector response. The comparisons indicate that as the energy of the collision increases, binary mechanisms may compete successfully with simple compound nucleus formation.

The fact that the binary simulations, which assume two very different sources in size, velocity and excitation energy, give a better fit to part of the data may be explained by various reaction mechanisms. One possibility is that for some of these violent events, the system retains a definite binary nature throughout the reaction. Another is that, at an early stage of deexcitation, an unequilibrated composite system produces two distinct sources, dynamically related to the projectile and the target. The difficulty of distinguishing between such possibilities offers a challenge to the capabilities of currently available theoretical calculations. To properly assess the phenomena, detailed data, such as those presented here, should be compared with a model that treats the dynamics of source formation as well as pre-equilibrium emission and the subsequent statistical decay.

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FIGURES

FIG. 1. Reconstructed center-of-mass velocity for exit channels with ΣZ=12 and ΣZ=18 from the ^{24}Mg+^{12}C reaction at 25A MeV (top) and 35A MeV (bottom). The arrows indicate beam velocity and CM velocity for the complete system of target plus projectile. Vertical lines show the ΣZ=18 events selected for further analysis.

FIG. 2. Centroids of the anisotropy ratios, R as defined in eq. (2), versus multiplicity for incompletely detected events (ΣZ=15,16,17) at 25A MeV (top left) and 35A MeV (bottom left). Completely detected experimental events (ΣZ=18) and the corresponding filtered simulations are shown for 25A MeV (top right) and 35A MeV (bottom right). Filled circles represent experimental data, open squares complete fusion simulations with GEMINI, and open triangles dissipative-binary collision simulations with TORINO and GEMINI. Error bars are the root-mean square divided by the square-root of the number of counts of the anisotropy distribution for a given multiplicity. Distributions with less than 25 counts were rejected. The horizontal lines represent R centroids, averaged over all multiplicities, for unfiltered simulations with the same codes, for complete fusion (full lines) and dissipative binary collisions (dashed lines).

FIG. 3. Ratio between the average parallel velocity of the six fastest alpha-particles and the average parallel velocity of the three slowest alpha-particles in the ^{24}Mg+^{12}C $\rightarrow$ 9 He channel at 25A MeV (top) and 35A MeV (bottom). Experimental events are shown as filled circles. The full line represents filtered complete fusion events simulated with SOS and the dotted line indicates the filtered TORINO-SOS simulation of dissipative binary collisions. Error bars show the square root of the number of counts.

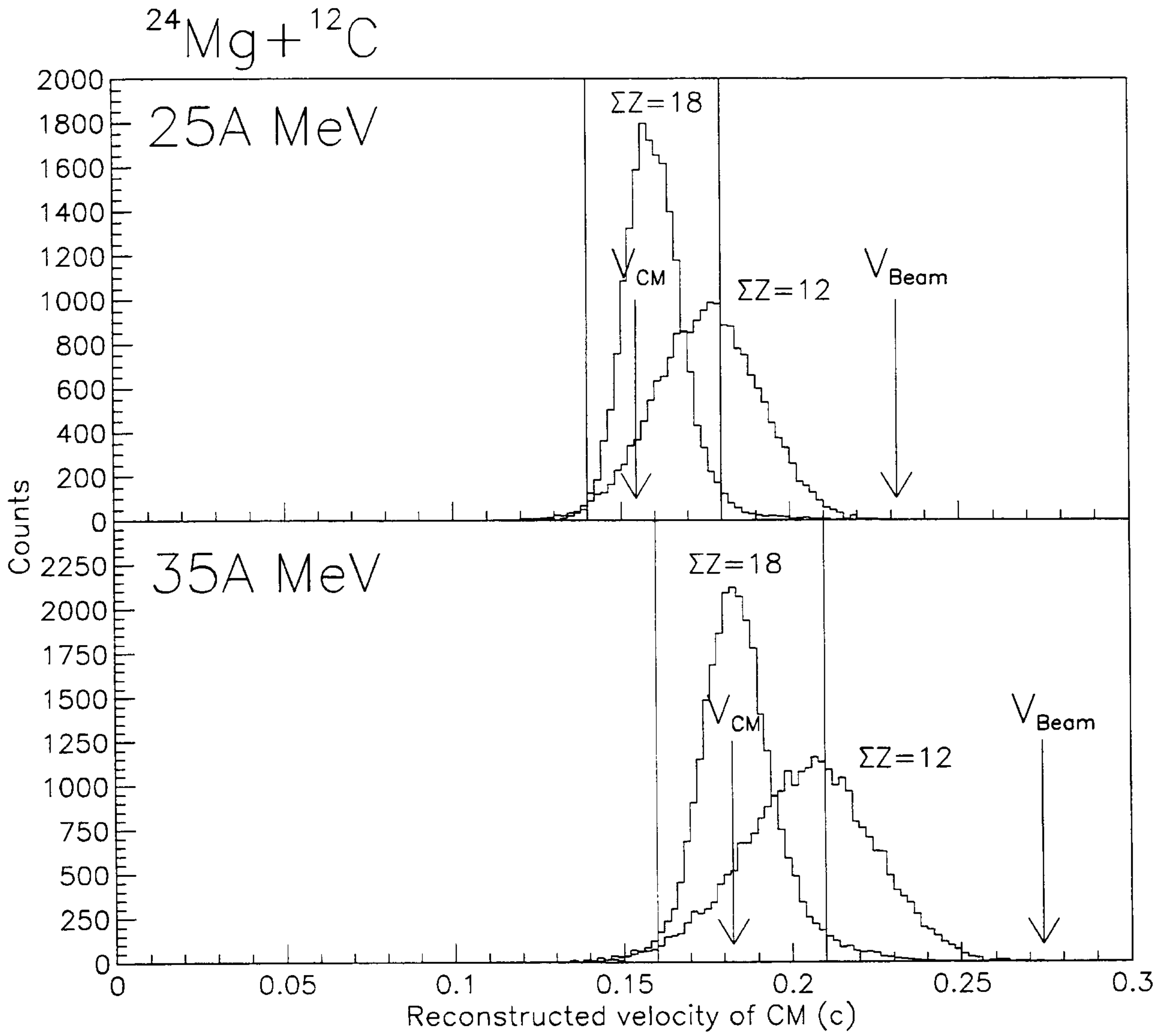

FIG. 1. Y.Larochelle et al.

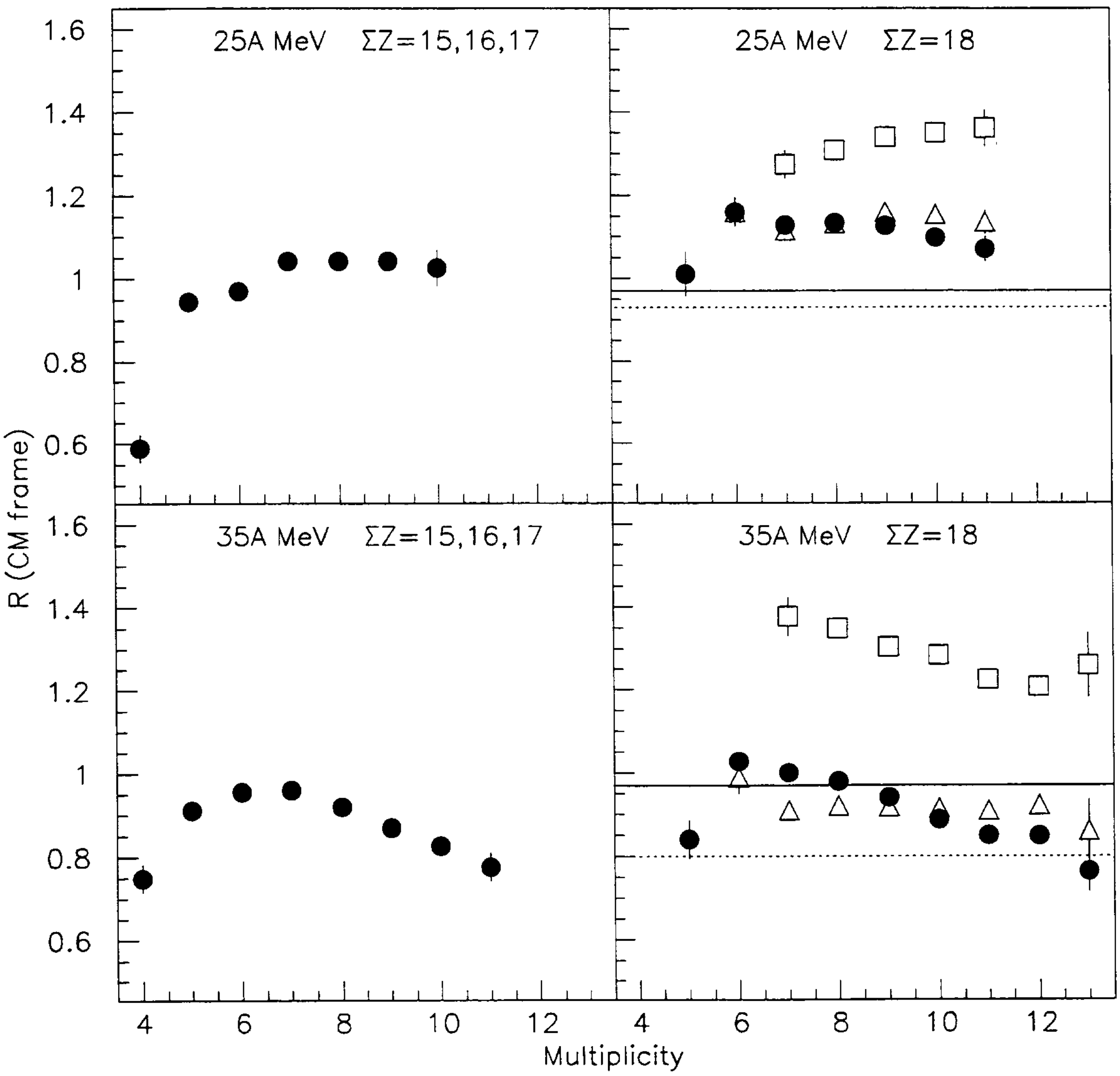

FIG. 2. Y.Larochelle et al.

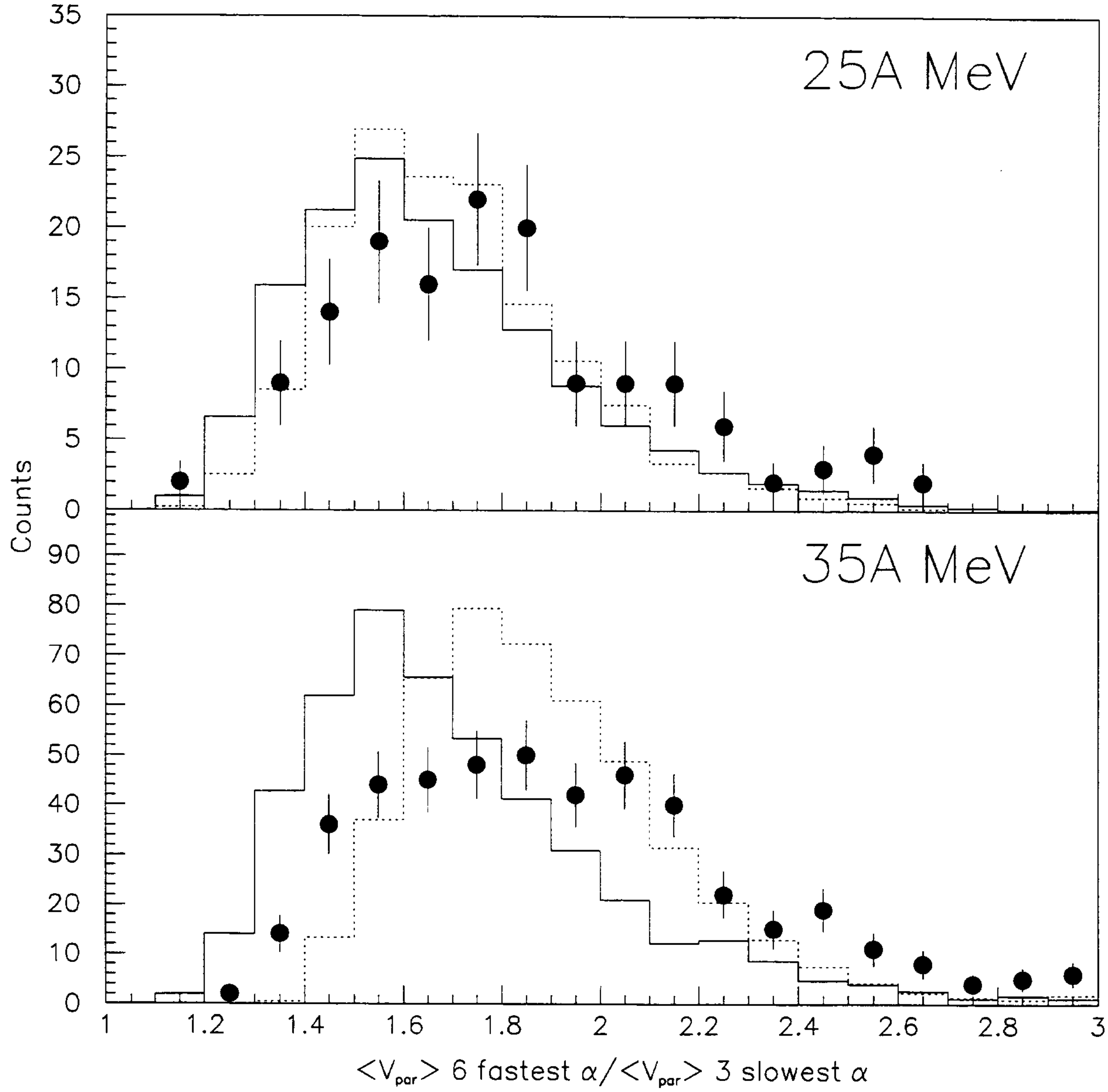

FIG. 3. Y.Larochelle et al.