REACTIONS OF 265 MeV NITROGEN ON CARBON

ROBERT MAX PATTON

Physics Department

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Prof. J. B. Natowitz

ABSTRACT

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Robert Max Patton

Research Advisor: Prof. J. B. Natowitz

Singles and coincidence energy spectra were obtained for ^{14}N projectiles at 265 MeV incident on a ^{12}C target. Model calculations were done for this system using the computer program LILITA and comparisons were made between the calculated and experimental spectra. From these comparisons we determined that the lower energy heavy fragments were predominantly fusion residues but that fusion accounted for a relatively small portion of the total reaction cross section. Plots of light particle energy versus heavy fragment energy were produced for coincidence events to determine what other reaction mechanisms may be occurring.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

Much research has been done with beams of atoms incident on thin foil targets as a means of exploring the nature of nuclear interactions. But due to the complexity and great variety of possible reaction mechanisms there is still much that is unknown.

Once the coulomb barrier is overcome and nuclear forces come into play, many different reaction mechanisms are possible depending on the masses of the target and projectile nuclei, the energy of the system, and the impact paramenter (that is, the closest distance between the centers of the two nuclei if no forces were to act upon their paths). Fusion occurs when the two nuclei form a compound nucleus which has equilibrated, meaning that the excitation energy is uniformly distributed amongst the nucleons. The excited compound nucleus can then evaporate light particles such as nucleons or alphas until it decays below the threshold for particle emission, at which point gamma decay may remove the residual energy. Large mass nuclei with higher angular momenta can fission into two fragments whose mass distributions are centered around a symmetric division.

In this same range of energies and for very high impact parameters, another kind of mechanism takes place in which the relative energy of the system is largely damped by means of friction forces between the two colliding nuclei. In this way a compound nucleus is not formed and the two fragments (with masses similar to those of the target and projectile) reseparate after having exchanged only a few nucleons. The observed energies can be explained by the angular momentum and coulomb repulsion of the two fragments. Many other mechanisms are possible at higher energies such as various types of mass transfers, total explosion for central collisions, and participant-spectator reactions where a portion of a projectile near the Fermi energy can continue unaffected while another portion is involved in some sort of reaction with the target. One such reaction which has been studied for the ^{14}N on ^{12}C system at energies of 86.9 MeV and 157 MeV is the production of Li and Be through the decay of a projectile-like particle excited in a peripheral collision.[10]

This research deals with the system of 265 MeV ^{14}N on ^{12}C, and attempts to determine the reaction mechanisms involved. Fusion has been studied for ^{14}N on ^{12}C for energies from 34.1 MeV to 248 MeV.[1-3] Compound nucleus formation followed by single particle decay for lower energies in this system has also been studied.[4-7] At low energies, three body processes are also observed. One such mechanism has been studied at a bombarding energy of 48 MeVin which a ^{13}C nucleus and a ^{12}C nucleus were detected in coincidence and the velocities of the missing proton were reconstructed from kinematical condiderations.[8]

At higher energies and larger impact parameters incomplete fusion can occur in which a pre-equilibrium light particle is emitted with an energy per nucleon close to that of the beam. The remaining mass of the system then fuses and undergoes evaporative decay. This has been studied as a mechanism in competition with fusion for the similar system of 293 MeV ^{12}C on ^{12}C.[9]

II. EXPERIMENTAL SET-UP

The data discussed here were collected in an experiment at the Texas A & M variable energy cyclotron. A nitrogen beam at 265 MeV was incident on a carbon target which had a thickness of $600\mu g/cm^2$. The detector set-up was as in Figure 1. A heavy ion detector stack consisting of a gas ionization chamber backed by a 43.8 μ Silicon detector and a 1000 μ Si detector remained at 8° throughout the experiment. A detector telescope consisting of three Si detectors with thicknesses of 23μ, 100μ, and 5000μ, was used to stop light particles.Data were taken with this stack at laboratory angles of 7.5°, 13°, 26°, 35°, 40°, and 58° to obtain angular distributions of the light ions. The electronics set-up was such thatboth singles and coincidence data were taken at each angle. If particles come into the detectors close enough together in time, then a signal reflecting the time between the particle in the heavy ion stack and the one inthe light ion stack is derived from a time-to-amplitude converter (TAC) and isrecorded on tape with the event so that coincident products from the same collision may be identified.

Data were recorded event-by-event onto magnetic tapes after initial processing by a PDP 15 computer. These tapes were later converted to VAX format to be processed on the VAX 11/780.

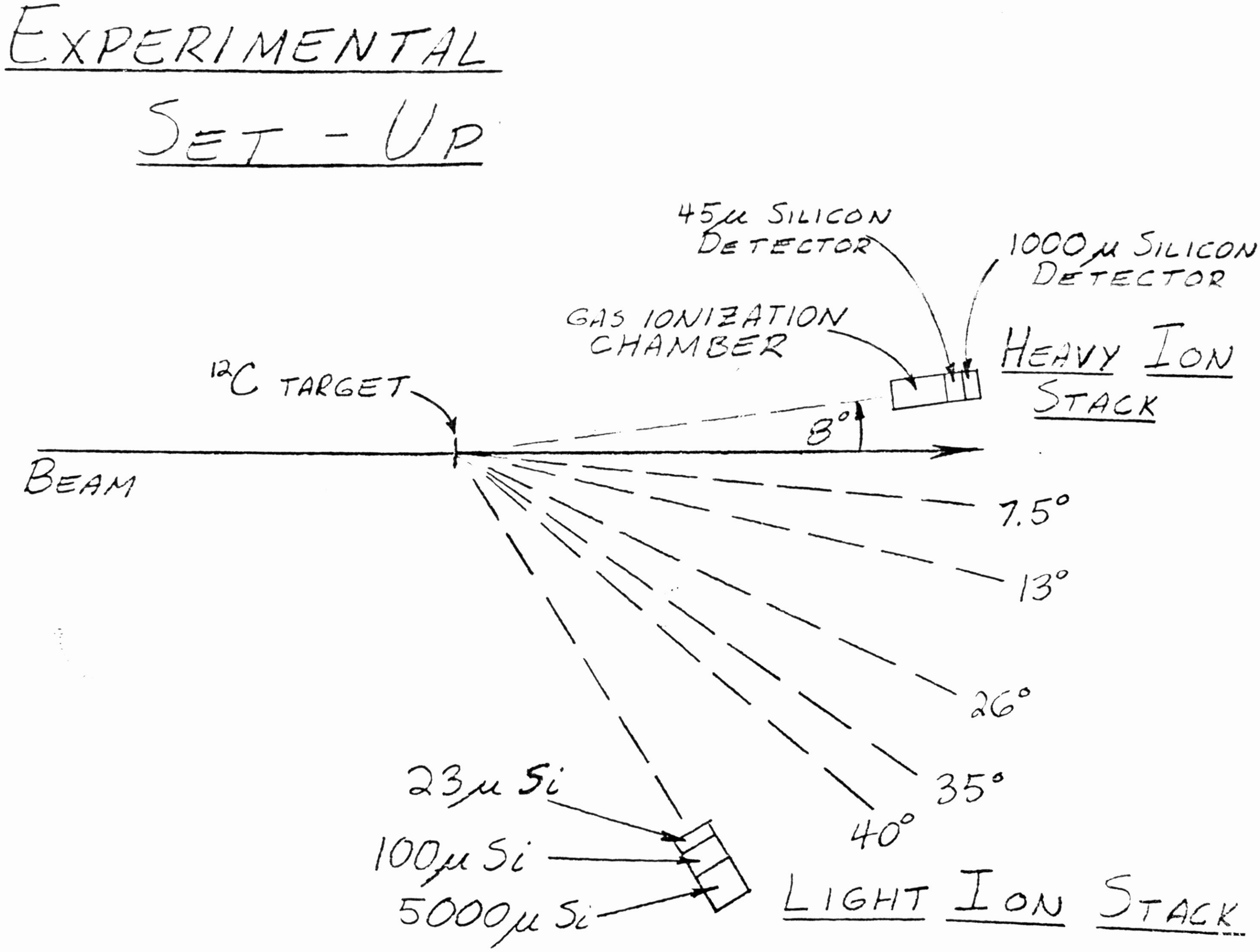

FIGURE 1. EXPERIMENTAL SET-UP

III. DATA ANALYSIS

Data analysis was done using an interactive computer code called LISA[12] which reads data event-by-event from magnetic tape and produces spectra and other information as defined by the user. Plots of the total energy versus theenergy deposited in the first detector result in E vs. dE plots such as in Figures 2 and 3. These two-dimensional spectra can be linearized into one-dimensional spectra useing the Poskanser-Butler formula.[13] This formula is utilized in INSERT one of the two user-written subroutines which LISA allows for and a PIO (Particle Identification Output) plot is created as in Figures 4 and 5. Windows can be easily applied to this spectrum which allow one to concentrate on a single element or a single type of coincidence event. Singles energy distributions for protons, deuterons, tritons and alphas were produced utilizing these windows. These were done for each detector angle (7.5°, 13°, 26°, 35°, 40°, 58°). Singles energy distributions were also produced for heavy ions Z = 4 through 11 at 8°.

Spectra were produced for heavy fragments in coincidence with light particles and vice versa. From the TAC signal, a spectrum is created which exhibits both accidental peaks, which are the result of detecting particles from different beam bursts, and one true peak of significantly greater magnitude than the accidental peaks. An accidental peak which should look the same as the others but comes from different events within the same beam burst also exists in the "true" peak and must be subtracted out. This is done by subtracting event by event those signals corresponding to an accidental

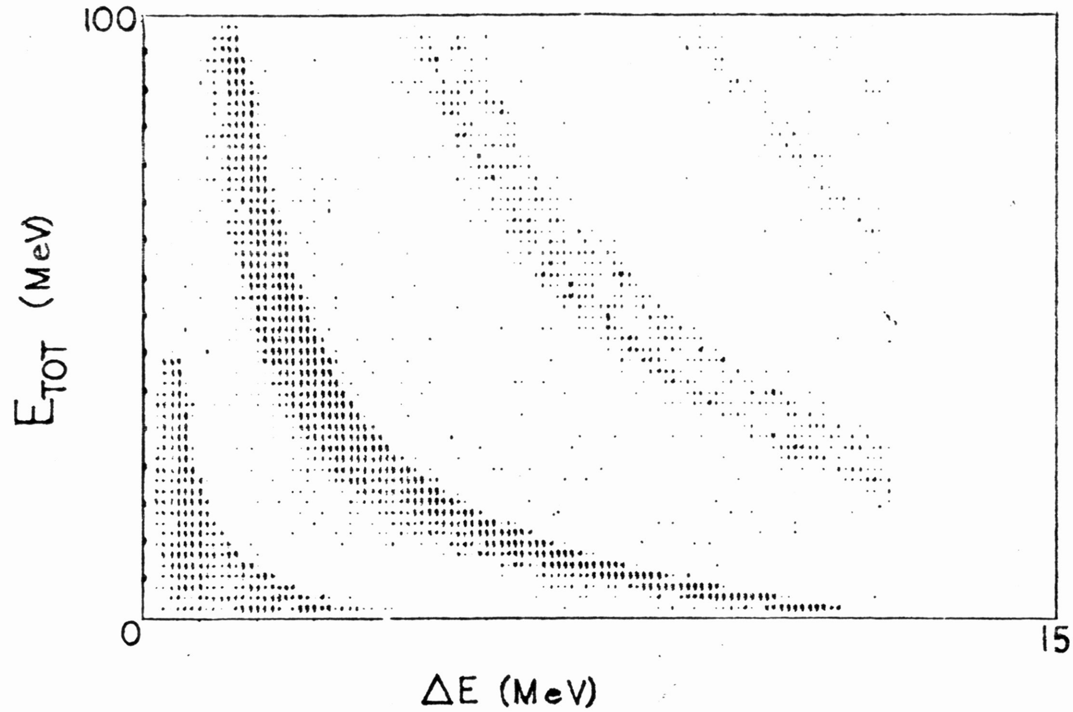

FIGURE 2. LIGHT ION E VS. ΔE

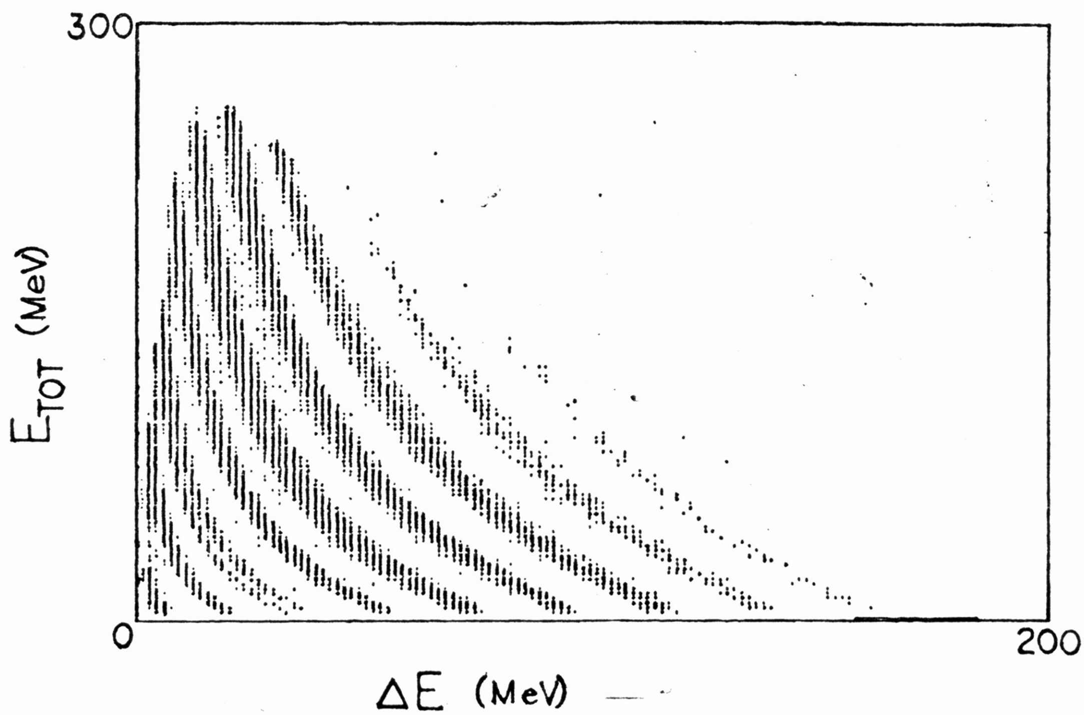

FIGURE 3. HEAVY ION E VS. ΔE

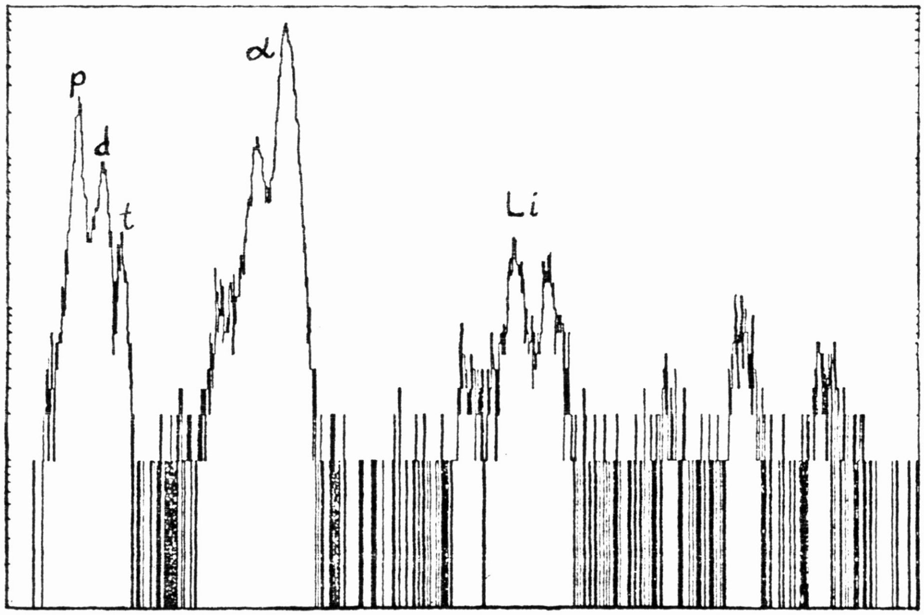

FIGURE 4. LIGHT ION PIO

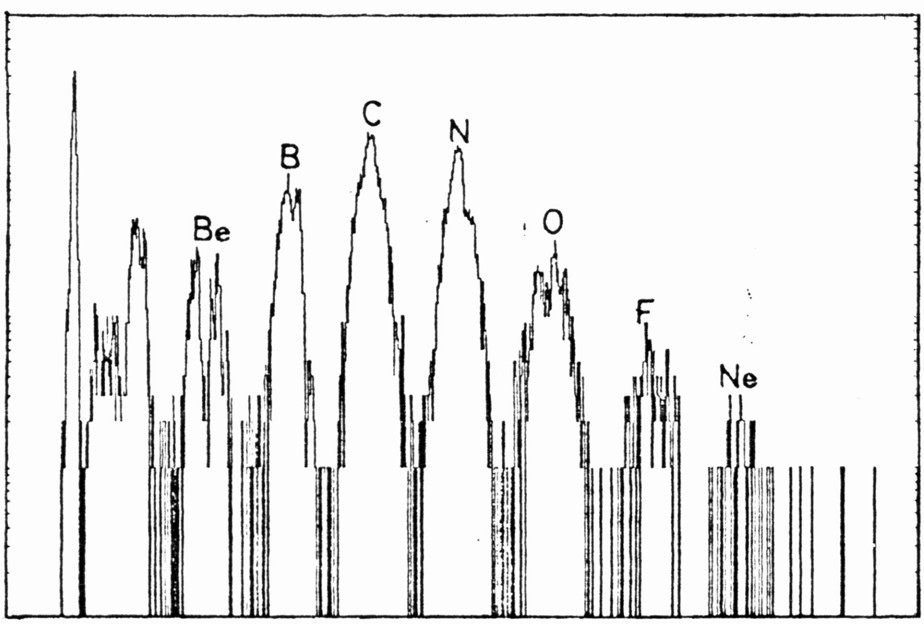

FIGURE 5. HEAVY ION PIO

coincidence from those corresponding to "true" coincidences. To do this the user-written subroutine EVBEV is used. EVBEV was written for two other special cases, one to produce two-dimensional spectra of the light particle energy versus the heavy fragment energy in a coincidence event as in Figure 11. The other was to produce spectra of alphas in coincidence with either low energy heavy fragments or with high energy heavy fragments.

IV. MODEL CALCULATIONS

The evaporative decay of an equilibrated compound nucleus is a process that has been statistically modeled. One such model is used in the Monte Carlo, Hauser-Feshbach computer program called LILITA.[11] It is useful to compare the experimental energy spectra, angular distributions, elemental yields, and coincidence data with those from LILITA since the similarities and differences may give us some insight into the reaction mechanisms of this system.

The calculation follows the history of the excited nucleus until the excitation energy is below the threshold for particle emission. The excitationenergy and angular momentum is calculated after each decay step so that sequential decay can be followed.[1] Before the first step decay is to be calculated, one must know the excitation energy and angular momentum of the compound nucleus. The excitation energy is a function of the beam energy and the angular momentum distribution is determined by J_{crit}, the critical angular momentum above which a compound nucleus will not be formed, which must be supplied. In the calculations performed here a value of $J_{crit} = 30h$ was used. This is an estimate made from cross section measurements done on the ^{14}N on ^{12}C system at a lower energy.[1]

One can draw some conclusions as to the experimental J_{crit} for fusion from comparisons between experimental and calculated spectra. Since

$$\sigma = \left(\frac{\pi h^2}{2\mu E_{cm}}\right) J^2$$

relates the angular monmentum J to the cross-section s we have the relation

$$J_{crit} = \left(\frac{\sigma_{cf}}{\sigma_{calc}}\right)^{\frac{1}{2}} J_{calc}$$

where σ_{cf} is the experimentally determined cross section for complete fusion, σ_{calc} is the same but from model calculations, and J_{calc} = 30h. This assumes a sharp cutoff model for fusion where fusion is the only process occuring up to J_{crit} and does not occur in significant proportions beyond J_{crit}.

V. COMPARISONS AND DISCUSSION

Comparing the elemental yields from the experiment with those from the calculation as in Figure 6 the differences are obvious. The shift toward lower masses indicates that some processes other than fusion are occurring.

When a comparison of experimental and calculated alpha singles energy spectra as in Figure 7 are examined the similarities are striking. Save for slightly higher yields in the high energy portion of some of the experimental spectra and for an apparent normalization problem in the 40 experimental spectra, the shapes and trends with increasing angle are the same as those in the calculated spectra. This could lead one to believe that the predominant mechanism is fusion were it not for more convincing evidence to the contrary. Since this similarity is not observed when we restrict both experimental and calculated alphas to coincidence with fragments at 8, these similarities could just be a coincidental result of the averaging effect of looking at all alphas.

The comparisons of heavy fragment singles spectra from the experiment andthe calculation in Figure 8 tell a much different story. The differences are obvious and for lower masses such as boron and carbon it would appear that fusion constitutes only a very small portion of the reaction cross-section yielding these elements. As the fragments get heavier, a fusion-like component becomes increasingly prominent until it appears that fusion could account for the whole spectrum of both flourine and neon. If we estimate the ratio of the experimental to calculated cross-section for flourine to be one-tenth

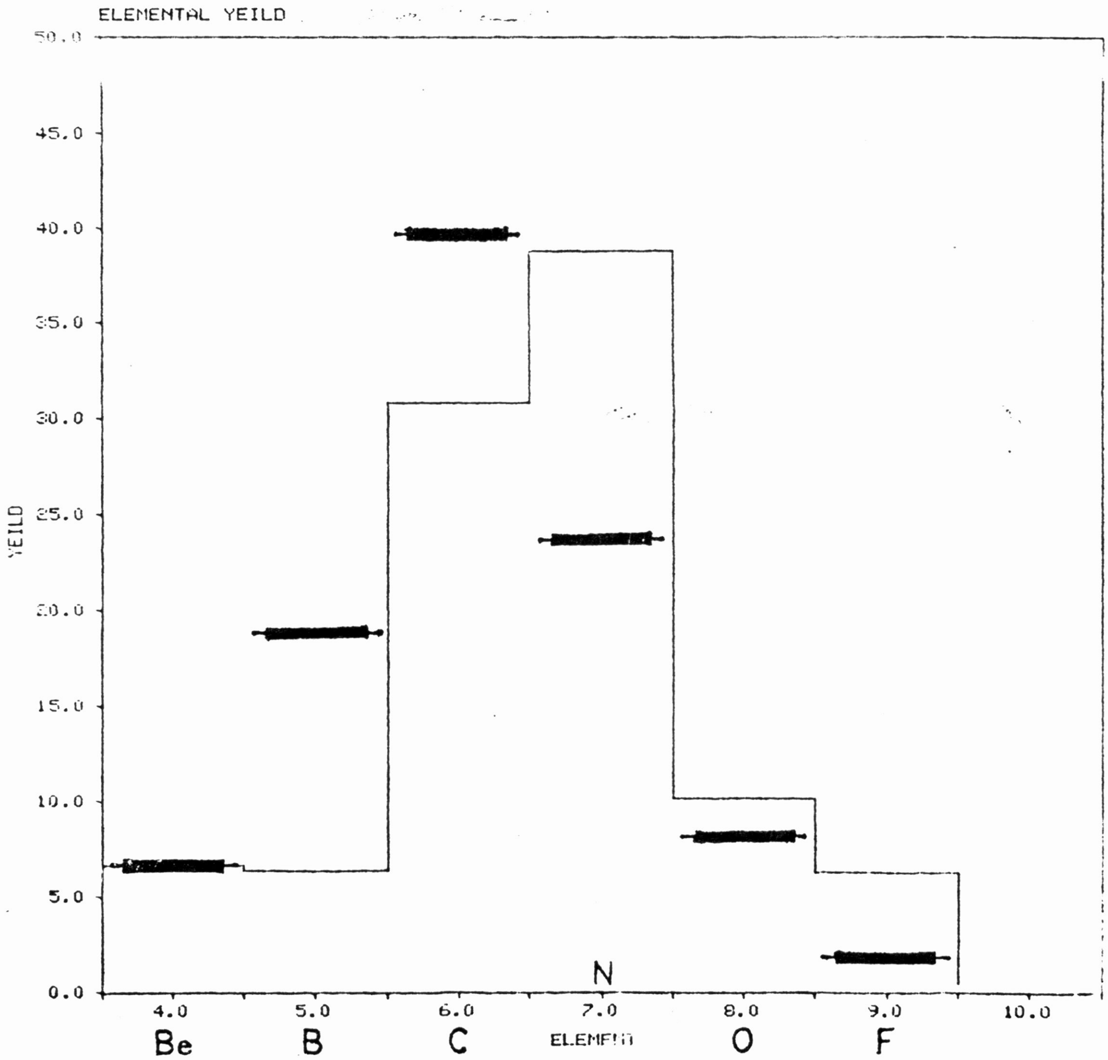

FIGURE 6. ELEMENTAL YIELDS CALCULATED (HISTOGRAM) AND EXPERIMENT (BARS)

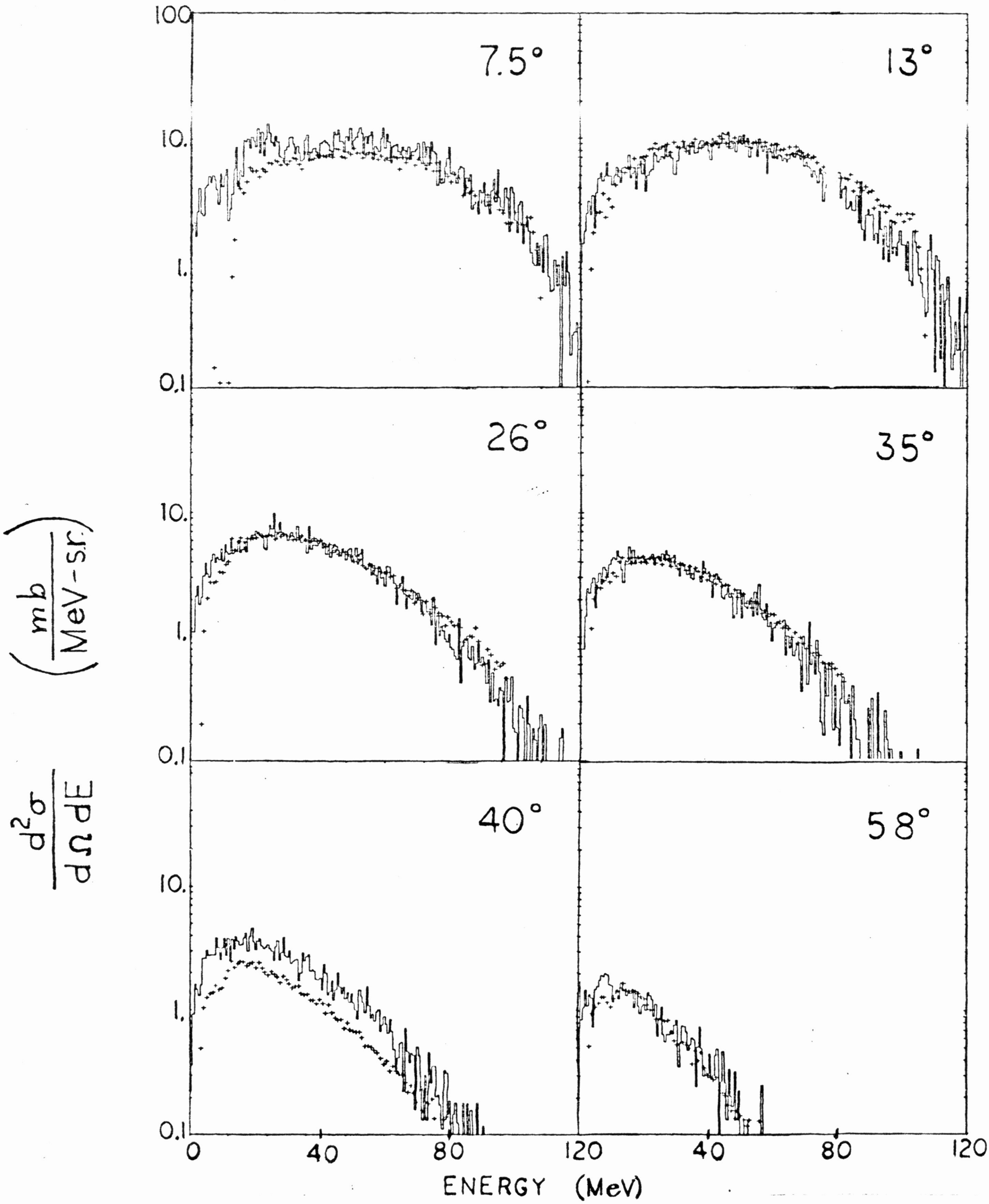

FIGURE 7. ALPHA SINGLES ENERGY SPECTRA CALCULATED (HISTOGRAM) AND EXPERIMENT (SYMBOLS)

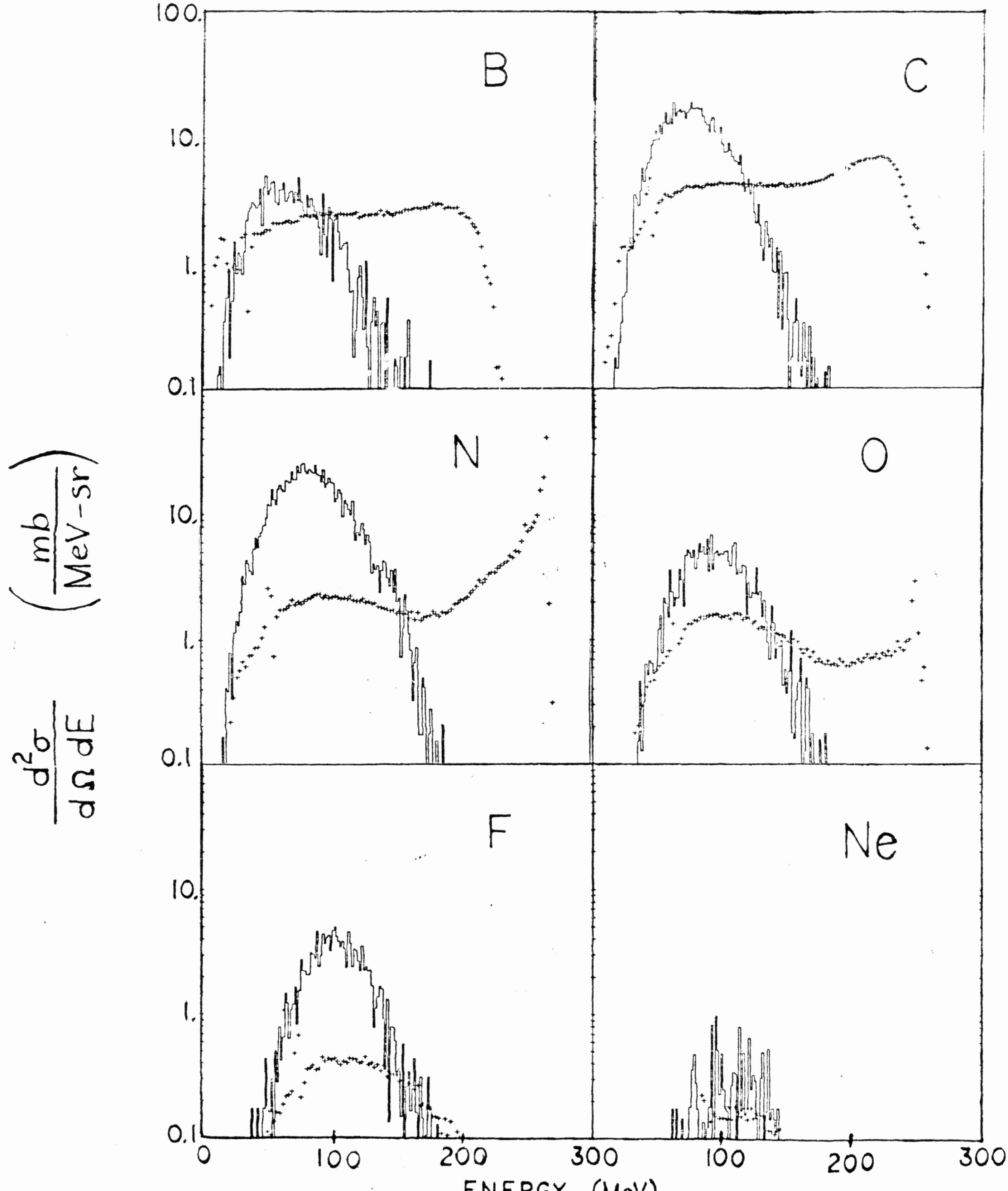

FIGURE 8. HEAVY ION SINGLES ENERGY SPECTRA CALCULATED (HISTOGRAM) AND EXPERIMENT (SYMBOL)

then

$$J_{crit} = \left(\frac{\sigma_{cf}}{\sigma_{calc}}\right)^{\frac{1}{2}} J_{calc} = \left(\frac{1}{10}\right)^{\frac{1}{2}} (30h) = 10h \ .$$

This is a very crude estimate for only one element and only one angle but it appears reasonable, and is close to the value for J_{crit} of 10h for 293 MeV ^{12}C on ^{12}C.[9]

The question remains as to whether or not these fusion-like components actually come from fusion reactions. To answer this question we compare the alphas in coincidence with lower energy heavy fragments to alphas in concidence with the high energy heavy fragments as in Figure 9. The shapes appear to be very much different. At the forward angles the spectra from high energy heavy fragments have a much flatter shape, and at larger angles they are much more strongly peaked toward low energy alphas. This validates the assumption that the different componentsin the heavy fragment spectra are from different reaction mechanisms.

If we now compare the same alphas in coincidence with low energy heavy fragments to coincidence alphas from the calculation as in Figure 10 we see that, barring statistical fluctuations and normalization differences, the shapes of the spectra are very similar. This is a good indication that the low energy component of the heavy ion spectra does indeed correspond to a fusion reaction mechanism.

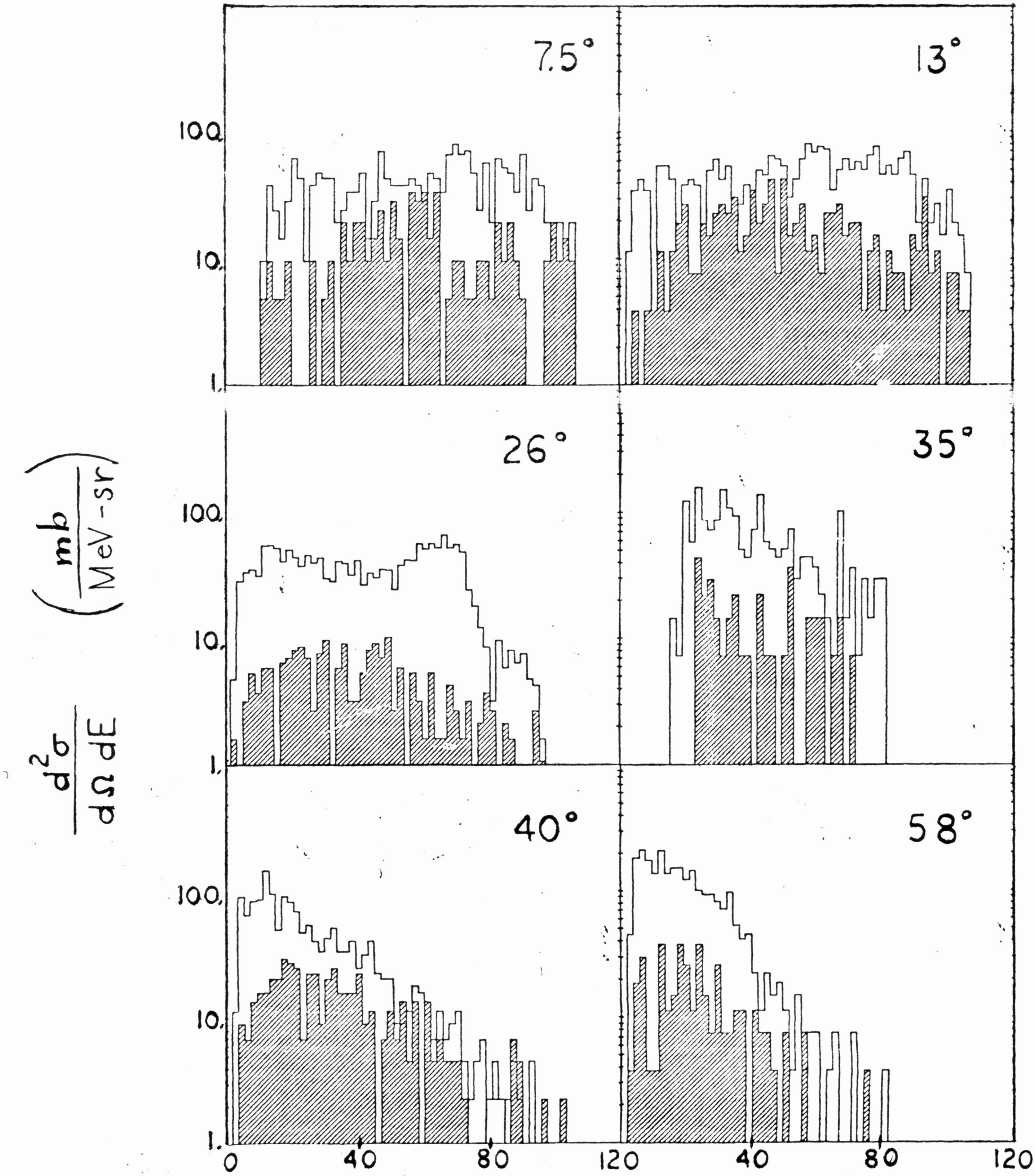

FIGURE 9. ALPHAS IN COINCIDENCE WITH LOW ENERGY FRAGMENTS (SHADED) AND HIGH ENERGY FRAGMENTS

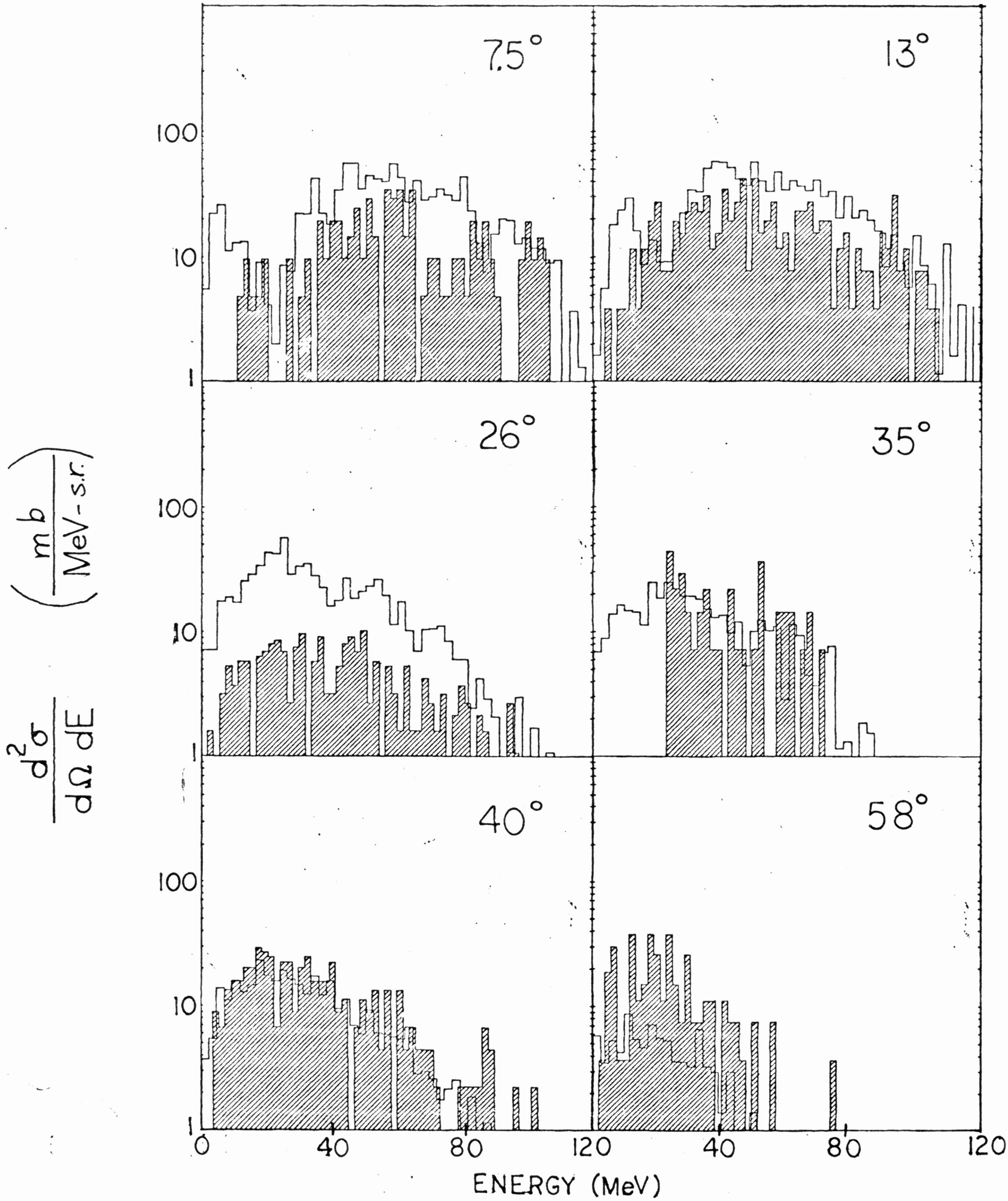

FIGURE 10. COINCIDENCE ALPHAS FROM LOW ENERGY FRAGMENTS (SHADED) AND CALCULATION

Prominent peaks were seen in both the energy spectrum of carbon in coincidence with alphas and that of alphas in coincidence with carbon as in Figure 11. To determine wether the events which constituted one peak were the same as those in the other peak we made a two-dimensional plot, also shown in Figure 11, of the alpha energy versus the carbon energy for carbon - alpha coincidence events. This plot exhibits a strong energy correlation between the two peaks indicating that some specific non-fusion reaction mechanism is occurring to cause the peaks. A possible reaction mechanism is

$$^{14}N + {}^{12}C \rightarrow ({}^{16}O^{*} + {}^{10}B)$$

$$^{14}C + {}^{4}He$$

Similar mass transfer reactions seem to be occuring for other elements but the correlations are not as strong and therefore not as conclusive.

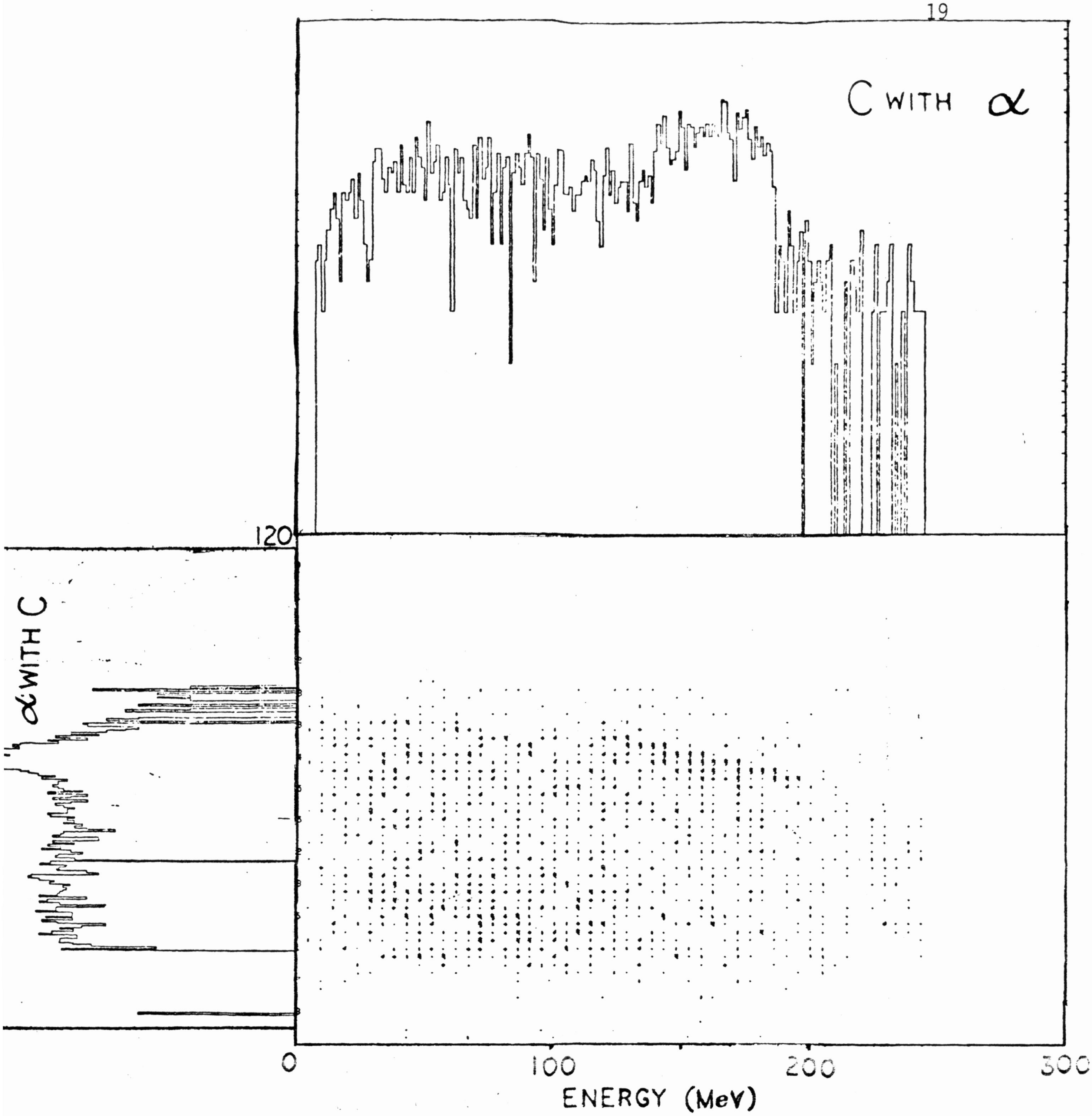

FIGURE 11. COINCIDENCE SPECTRA AND E-E PLOT FOR CARBON-ALPHA COINCIDENCES

VI. SUMMARY AND CONCLUSIONS

We have determined that the low energy components in the heavy ion energy spectra appears to correspond to the reaction mechanism of fusion and have therefore concluded that fusion accounts for a relatively small part of the total reaction cross-section. A rough estimate for Jcrit, the critical angular momentum for fusion, is 10h but exact numbers have not yet been extracted for either the fusion cross-section or J_{crit}. Evidence has also been found to exist for peripheral mass transfer reaction such as a deuteron transfer from the target to the projectile and the subsequent decay of the excited ^{16}O into ^{12}C and an alpha particle.

Further research must still be done to more accurately determine the critical angular momentum for fusion and what other reaction mechanisms involved. The total reaction cross-section could be determined and therefore what pecentage fusion accounts for. It would be useful to obtain both singles and coincidence data at larger angles for the light and heavy ions. Model calculations could be made for the case of incomplete fusion as a competing reaction mechanism in an attempt to fit the spectra and thereby more fully understand what mechanisms are involved and in what proportions.

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