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Characterization of Hot Compound Nuclei From Binary Decay Into Complex Fragments

by

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Abstract:

The emission of complex particles at intermediate energies has been characterized through the reverse kinematics reactions 25 and 30 MeV/u ^{93}Nb + ^{9}Be,^{27}Al. Complex particles are shown to be emitted in binary decays from very hot incomplete-fusion intermediates with momentum transfer consistent with the Viola momentum-transfer systematics. The process of complex particle emission provides a method, applicable throughout the periodic table, for studying compound nuclei with temperatures and excitation energies near the expected limit of their existence.

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One of the foremost questions in the intermediate energy regime of heavy ion reactions concerns the maximum excitation energy a fusion-like product can hold, and the modes of decay of this hot object.[1] In heavy systems, which subsequently undergo fission, very large energy depositions have been inferred from linear momentum transfer data.[2-4] Similarly, in lighter systems, a component of the resulting distribution of reaction products has been interpreted as arising from the ordinary evaporation of a very hot compound nucleus.[5-6] Unfortunately, the technique involving the measurement of the folding angle between fission fragments is applicable only in a narrow mass region, while measurements on evaporation residues leads to ambiguities in determining the mean momentum transfer. Such difficulties are nicely avoided by utilizing the recently characterized compound nucleus emission of complex particles[7,8] combined with a reverse kinematics reaction,[9,10] which permits both a verification of compound nucleus decay, and the determination of the momentum transfer.

Several theories have been advanced for the production of intermediate mass fragments in reactions at bombarding energies of 10 to 100 MeV/u. The most familiar are those based upon the Fisher model of droplet condensation out of a vapor[11,12], and those based upon the cold fragmentation of a nucleus.[13] Despite the theoretical appeal of these hypotheses, there are recent experimental indications[10] that the compound nucleus plays a dominant role in the production of these particles. In a series of low energy experiments[7-9], where complex fragment emission was studied as a function of mass and excitation energy(50-140 MeV), it was concluded that in the energy range explored, these processes could be unequivocally and completely characterized as due to compound nucleus decay. If these intermediate mass fragments do indeed arise from compound nuclus emission even at intermediate energies, they are ideally suited to investigate compound nucleus decay over the broadest range of masses and excitation energies.

In this paper we show that the same compound nucleus mechanism of complex particle production operating at low bombarding energies prevails also in this higher energy regime. More specifically, we have obtained conclusive evidence that the reactions of 25 and 30 MeV/u ^{93}Nb + ^{9}Be,^{27}Al give rise to a thermalized intermediate formed with a very large momentum transfer and energy deposition as high as 400 MeV, which then undergoes a compound nucleus binary decay producing fragments of intermediate mass and charge. Although the term compound nucleus is usually employed for complete fusion reactions, we will use the same term to also refer to the equilibrated product produced in an incomplete fusion reaction.

The experiments have been carried out at the BEVALAC of Lawrence Berkeley Laboratory. Beams of 10^7 particles/pulse of ^{93}Nb with energies of 25 and 30 MeV/u impinged on targets of ^{9}Be (2.3 gm/cm^2) or ^{27}Al (3.0 mg/cm^2). Two large acceptance angle ΔE(gas), E(Si) telescopes were placed on either side of the beam at angles of 5.5^0 and -11^0, respectively. These telescopes were position sensitive in two dimensions and covered an angular aperture of 5^0 and 7^0, respectively. The fragment atomic number could be identified over the entire range of reaction products.

The singles invariant cross sections plotted in the velocity- Z plane[14] are shown in Fig. 1 for the two targets and the two bombarding energies. For all systems, the charge distributions consist of three components: a) a prominent hill, beginning near the projectile Z value(41) and extending toward smaller atomic numbers; b) two distinct ridges at intermediate atomic numbers whose separation in velocity increases with decreasing atomic number; and c) a low velocity hill near the target Z-value.

The first and strongest component consists of a large number of events near the projectile Z value and is visible only at small angles in the most forward telescope. This component is consistent with the tail end of the evaporation residue distribution from a highly excited compound nucleus. A simulation based upon the evaporation code PACE[15] has been used to verify that evaporation residues should extend somewhat beyond the inner edge of our forwardmost telescope.

The third component which is visible at small Z values and low velocities is apparently related to the target. It may be possible to explain this component in terms of a transfer of a few nucleons from the projectile to the target followed by evaporation. These products should be slow moving because of the low momentum transfer. This process may be the counterpart of the dominant process where the projectile abrades and fuses with a good portion of the target.

The second component, on which this paper concentrates, consists of fragments of intermediate Z value, which present two well separated velocity components of nearly equal intensity. The presence of two velocity components is practically by itself spectacular evidence for the binary decay of a compound nucleus system. In fact the splitting into two components arises from forward and backward emission of fragments with Coulomb-like energies in the center of mass.

From the average velocity of the two components, one can derive the mean source velocity for each reaction system. These are indicated by the arrows labeled 2 in Fig. 1. For comparision, the recoil velocity for complete fusion (v_{cf}) and the beam velocity are indicated by the arrows labeled 1 and 3, respectively. For each reaction, the mean source velocity is somewhat larger than v_{cf}, thus indicating that the complex fragments are emitted following an incomplete fusion reaction, where a large fraction of the target nucleus fuses with the Nb projectile. Incomplete fusion reactions have been extensively investigated. Fig. 2 shows the ratio of the mean recoil velocity relative to v_{cf}, obtained from data in Refs. 16-19. After transforming from reverse to normal kinematics, our data indicated by the solid points are in good agreement with the above systematics. The momentum transfer and the resulting mass transfer, energy deposition and temperature are presented in Table 1.

From the above data, it appears that a very large transfer of mass and energy leads to the formation of an object that relaxes into a hot compound nucleus. Such a fast moving compound nucleus in turn emits fragments in binary decay with Coulomb-like energies, thus leading to the appearance of the double velocity solution for intermediate Z values. The velocities of the two components can be evaluated theoretically by assuming that the fragments possess Coulomb energies and by correcting the final charge of the observed fragment for sequential decay. The dashed lines shown in Fig. 1 for all reactions correspond to calculations for the extreme acceptance angles of the telescopes and are in good agreement with the data (the corrections to the final fragment Z value were made assuming first chance decay, energy partition proportional to A and using the evaporation code PACE[15]). The widths of the two velocity components increase with the excitation energy. At 25 MeV/u with ^{9}Be target, the width is almost completely explained by the telescope acceptance angle. At higher energies the widths increase either due to recoil effects associated with sequential evaporation or to the width of momentum transfer or to both.

The binary nature of the intermediate mass fragment production process is confirmed by the coincidence data shown in Fig. 3 for the four reaction systems. The correlation of the Z_1-Z_2 data is emphasized by the calculated bands (PACE) where binary events should fall after sequential evaporation. The concentration of our data on one side of the band is trivially related to the asymmetric location of our detectors with respect to the beam. The lack of events in the region to the left of the band in the case of the ^{9}Be target is an indication that the partition into 3 or more comparable fragments is not an important process in this energy regime. The few events appearing to the left of the band in the case of the ^{27}Al target, especially at 30 MeV/u, may be higher multiplicity events and are clearly related to the higher excitation energy of this system. These events may possibly indicate the onset of multiple fragment decay.

The consistency of the binary decay picture is further emphasized in Fig. 4, where the sum $\langle Z_1 + Z_2 \rangle$ is presented as a function of Z_2. The dashed lines are estimates of the mean compound nucleus charge extracted from the linear momentum transfer. The measured total charge is smaller due to light particle evaporation from the excited primary products and/or the initial system. For the ^{9}Be target, the average charge loss is 2-4 Z-units, while for the ^{27}Al target, it is 13-15 Z-units, reflecting the differing amounts of excitation energy with which the compound nuclei are formed. In the same figure, calculations(solid lines) from the evaporation code PACE[15] are presented. The excitation energies employed(see Table 1) were those deduced from the measured momentum transfer, partitioned proportionally to the fragment charge. The agreement with the data is quite good and supports the general picture.

The results from our measurement imply the formation of a compound nucleus in an incomplete fusion process with momentum transfer consistent with the Viola systematics[20] and an excitation energy corresponding to the associated mass transfer. The excitation energies range from 150 to 400 MeV (up to 4 MeV/nucleon) with corresponding temperatures of 4.0 and 6.4 MeV, respectively. Throughout this range of excitation energies, complex particle emission occurs consistently and abundantly as an important decay process, easily identifiable because of its binary nature and very useful for the determination of momentum and energy transfer. It appears that despite temperatures comparable with the nuclear binding energy and energies per nucleon approaching the same, the system still manages to fuse, relax and decay as a compound nucleus. Thus it appears that multifragmentation does not yet play a major role for these systems at these bombarding energies.

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Table 1. The momentum transfer, mass transfer, excitation energy and temperature for the reactions studied.

$E(^{93}Nb)$ (MeV/u)	Target	$\langle p/p_{beam}\rangle$	$\langle M_{trans}\rangle$ (u)	$\langle E^*\rangle$ (MeV)	$T^{\dagger}$ (MeV)
25.4	^{9}Be	.72 ± .1	6.5 ± 1	148 ± 20	4.0
30.3	^{9}Be	.79 ± .1	7.1 ± 1	194 ± 23	4.6
25.4	^{27}Al	.77 ± .1	20.8 ± 3	392 ± 45	6.2
30.3	^{27}Al	.64 ± .1	17.2 ± 3	407 ± 59	6.4

$^{\dagger}a = A/11$

Figure Captions

Fig. 1 Singles distribution of reaction products plotted as logarithmic contours of invariant cross section($(1/V^2)(\partial^2\sigma/\partial\Omega\partial V)$) in the Z-velocity plane for the 5.5° telescope. The arrows indicate the velocities for 1) full momentum transfer 2) the experimentally determined momentum transfer and 3) the beam. Calculated(dashed lines) average velocities of complex fragments for the maximum and minimum angles of the telescope (3° and 8°) are indicated.

Fig. 2 Systematics of the mean recoil velocity for incomplete fusion reactions relative to that for complete fusion are plotted against the relative velocity of the target and projectile nuclei at the interaction barrier. The hollow points were derived from Refs. 16-19.

Fig. 3 Scatter plots of coincidence events between the 5.5° telescope(Z_1) and the -11° telescope(Z_2). The shaded areas represent an estimation of regions where binary events should lie following sequential evaporation from the primary fragments.

Fig.4 The mean sum, $\langle Z_1 + Z_2 \rangle$ of coincidence events(solid symbols) plotted as a function of Z_2. The dashed lines indicate the average charge of the compound system as estimated from the mass transfer. The charge loss for binary events, due to sequential evaporation, was estimated using the PACE[15] code and the residual $Z_1 + Z_2$ values are indicated by the solid curves.

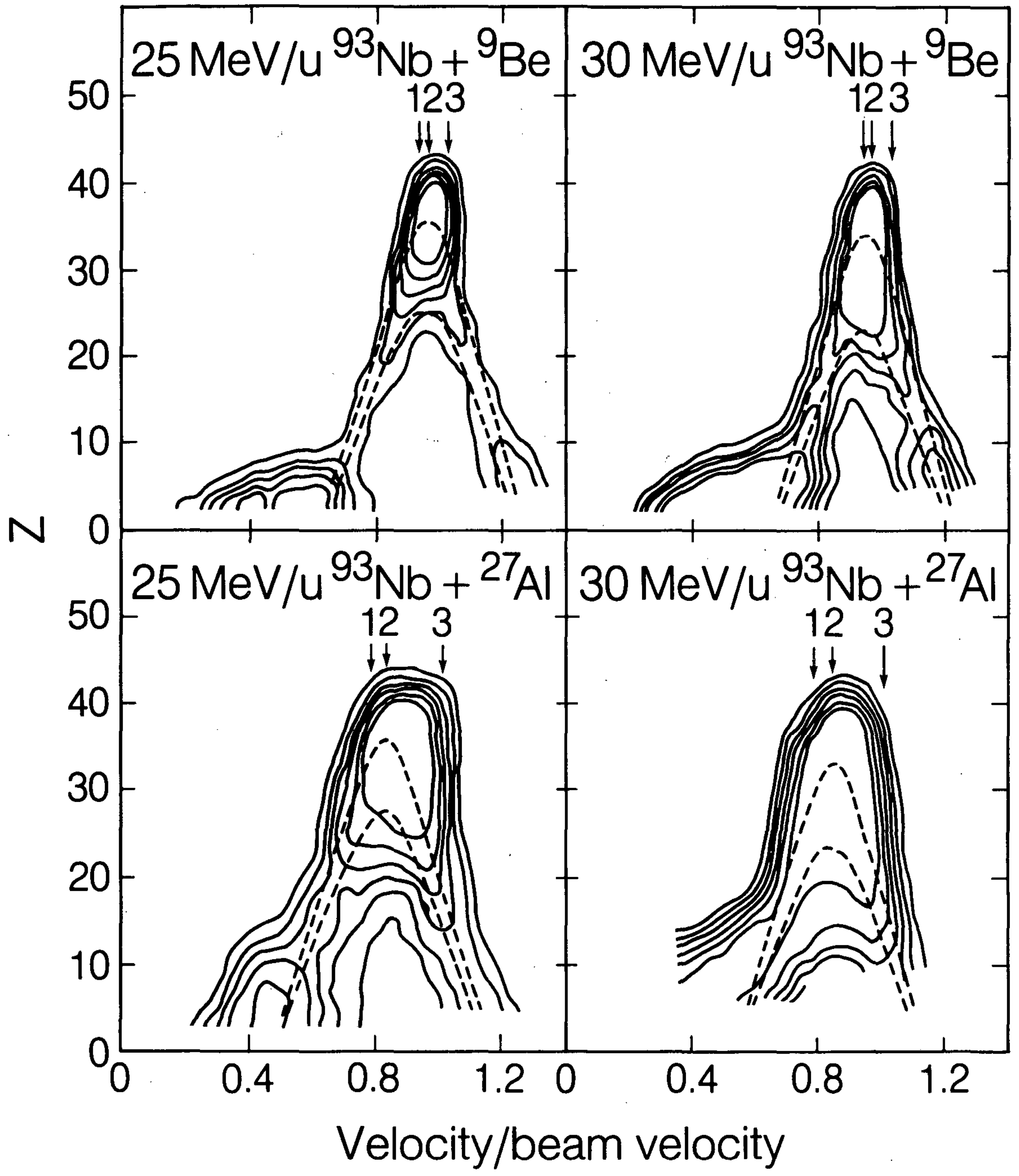

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Fig. 1

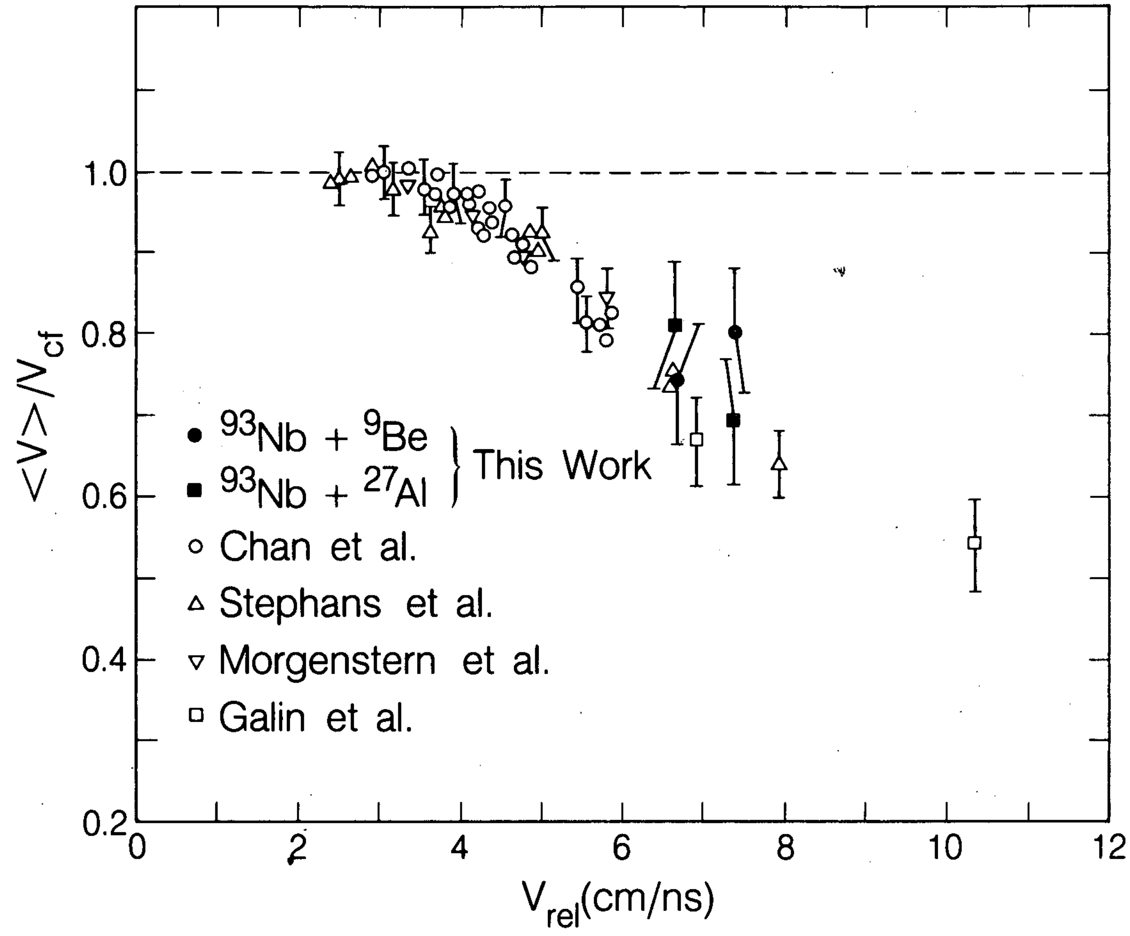

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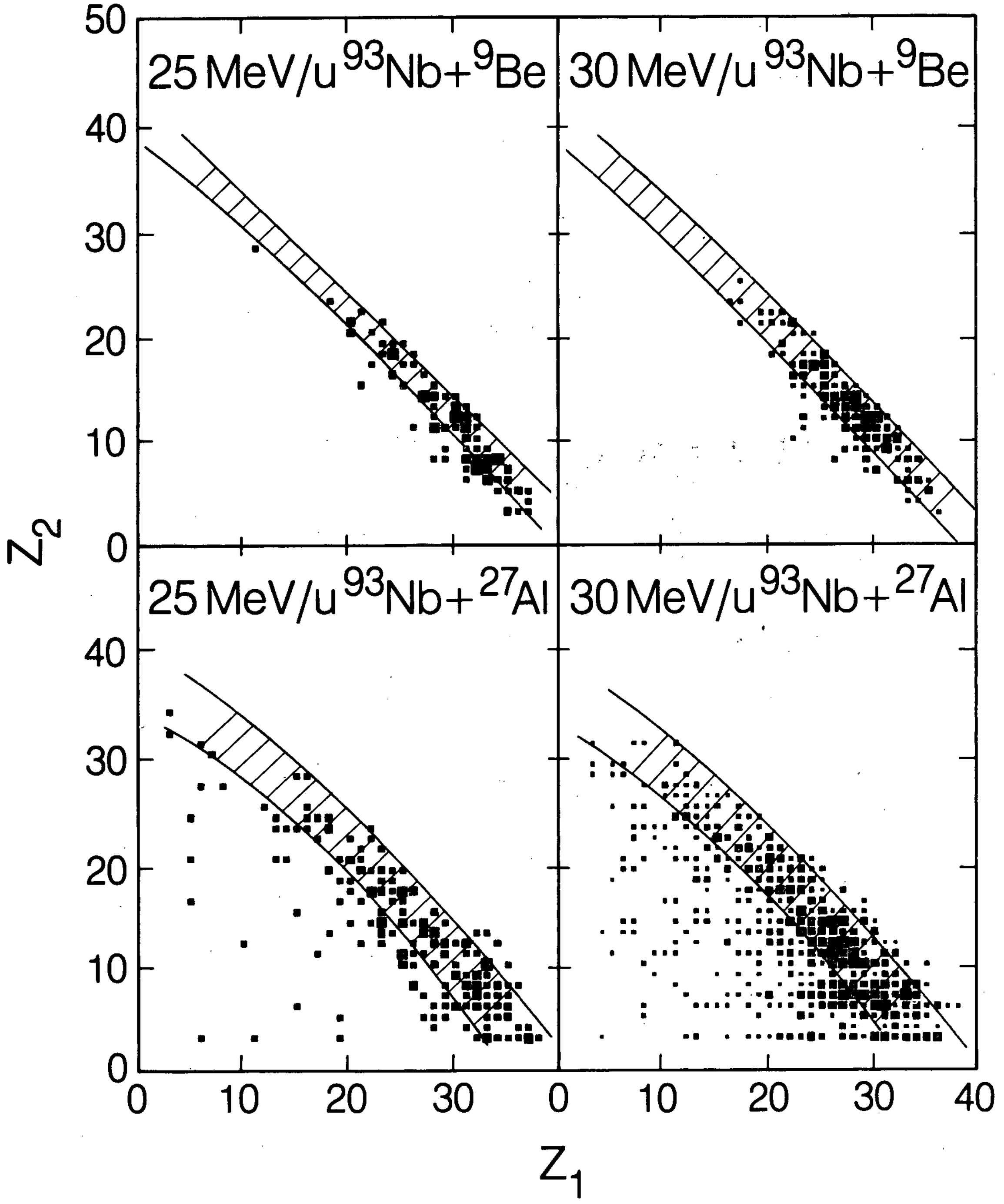
Fig. 2



XBL 859-8976

Fig. 3

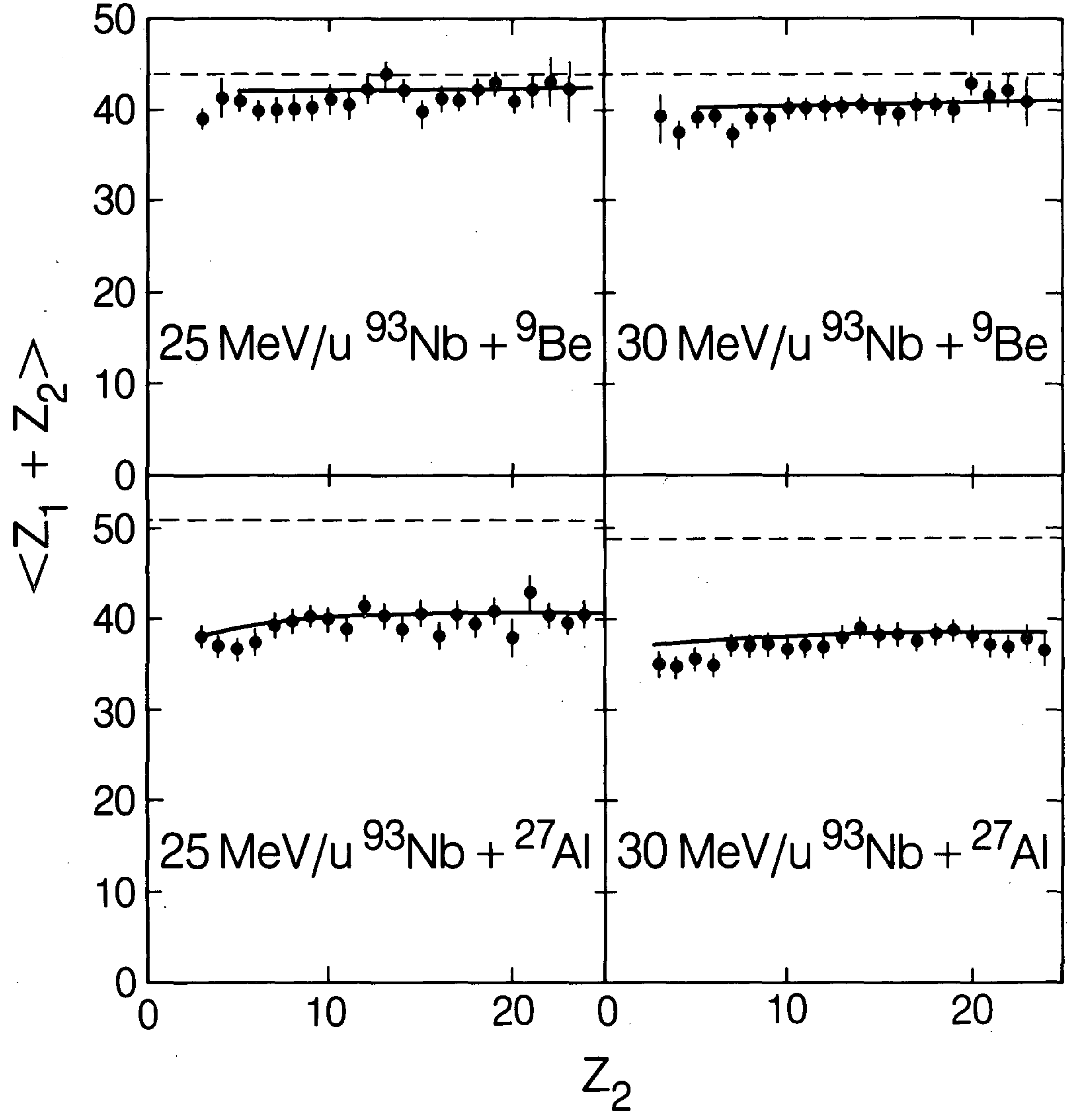


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Fig. 4

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