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Author
Harvey, B.G.

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B.G. Harvey

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Bernard G. Harvey

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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FRAGMENT YIELDS AND MOMENTA IN NUCLEUS-NUCLEUS COLLISIONS FROM 20 MeV/nucleon to 200 GeV/nucleon.

Bernard G. Harvey

Nuclear Science Division, Lawrence Berkeley Laboratory,

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ABSTRACT

New measurements of beam-velocity fragment yields at projectile energies of 50 and 70 MeV/nucleon show that the yields of fragments with Z>1 are remarkably independent of beam energy from 20 MeV/nucleon to 200 GeV/nucleon. The yields of $^{2}H+^{3}H$ increase by a factor of only 1.7 between 50 and 2000 MeV/nucleon. Statistical decay of primary fragments accounts reasonably well for the measured fragment and coincidence channel cross sections, and for the fragment momentum distributions at energies from 70 MeV/nucleon to 200 GeV/nucleon.

I. INTRODUCTION.

The strong similarity of cross sections for the fragmentation of ^{16}O at 20 MeV/nucleon and 1 and 2 GeV/nucleon has long been known (1,2). There is an equally great similarity between fragmentation cross sections for ^{40}Ar at 44 and 213 MeV/nucleon (3). Cross sections for ^{12}C fragmentation at 85 MeV/nucleon differ from those at 2 GeV/nucleon by an average of only 3.3% [4]. The fragmentation of ^{16}O at 2 and 200 GeV/nucleon in nuclear emulsion has been compared[5]. The relative yields of six different coincidence channels and widths of the perpendicular momentum distributions of He fragments from the break-up of the ^{16}O into 1,2,3 or 4 He nuclei were shown to be independent of the projectile energy.

In experiments with ^{12}C and ^{16}O beams at relativistic energies on a wide range of targets, it was found [6] that cross sections for the production of beam-velocity deuterons (d) were remarkably high - almost as large as for the production of the much more stable ^{4}He. Thus, for ^{16}O + C (2 GeV/nucleon), the d and ^{4}He cross sections are 406 mb and 474 mb respectively. In the lower energy experiments, though, the yields of fragments with $Z<3$ were not measured. Thus the possibility was left open that the high d yields at 1-2 GeV/nucleon might result in some way from pion production.

In new experiments with ^{16}O + Au at 50 and 70 MeV/nucleon [7], relative yields for formation of fragments with Z = 1 to Z = 5 were measured. Table 1 compares the charge yields for ^{16}O+Pb or Au relative to the yield of Z=3 isotopes at energies from 20-2000 MeV/nucleon. Although protons were measured at 50 and 70 MeV/nucleon, the Z=1 yields at all energies are for d+^{3}H (t). Only the (d+t) yield shows any significant variation with energy, increasing slowly from 50 to 2000 MeV/nucleon. It does not show the abrupt rise between 70 and 2000 MeV/nucleon that would be expected if high (d+t) yields were due to the onset of pion production.

In fact, pion production at 2 GeV/nucleon produces only about 0.1 mb of ^{12}N and ^{12}B from ^{12}C + C [6]. Measurements of all coincidence channels from the fragmentation of ^{12}C + C (2 GeV/nucleon)[8,9] show that only about 5.9% of the fragment yields come from channels whose charge sum is greater than 6, and presumably a similar amount from channels whose neutron number sum is greater than 6. Even though the inelastic nucleon-nucleon (NN) cross sections are somewhat greater than one half of the total NN cross section, pion production seems to play an insignificant role in fragment production. Even at 200 GeV/nucleon, where the inelastic NN cross section is about 80% of the total, the relative yields and the momentum distributions of He fragments are the same as at 2 GeV/nucleon [5].

These results are not surprising if pions always (or nearly always) escape capture in the projectile. Using the known inelastic cross sections at 2 GeV and the fraction of the inelastic collisions that produce charged pions shows that about 5.3% of all collisions (elastic + inelastic) should produce primary projectile fragments with Z = 7 and the same number with N = 7, if all charged pions escape capture in the projectile. If some of them are absorbed, the amount of charge exchange will be reduced. The similarity of this estimate to the experimental value (5.9%) strongly suggests that pions are rarely absorbed in small projectile nuclei such as ^{12}C. In the Monte Carlo NN collision calculations described below, pion production was therefore ignored.

II. CALCULATIONS.

Fragment production is assumed to proceed in two separate steps. Primary projectile fragments are formed as a result of NN collisions: they may or may not be excited. These fragments then undergo statistical decay to produce the final unexcited fragments that are observed experimentally.

A. Formation of primary fragments

The Monte Carlo NN collision calculations have already been described [8]. The projectile and target nuclei were assumed to have Fermi density distributions[9] for neutrons and protons (not necessarily the same). The two nuclei were allowed to collide at impact parameters from 0 to a value large enough that no further NN collisions occured. The coordinates of all nucleons were chosen at random to reflect, on the average, the density distributions. When two nucleons passed each other within a distance corresponding to the free NN total cross section, they were assumed to collide. All nucleons (target and projectile) were allowed to make no more than one collision (the "wounded nucleon" model)[10]. Since a large part of the cross section comes from peripheral collisions, where the densities of the two nuclei are low, the probability of multiple collisions was in any case very small.

In the projectile rest frame, the struck projectile nucleon was assumed to be scattered at 90° and in a random direction around the z-axis (the direction of the target nucleon in the projectile frame). Although a scattered projectile nucleon was not allowed to be struck again by a target nucleon, it was allowed to interact with other projectile nucleons. The probability that this happened was calculated by assuming a mean free path of 3 fm.

If the nucleon escaped, it was assumed that the projectile remnant was not excited unless the nucleon came from an inner shell. The probability that this was so was obtained by the use of harmonic oscillator wave functions to calculate the relative densities of nucleons in the several shells at the radius from which the nucleon was initially scattered. For ^{12}C and ^{16}O projectiles, only the removal of nucleons from the s-shell was counted as an excitation. It was assumed that an s-shell hole was not filled by an Auger transition during the time scale of the initial nucleus-nucleus collision and the subsequent decay of the primary fragment.

In fact, this last assumption made surprisingly little difference to the final fragment yields. An Auger transition would cause the loss of an extra nucleon from the primary fragment, but it would at the same time reduce the excitation energy. That in turn would reduce the number of evaporated nucleons in the decay phase of the reaction. Hüfner et al. also found that the inclusion of Auger transitions made little difference[11].

If the nucleon failed to escape without a further NN collision in the projectile, it was assumed to be either recaptured or to induce secondary reactions such as (n,p),(n,pn) and so on. The relative probabilities for these various kinds of events were taken from reference 11, and it was assumed that in each case (reabsorption or secondary reaction) the projectile fragment would be excited. When a secondary reaction occured, the probability that it formed an inner shell hole was calculated. The calculations were repeated at each of 150 equal steps in impact parameter out to a value where the nuclear densities were sufficiently low that no further NN collisions occured.

The NN collision calculation gave the cross section for the formation of each primary fragment, the total reaction cross section, and the distribution in number of excitations of each kind and of the total number of excitations for each fragment. Fig. 1 shows the distribution of the total number of excitations for ^{11}C, ^{8}Be and ^{6}Li fragments from ^{12}C + C at 2 GeV/nucleon. As expected, the excitation increases with the number of lost nucleons and falls off nearly exponentially at large excitations. No attempt was made to calculate the absolute excitation energy distribution.

B. Decay of primary fragments

The excitation energy spectrum of each primary fragment (Z,A) was obtained from the distribution of the total number of excitations. Each of the three types of excitation (nucleon recapture, secondary reaction and inner shell hole) should have a different energy spectrum, but its calculation, especially for the reactions, is difficult. Therefore, an average value per excitation for the combined total excitation number distribution was chosen by comparing the results of the calculations with experiment. Best agreement with inclusive fragment and coincidence channel cross sections was obtained with 20 MeV/excitation at 70 MeV/nucleon and 30 MeV/excitation at 1-200 GeV/nucleon These values seem reasonable. In light nuclei, the excitation energy of an s-shell hole is about 20 MeV. The average kinetic energy of a scattered projectile nucleon in the projectile frame is about 70 MeV for a beam of 2 GeV/nucleon [11]. The excitation from a secondary reaction must be less than that.

Assuming an excitation energy of 30 MeV/excitation, the

<u>average</u> excitation energy was about 38 MeV for primary fragments with mass equal to A_{proj} or $(A_{proj}-1)$. For a mass of $(A_{proj}-8)$, it rose to about 250 MeV. For even lighter masses, the excitation was sufficiently high that decay into protons and neutrons was almost complete.

The excited nucleus was allowed to decay by the emission of any fragment with charge and neutron number up to one half of the initial value. The probability of decay into a given channel was calculated from the transition state formalism [12-14] from which the probability P(i) of decay into the i th channel is

$$P(i) = T(E^*/U)^2 \exp\left[2(aU)^{1/2}-2(aE^*)^{1/2}\right] \qquad (1)$$

The temperature T was obtained from the excitation energy E^*:-

$$T = (E^*/a)^{1/2} \qquad (2)$$

where the liquid drop parameter a was equal to A/8. The free energy U at the point of scission was

$$U = E^* + Q - V_c \qquad (3)$$

where V_c is the Coulomb barrier. If U was equal to or less than zero, P(i) was set to zero.

When the temperature of the decaying nucleus was below 1 MeV, the Q-values for each decay channel were calculated from the ground state (gs) masses. Above that temperature, the ground state masses were progressively replaced by liquid drop (ld) masses obtained by fitting experimental mass values from 3 to 60 with a liquid drop mass equation, but leaving out the values for magic nuclei such as ^{4}He, ^{12}C, ^{16}O and so on. Following ref.14, the Q-value then became

$$Q = X.Q_{gs} + (1-X).Q_{ld} \qquad (4)$$

where

$$X = \exp(-T/5) \qquad (5)$$

The relative decay probabilities P(i) (eq. 1) turn out to be not very different from exp(Q/T). The yields of fragments and of coincidence channels have often been shown to depend approximately on the Q-value in this simple way. However, there are often wide excursions. Although the probability of forming a fragment may well depend mainly on Q, its survival as an observable fragment depends also on the Q-value for its further decay. An extreme example is the alpha-decay of excited ^{12}C. The ^{8}Be is formed with high probability, but since it has a positive Q-value for decay to two alpha particles, it never survives.

At each stage of the decay sequence, the relative kinetic energy E_k of the two decay fragments was calculated from a Maxwellian distribution:

$$P(E_k) = E_k \exp(-E_k/T) \qquad (6)$$

with the requirements that E_k be greater than the Coulomb barrier V_c and lower than the available residual excitation energy $E^* + Q_{gs}$. The residual thermal excitation energy was therefore

$$E^{*}_{(res)} = E^{*}_{(init)} + Q_{gs} - E_{K} \tag{7}$$

This excitation energy was divided between the two fragments, on the average, in proportion to their masses. However, the excitation of the lighter of the two fragments was given a Gaussian distribution about the mean value with a full width at half maximum of one half of the mean value. The results of this energy split are discussed in Sect. IIIA below. If one of the fragments was a nucleon, its excitation energy was given to the other.

The momenta of the final fragments in the projectile frame were assumed to come from three sources: 1) the momentum of recaptured projectile nucleons in the cascade step of the reaction, 2) recoil from the Fermi momentum of a projectile nucleon knocked out, and 3) from the decay stage. The Fermi momentum was taken as 270 MeV/c per lost nucleon, and was assumed to be isotropic in the projectile frame. The decay momentum too was assumed to be isotropic in the frame of the decaying nucleus. The momentum of a final fragment in the projectile frame was the vector sum of all these contributions.

In fact, most of the final momentum of light fragments came from the decay step. The contributions from recapture and the Fermi momentum were made to a nucleus with a mass close to that of the initial projectile. Thus the momentum given to ^{4}He from a ^{16}O projectile was only one quarter of the initial amount. The decay of ^{8}Be formed from ^{12}C by the loss of four nucleons in NN collisions gave widths (σp_z) of 125, 143 and 177 MeV/c for fragments of mass

2, 3 and 4 from all three sources of momentum. From decay alone, the values were 112, 131 and 165 MeV/c.

The decay calculations gave the following results: 1) the inclusive cross sections for final fragments, 2) the cross sections for any chosen sets of coincident fragments, and 3) the momentum distributions parallel and perpendicular to the beam direction in the projectile frame. It should be emphasized that the cross sections were absolute and were not renormalized in any way.

III. COMPARISON WITH EXPERIMENT

A. Inclusive fragment cross sections

Figs. 2 and 3 show a comparison of the calculated and experimental[6] cross sections of final fragments from ^{12}C and ^{16}O projectiles, both at 2 GeV/nucleon on C targets. All primary fragments with masses down to $(A_{proj}-7)$ were allowed to decay. Lighter mass primary fragments were so excited that they contributed almost nothing to the formation of bound final nuclei. The cross sections from fragment decays were added to those of unexcited nuclei produced in the NN collision step. These latter were mainly for nuclei with $(A_{proj}-1)$ and $(A_{proj}-2)$.

The method of dividing the residual excitation energy between the two partners of a decay, described in Sect. IIB, results in an increase of about 20% in the calculated yield of deuterons as well as of intermediate mass fragments such as ^{6}Li and ^{7}Be, but it has almost no effect upon coincidence channel yields or fragment momenta. The lighter of the two decay partners is very often ^{4}He. When it receives more than its average share of the residual excitation energy, it is more likely to decay again to ^{3}He, ^{3}H or into two deuterons. These decays require a rather large excitation, about 20 MeV. The heavier of the two fragments, in this case, receives less than its average share of the energy. If it decays to intermediate mass fragments, they are therefore more likely to survive further decay.

Even so, the calculated cross sections for ^{4}He are about 40% too high and for deuterons they are only one half of the experimental values. The decay calculation does not contain detailed information about the level densities of the various nuclei. It is therefore unaware that the first excited state of ^{4}He lies especially high, at 20.1 MeV. The decay probability to produce ^{4}He at an excitation below its decay threshold (also 20 MeV) is therefore unaffected by the particularly low level density in that region. Figs. 2 and 3 show that if the excess of the calculated over experimental ^{4}He cross section had been produced at an excitation energy above 20.1 MeV, and had then decayed further to d+d, ^{3}He+n or t+p, it would have increased the deuteron yield enough to put it into reasonably good agreement with the experimental value.

Fig. 4 shows the calculated yields of d, t, ^{3,4}He and ^{6}Li from the decay of 500 ^{7}Be nuclei as a function of the excitation energy. At low excitations, there is substantial production of ^{6}Li and ^{4}He, but beyond about 12 MeV per nucleon, the yield of deuterons exceeds that of ^{4}He and becomes twice the yields of t, ^{3}He. The experimental cross sections for d, t, ^{3}He at 1-2 GeV/nucleon are in fact in this same proportion. At high enough excitations, ^{4}He that is initially formed is often excited enough to decay again into n+^{3}He, p+t or d+d with roughly equal relative probabilities. The large negative Q-values for these decays (about -20 MeV) cool the system so that the bound nuclei have a good chance of survival. Since two d's are formed, the d cross section becomes twice those of t, ^{3}He, as observed experimentally.

B. Coincidence channel cross sections

At 50 and 70 MeV/nucleon, the relative yields of eleven different coincidence channels were measured for ^{16}O + Au [7]. The fragment charges in the coincidences sum to 8, but there was no mass determination in the experiment. Fig. 5 shows a comparison between experimental (70 MeV/nucleon) and calculated yields relative to that of the channel C+He. The channels are shown in increasing order of (negative) Q-value. The calculation used an average excitation energy of 20 MeV/excitation.

While there is a general trend for the yield to decrease as Q becomes more negative, the effect of the stability of the channel components is clearly visible. Channels that contain two relatively unstable nuclei (B+Li, Li+Li+He and Li+Li+H+H) lie below their neighbors. This effect is reproduced in the calculations.

Fig. 6 compares the coincidence channel yields obtained in the reaction ^{12}C + C at 2 GeV/nucleon [9] with calculations. In this case, masses were measured in the experiment, so channels were chosen whose charges and masses sum to those of the projectile. Channels containing one or more protons were excluded since the experiment was unable to distinguish between protons emitted in the cascade step and those originating from decay. Again, the channels are presented in order of increasing negative Q-value. The calculated cross sections were not renormalized to the experimental values. The calculation is in good agreement with experiment.

If the energy per excitation is reduced from 30 MeV to 15 MeV, the cross sections of the coincidence channels (Fig. 6) beyond d^3He^7Li fall to zero. In fact, the cross sections for all coincidence channels containing d, t and ^3He drop considerably and agreement with experiment is much worse. This result confirms that the A = 2,3 nuclei are produced in large measure from the decay of ^4He, a process that requires large excitation energy.

Fig. 7 shows the relative yields of five different coincidence channels measured with 2 GeV/nucleon ^{16}O in nuclear emulsion[5]. The first four channels contain 1-4 He fragments in coincidence with no fragments with Z>2. The fifth channel gives the relative yield of channels that contain at least one fragment with charge >2. The calculation was made for ^{16}O on a target of ^{58}Ni as a rough approximation to the target nuclei in the emulsion. In fact, calculations with a C target were virtually identical with those from ^{58}Ni. Experimental and calculated relative coincidence channel yields for 200 GeV/nucleon ^{16}O are identical, within error bars, with those at 2 GeV/nucleon [5]. The coincidence channel containing only H isotopes[5] has been omitted from Fig. 7 since this channel should contain mainly cascade protons coming from nearly central collisions, which the experiment could not distinguish from decay protons.

The Q-values of the coincidence channels shown in Fig. 7 range from -14.4 MeV for the decay of ^{16}O into four alpha particles to -99.3 MeV for decay into one ^{4}He+nucleons. That about 20% of the yield goes into this latter channel shows that primary fragments with very high excitation energies are indeed formed in the first step of the reaction.

C. Fragment momentum distributions

Fig. 8 compares the experimental(5) and calculated widths of the perpendicular momentum distributions of He fragments from ^{16}O at 2 GeV/nucleon in nuclear emulsion. The calculation was made with a ^{58}Ni target. Within error bars, experimental results at 200 GeV/nucleon were found to be the same as at 2 GeV/nucleon (5).

In both the experiment and the calculation, the perpendicular momentum distributions were accurately Gaussian in shape. In both cases, the widths were obtained by a least squares fit to points between -350 MeV/c and +350 MeV/c.

For He multiplicities of 2,3 and 4, the momenta were measured and calculated for He in coincidence with any fragments. For multiplicity 1, three points are shown. The highest is for He in coincidence with H only, the middle point is for He in coincidence with anything, and the lowest point for He in coincidence with at least one fragment with charge greater than 2.

To produce 1 He+H requires a greater excitation energy than to produce 1 He+Z>2. The temperature of the decaying nucleus is therefore greater, and thus so are the kinetic energies and momenta of the decay fragments. Although the calculated widths for 1 He are 20% lower than the experimental values, they clearly show this same trend.

The momentum widths of He fragments measured in emulsion seem, in fact, to be too large. The width for inclusive ^{4}He fragments from ^{16}O break-up measured with a magnetic spectrometer [15] is only 131±1 MeV/c, substantially lower than all the emulsion values shown in Fig. 8 except for the 4 He point. The 4 He channel, though, is only a small contributor to the total He yield, as shown in Fig. 7. The calculated momentum width for ^{4}He fragments from ^{12}C+C (2.1 GeV/nucleon) is 129 MeV/c, in agreement with the experimental value, 129±1 MeV/c [15].

Extensive measurements have been made [15] of the width of the fragment momentum distributions in the projectile frame. The distributions were found to be Gaussian and consistent with isotropy. There was no significant correlation with target mass in the range from 1 to 208, nor was there any difference between the results at beam energies of 1.05 and 2.1 GeV/nucleon. Fig. 9 compares the experimental and calculated parallel momentum distribution widths of fragments from ^{12}C projectiles at 2.1 GeV/nucleon. The widths of the distributions have been divided by the fragment mass to provide a measure of the fragment velocities. These rise slowly as the mass decreases from 11 to 4, but much more rapidly for masses 3 and 2. These details are nicely reproduced by the calculation. They result from the conservation of momentum in a decay which requires a higher velocity for the lighter fragment of the pair.

The effect of primary fragment excitation energy is illustrated by comparing the momentum widths calculated for fragments from the decay of A=11-12 primary fragments with those from the more excited A=7 primaries. The widths are 109 and 142 MeV/c respectively for deuterons, 118 and 204 MeV/c for A=3 fragments, and 133 and 212 MeV/c for ^{4}He fragments. Thus, as expected, increasing the excitation and temperature of the primary fragment increases the decay kinetic energy and the momenta of the final fragments.

IV. CONCLUSIONS

The relative cross sections for the formation of beam-velocity fragments in nucleus-nucleus collisions change remarkably little over the enormous energy range from 20 MeV/nucleon to 200 GeV/nucleon. This experimental observation strongly suggests that a mechanism depending on the low energy properties of nuclei is responsible for fragment formation. In particular, pion production, even at the highest energies, seems to play an insignificant role.

A two-stage mechanism involving the formation of excited fragments as a result of NN collisions between projectile and target nucleons followed by statistical decay accounts reasonably well for the inclusive fragment and coincidence channel cross sections with the exception of the inclusive yields of ^{4}He and deuterons, which are respectively too high and too low.

It is likely that the solution of these problems will require a more detailed decay calculation that takes account of the specially low level density of ^{4}He at an excitation of less than 20 MeV. It is, though, also possible that extra deuterons are formed by the coalescence of beam-velocity nucleons, or that the nuclei decay before they have reached full thermal equilibrium. A zone at a higher than average temperature would tend to produce more A = 2,3 fragments, and favor the production of heavier fragments from the "cooler" part of the decaying nucleus.

If there is failure to attain full thermal equilibrium, it should become more apparent for large decaying nuclei, but unfortunately there are no experimental measurements of deuteron, triton and ^{3}He cross sections from medium weight projectiles.

Calculated fragment momenta parallel and perpendicular to the projectile direction are shown to originate mainly from the decay step of the reaction. Calculated widths of the momentum distributions are in quite good agreement with experiment.

V. ACKNOWLEDGEMENTS

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REFERENCES.

1. M. Buenerd et al., Phys. Rev. Lett. <u>37</u> 1191 (1976)
2. C. K. Gelbke et al., Physics Reports <u>42</u> No. 5 312 (1977)
3. B. G. Harvey, Nucl. Phys. <u>A444</u> 498 (1985)
4. H. Ryde, Physica Scripta, <u>75</u> 114 (1988)
5. M. I. Adamovich et al., (EMU-01 Collaboration), Phys. Rev. <u>C40</u> 66 (1989)
6. D. L. Olsen et al., Phys. Rev. <u>C28</u> 1602 (1983)
7. J. Pouliot et al., submitted to Phys. Lett. B, and J. Pouliot, private communication.
8. B. G. Harvey et al., Phys. Rev. <u>C39</u> 841 (1989)
9. H. J. Crawford et al., unpublished data.
10. A. J. Baltz, Phys. Rev. <u>C43</u> 1420 (1991)
11. J. Hüfner, K. Schäfer and B. Schürmann, Phys. Rev. <u>C12</u> 1888 (1975)
12. L. G. Moretto, Nucl. Phys. <u>A247</u> 211 (1975)
    L. G. Sobotka et al., Phys. Rev. Lett., <u>51</u> 2187 (1983)
13. W. J. Swiatecki, Lawrence Berkeley Lab. Report No. LBL-11403, 1983
14. F. Auger et al., Phys. Rev. <u>C35</u> 190 (1987)
15. D. E. Greiner et al., Phys. Rev. Lett., <u>35</u> 152 (1975)

TABLE I. Ratios of fragment charge yields relative to the yield of charge 3 for the reaction ^{16}O + Pb or Au. The Z=1 yields are for $^{2}H+^{3}H$ only. The 2 GeV/nucleon yields have been corrected for the contribution from Coulomb excitation[c].

	PROJECTILE ENERGY			
Z	20 MeV/ nucleon[a]	50 MeV/ nucleon[b]	70 MeV/ nucleon[b]	2 GeV/ nucleon[c]
1	-	5.06	7.64	8.53
2	-	9.49	9.26	9.37
(3	1	1	1	1)
4	0.64	0.69	0.59	0.54
5	1.11	0.65	0.48	0.77
6	2.36	-	-	1.82
7	2.25	-	-	1.60

a) ref.2, Pb target.

b) ref.7, Au target.

c) ref.6, Pb target.

FIGURE CAPTIONS.

Fig. 1. Calculated distributions of the total number of excitations in the formation of primary fragments of ^{11}C, ^{8}Be and ^{6}Li from the collision of ^{12}C + C at 2 GeV/nucleon.

Fig. 2. Comparison of the calculated (open squares) and experimental (closed squares) inclusive fragment cross sections for ^{12}C + C, 2 GeV/nucleon. Cross sections of H and He divided by 10.

Fig. 3. As Fig.2, for ^{16}O + C, 2 GeV/nucleon.

Fig. 4. Calculated yields of d, t, ^{3}He, ^{4}He and ^{6}Li from the decay of 500 nuclei of ^{7}Be, as a function of the initial excitation energy. The ^{6}Li yield is multiplied by 10.

Fig. 5. Comparison of calculated (open squares) and experimental (closed squares) coincidence channel yields relative to the channel C+He from the reaction ^{16}O+Au at 70 MeV/nucleon. Primary fragment excitation was 20 MeV/excitation. All primary fragments with Z=8 contributed to the calculated values in proportion to their production cross sections from NN collisions.

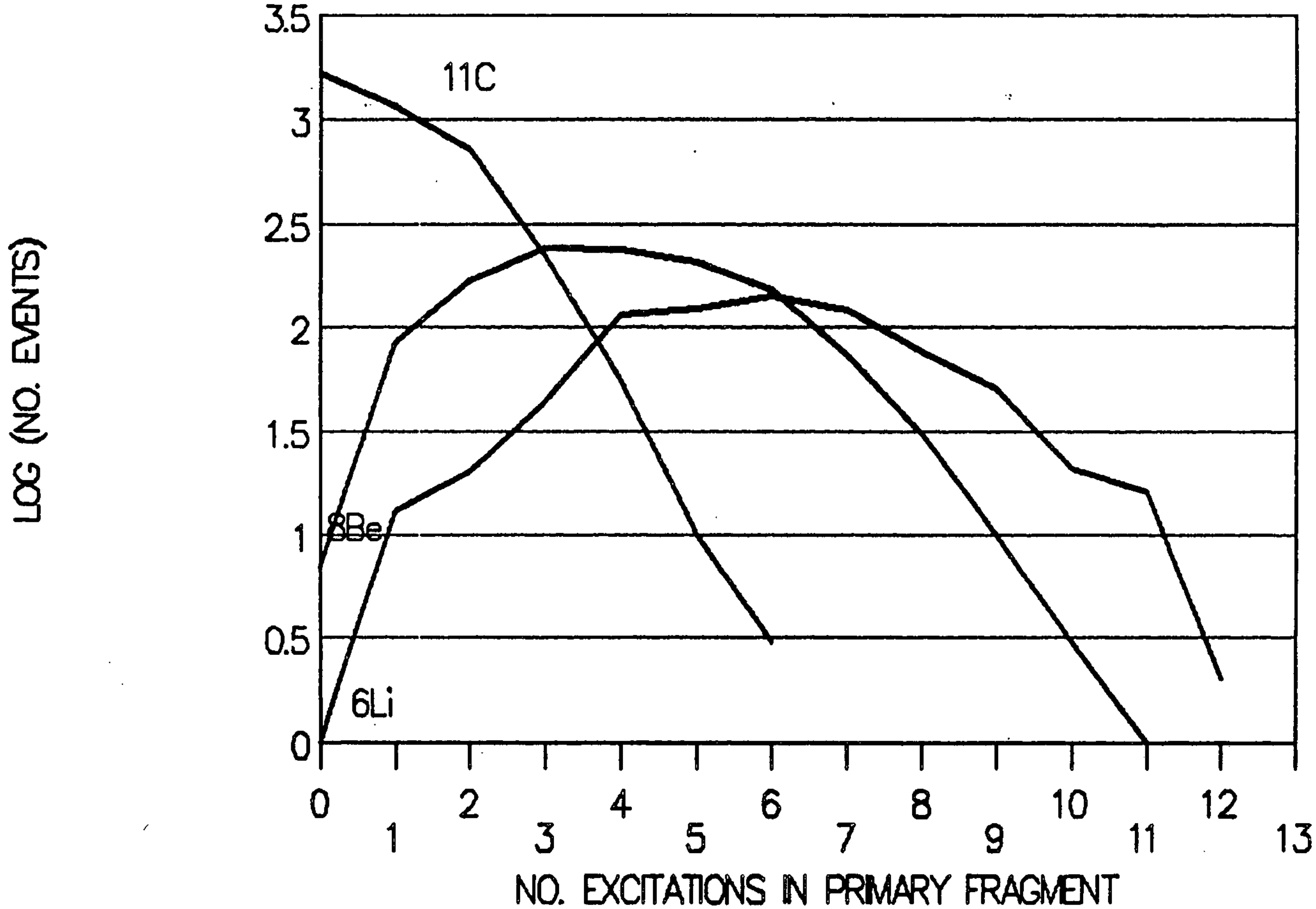
Fig. 6. Comparison of calculated (open squares) and experimental (closed squares) coincidence channel cross sections from ^{12}C + C at 2 GeV/nucleon. The calculated cross sections were not normalized to fit the experiment. Primary fragment excitation was 30 MeV/excitation.

Fig. 7. Calculated (open squares) and experimental (closed squares) coincidence channel yields from 2 GeV/nucleon ^{16}O in nuclear emulsion.

Fig. 8. Comparison of calculated (open squares) and experimental (closed squares) perpendicular momentum distributions for He

fragments from ^{16}O (2 GeV/nucleon) in nuclear emulsion. For multiplicities 2,3 and 4, the He was in coincidence with anything. The highest point for multiplicity 1 is for He in coincidence with H only, the middle point for He in coincidence with anything, and the lowest point for He in coincidence with at least one fragment with Z>2.

Fig. 9. Comparison of calculated (open squares) and experimental (closed squares) fragment parallel momentum distributions for ^{12}C + C at 2 GeV/nucleon. The momentum widths have been divided by the fragment mass numbers. They are in units of MeV/c per mass number.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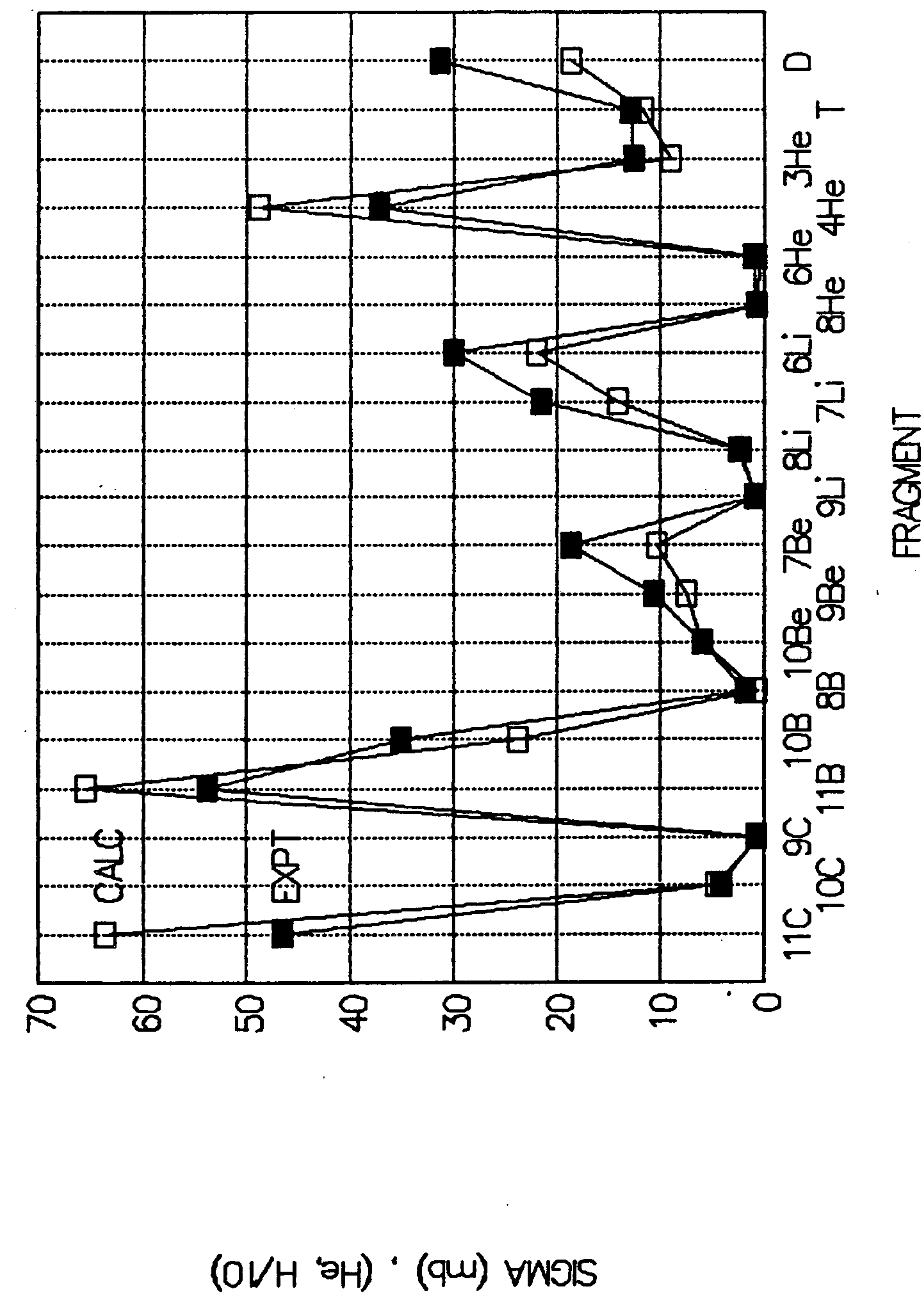
NO. EXCITATIONS IN PRIMARY FRAGMENT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9Li
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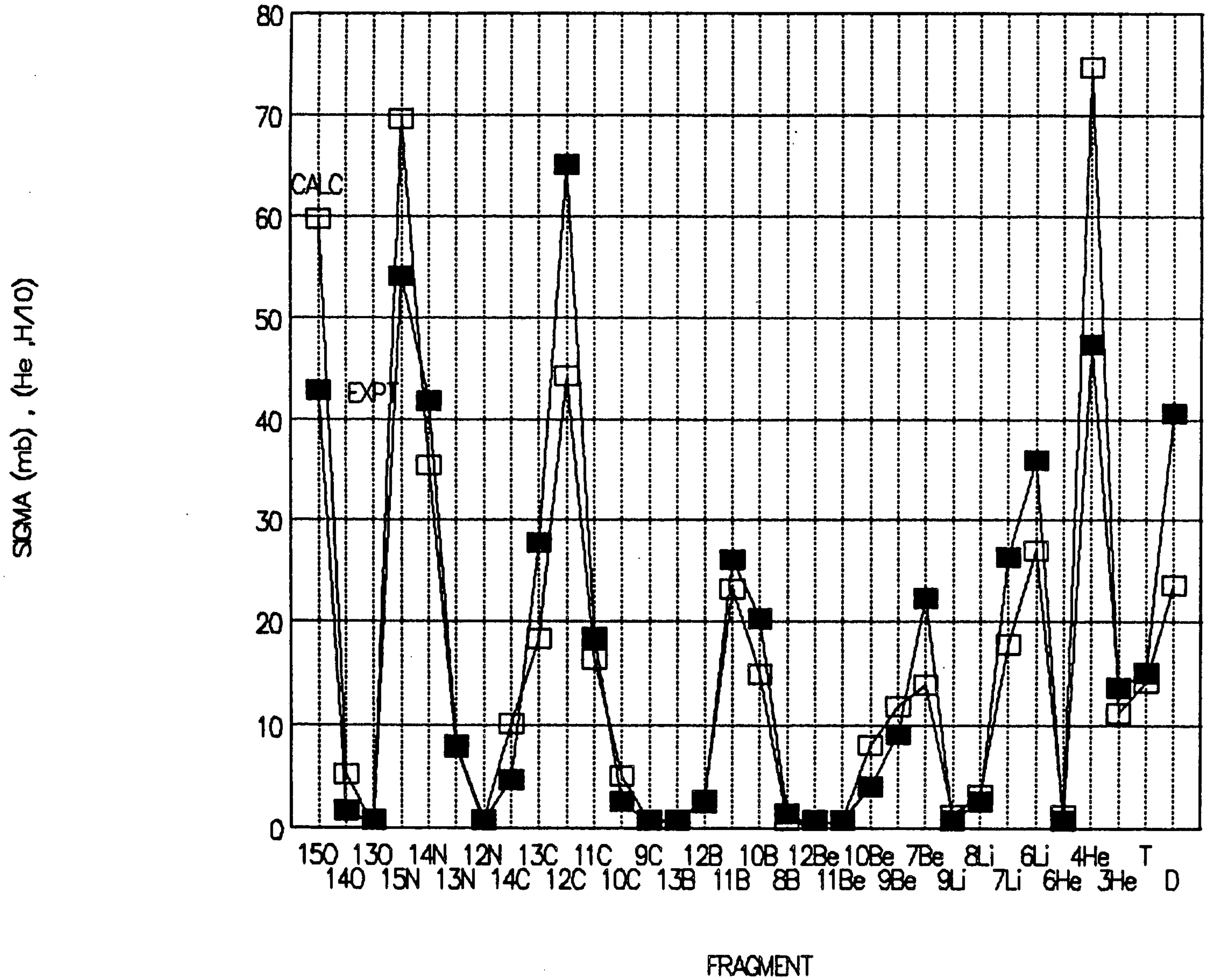
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EXPT
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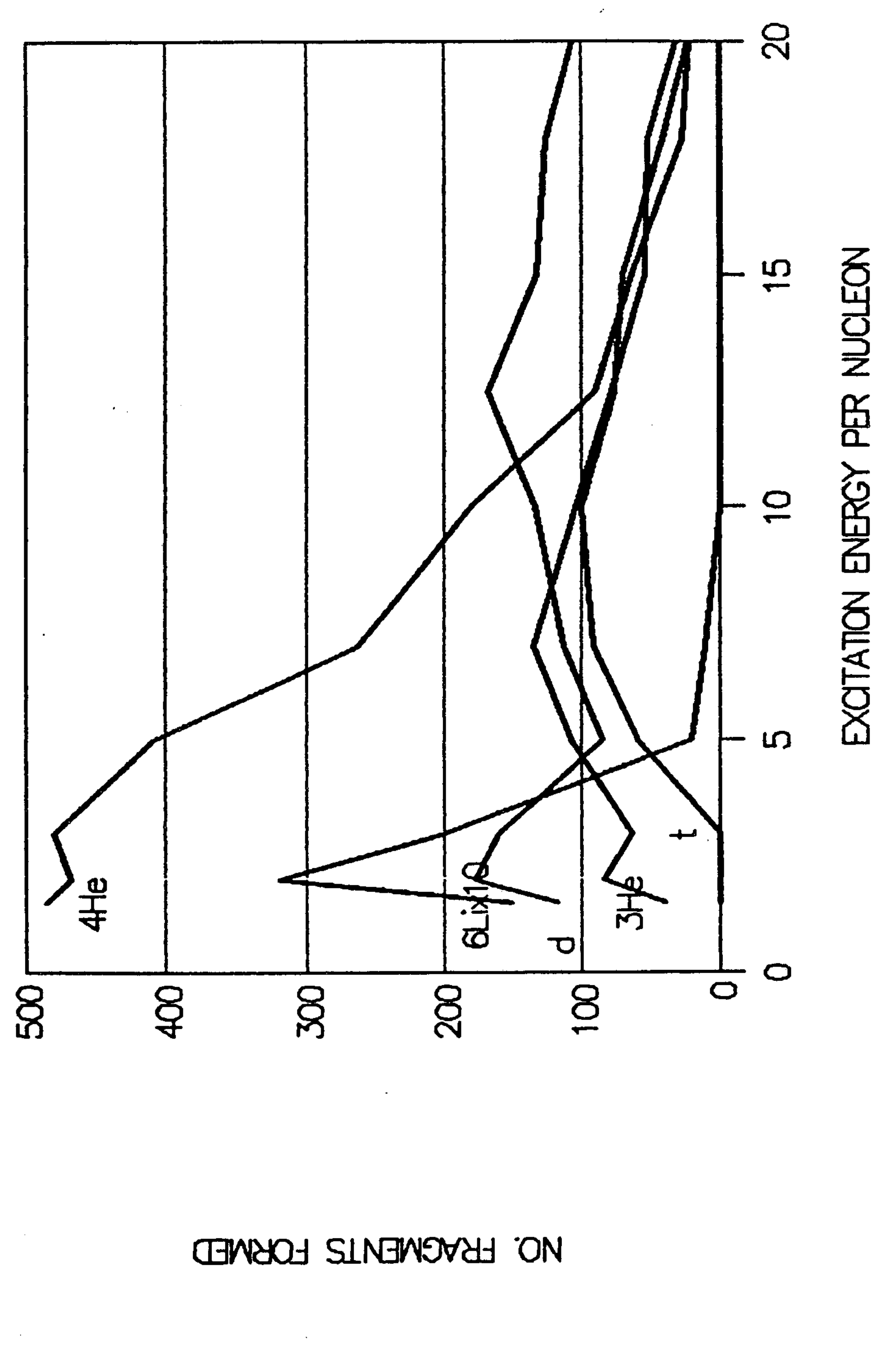
FRAGMENT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d
3He
t
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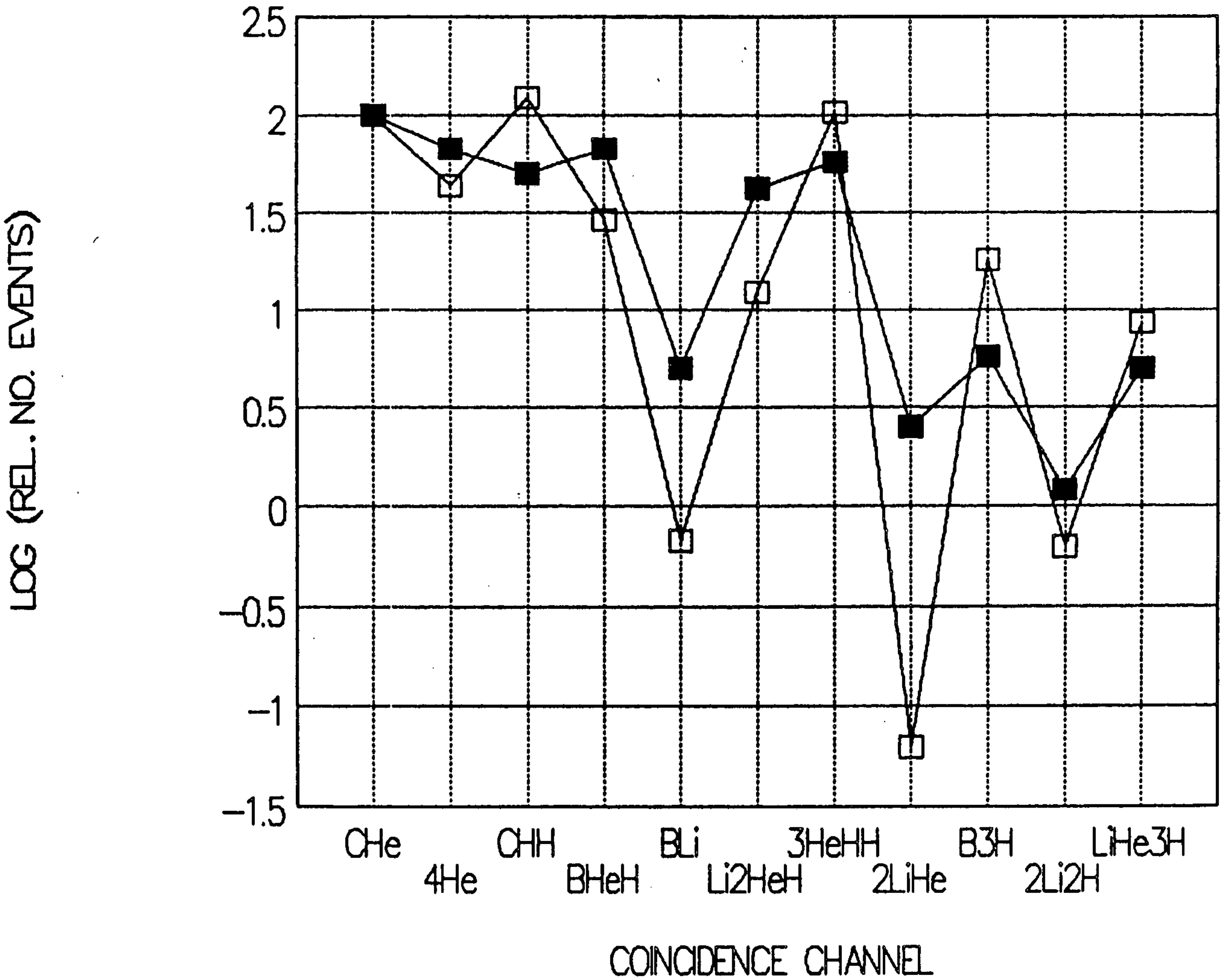
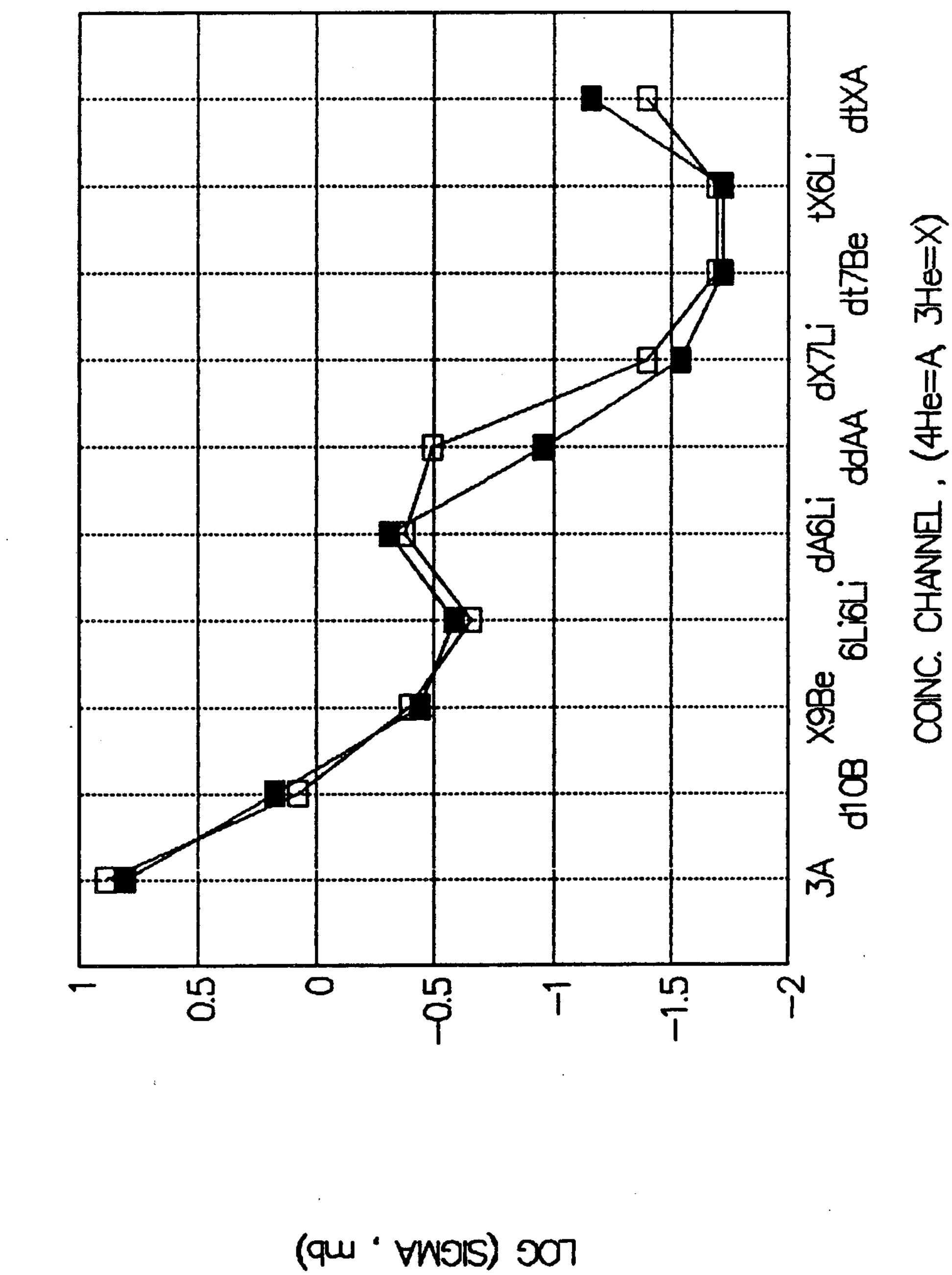
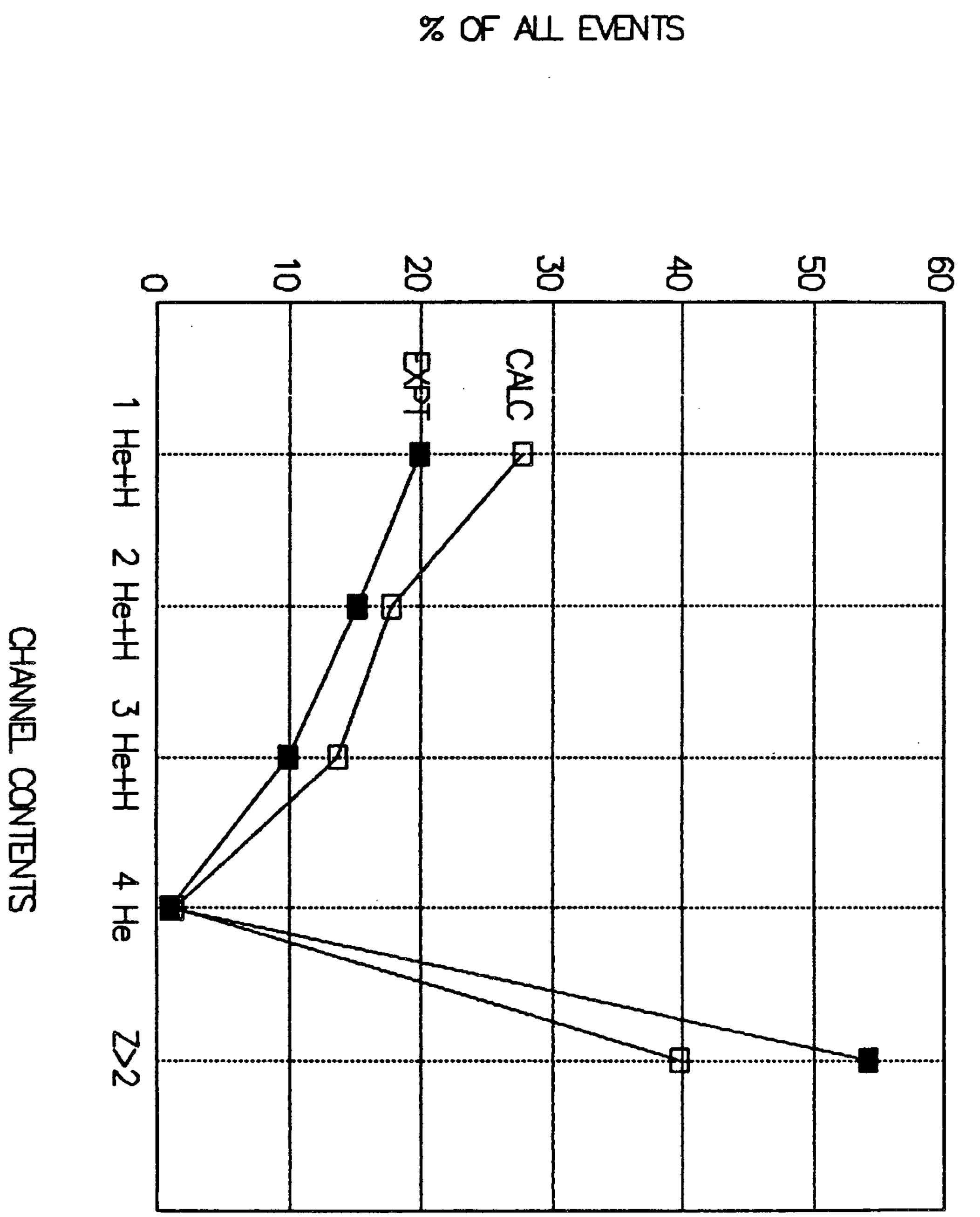
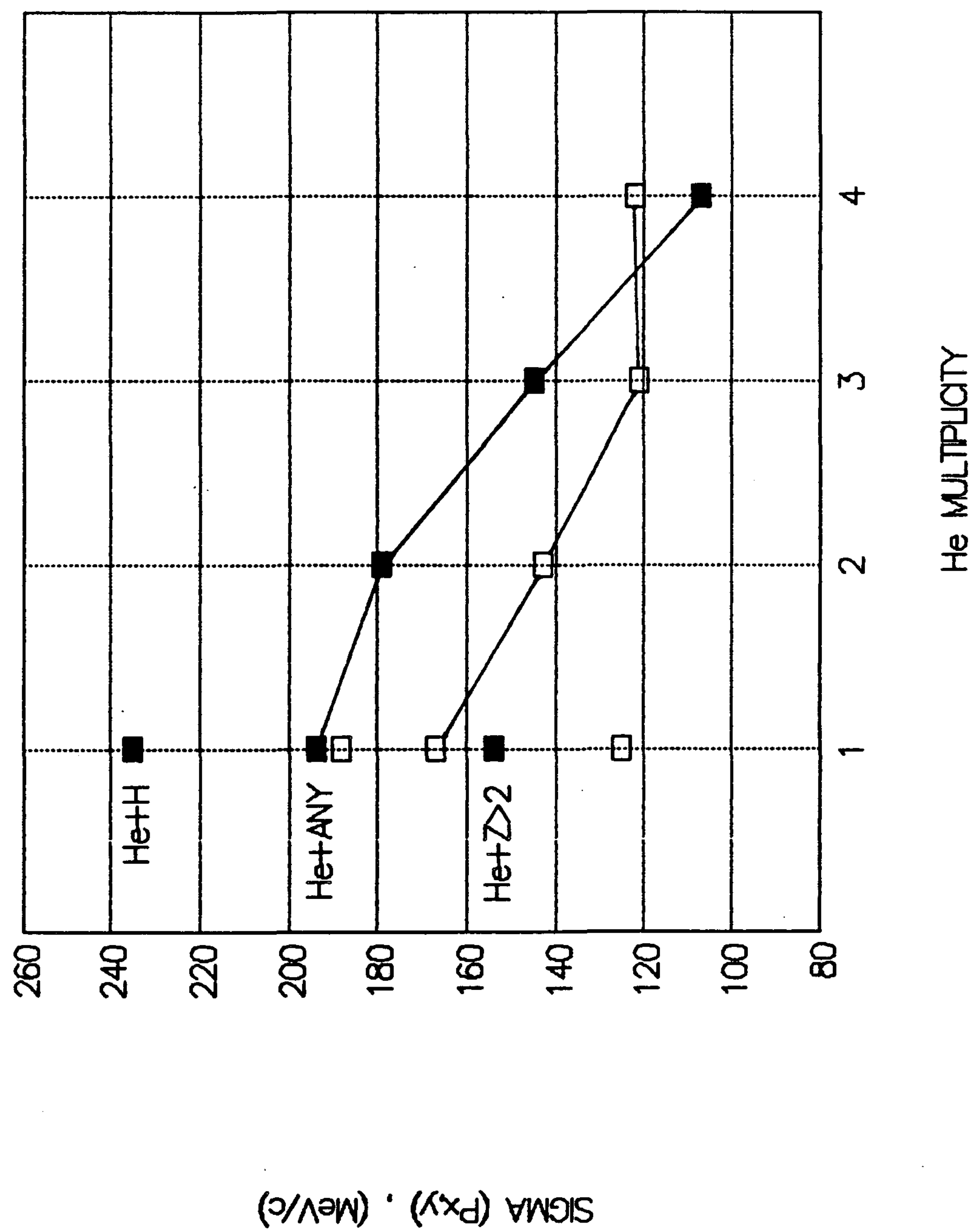
100
200
300
400
500
0
5
10
15
20
EXCITATION ENERGY PER NUCLEON
NO. FRAGMENTS FORMED

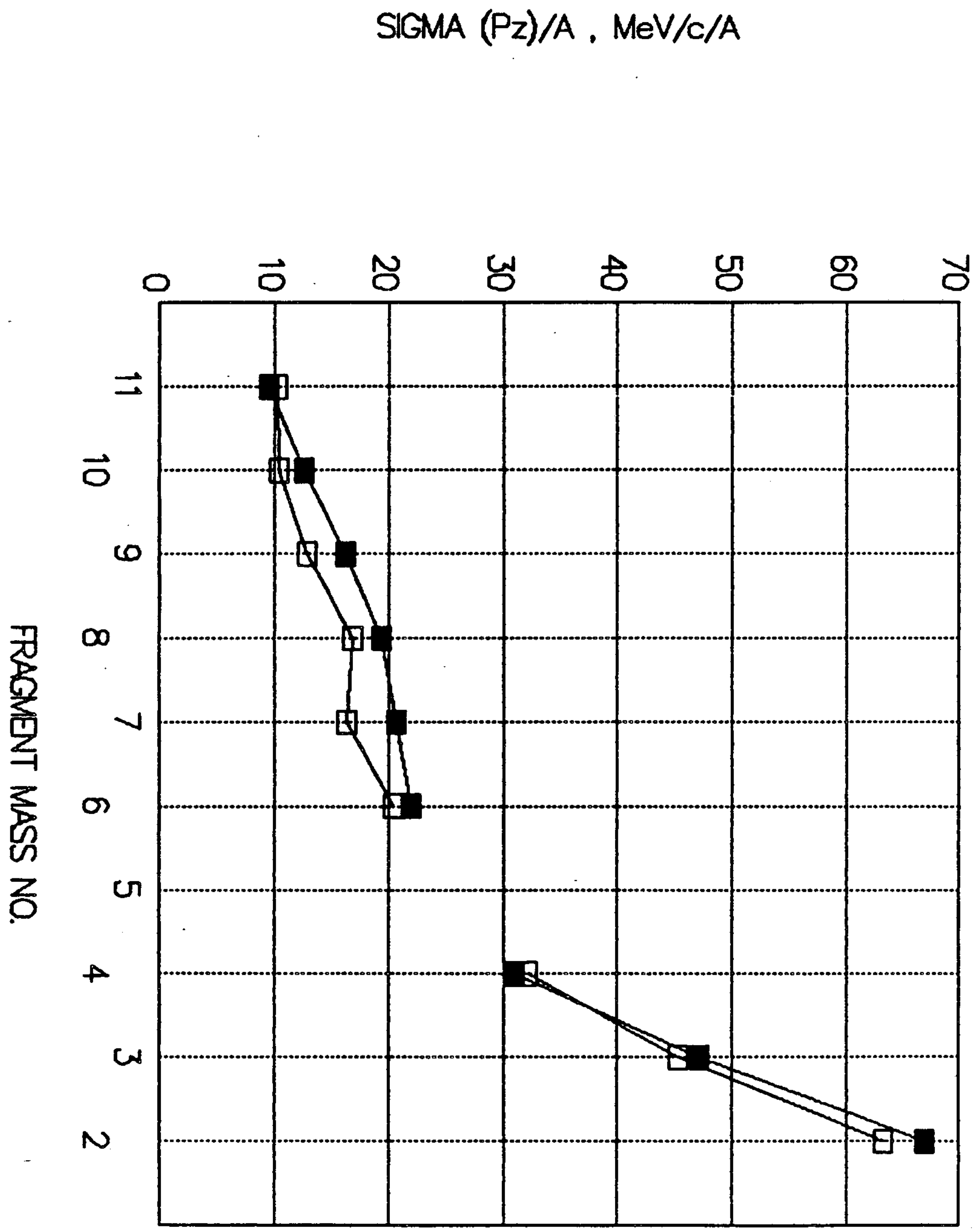

LOG (REL. NO. EVENTS)
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
CHe
4He
CHH
BHeH
BLi
Li2HeH
3HeHH
2LiHe
B3H
2Li2H
LiHe3H
COINCIDENCE CHANNEL



LOG (SIGMA , mb)
1
0.5
0
-0.5
-1
-1.5
-2
3A
d10B
X9Be
6Li6Li
dA6Li
ddAA
dX7Li
dt7Be
tX6Li
dtXA
COINC. CHANNEL , (4He=A, 3He=X)


% OF ALL EVENTS
0
10
20
30
40
50
60
CALC
EXPT
1 He+H
2 He+H
3 He+H
4 He
Z>2
CHANNEL CONTENTS


He+H
He+ANY
He+Z>2
260
240
220
200
180
160
140
120
100
80
1
2
3
4
He MULTIPLICITY
SIGMA (Px,y) , (MeV/c)


SIGMA (Pz)/A , MeV/c/A
0
10
20
30
40
50
60
70
11
10
9
8
7
6
5
4
3
2
FRAGMENT MASS NO.