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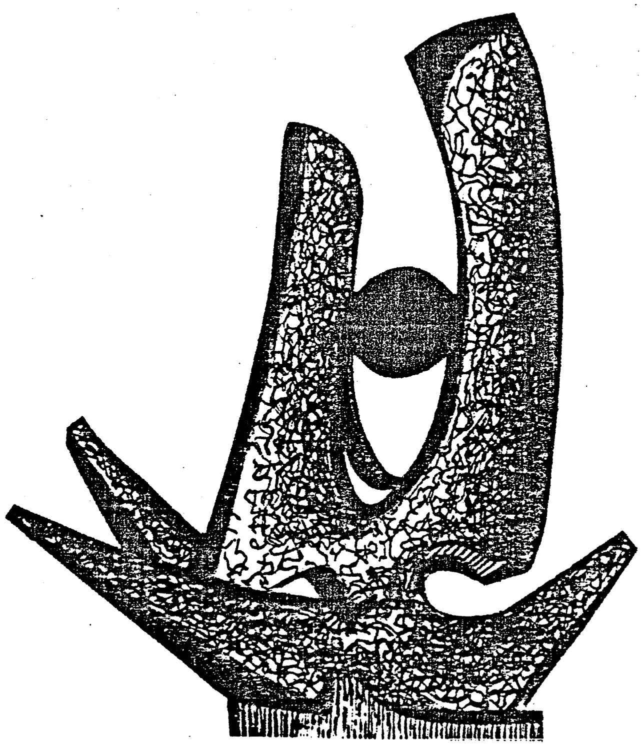

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Abstract

Linear momentum transfer distributions have been determined for ^{14}N induced reactions on ^{238}U by measuring the folding angle between two coincident fission fragments. The data follow the systematic trends previously established for alpha conjugate projectile nuclei. Over the range of energies investigated, the most probable linear momentum transfer has not reached a limiting value. Extrapolation of the present results indicates that complete fusion should cease to be a relevant reaction mechanism above incident energies of E/A = 40 - 45 MeV.

For nucleus nucleus collisions at energies well above the Coulomb barrier, the probability for complete fusion decreases markedly due to a rapid growth in fusion-like processes involving incomplete linear momentum transfer [1-8]. Existing data on alpha conjugate projectiles indicate that the fraction of the projectile momentum transferred to the struck system decreases approximately linearly as the relative velocity of the projectile increases [3-6]. Based on recent studies of ^{12}C induced reactions up to E/A = 84 MeV, it has been further suggested that there exists a saturation limit of about 2 GeV/c for the most probable linear momentum transfer for fusion-like events produced in heavy-ion collisions [9]. Up till now, little information exists for projectiles other than alpha conjugate nuclei which could provide some insight into the relative importance of nuclear structure to fusion-like intermediate energy heavy-ion induced reactions. To provide a more complete basis for evaluating the systematic projectile and bombarding energy dependence, linear momentum transfer distributions were measured in reactions between ^{14}N and ^{238}U at incident energies of E/A = 15, 20, 25, and 30 MeV.

The experiment was performed using ^{14}N beams from the K500 superconducting cyclotron of the National Superconducting Cyclotron Laboratory of Michigan State University. Linear momentum transfer distributions were determined by measuring the folding angles between coincident fission fragments using two position sensitive parallel plate detectors [10] of active area 12 cm x 14 cm. The centers of these detectors were positioned at the angles of $\Theta_A{}^o=70^o$ and $\Theta_B{}^o=80^o$ with respect to the beam axis and at a distance of 17 cm from the target. A UF_4 strip target of areal density of .4 mg/cm^2 and dimensions 3 mm x 22 mm , evaporated onto a .1 mg/cm^2 carbon backing was used. Absolute cross sections were obtained from the measurement of elastically scattered ^{14}N ions with two 1.5mm thick monitor detectors positioned at the scattering angles of 8^o. Optical model calculations using different sets of optical potentials [11] were used to assess the deviations from Rutherford scattering, which were negligible at the three lower energies and about 20% at the highest energy. We estimate the error of the absolute normalization to be 10% at the three lower energies and 15% at the highest energy.

Fission fragment folding angle distributions measured in this experiment are shown in Fig. 1, where Θ_A and Θ_B denote the laboratory angles of the two coincident fission fragments measured with respect to the beam axis and $\Delta\Phi$ denotes the angle between the two planes defined by the beam axis in combination with either of the fission fragment velocity vectors. In order to ensure full coincidence efficiency, these folding angle distributions were obtained by setting a gate on one of the fission detectors corresponding to an area of 2.4 x 2.4 cm^2 and an average scattering angle of $\Theta_A= 86^o$ for E/A=15 and 20 MeV and $\Theta_A=83^o$ for E/A=25 and 30 MeV. The right hand parts of the figure show contour plots of the number of coincident events in the $\Theta_A + \Theta_B$ vs. $\Delta\Phi$ plane. Two peaks corresponding to (i) large momentum tranfer or fusion-like reactions, and (ii) small momentum transfer or peripheral reactions can be clearly distinguished.

The center column of Fig. 1 shows the out-of-plane distributions for the large momentum tranfer reactions. For the ideal case of compound nucleus fission without light particle emission, two-body kinematics requires $\Delta\Phi=0$. Non-coplanar emission of fission fragments is caused by light particle emission which may occur either before or after the system fissions. As is evident from the figure, the widths of the out-of-plane distributions increase significantly with incident energy in accordance with an increase in the emission of light particles at higher energies.

The left hand parts of Fig. 1 show the dependence of the fission cross sections on the folding angle $\Theta_{AB} = \Theta_A + \Theta_B$ which is related to the projection of the linear momentum of the fissioning nucleus onto the beam axis [12,13]. The upper scales show the average recoil momentum Δp of the fissioning nucleus in units of the beam momentum p. This scale was established by assuming symmetric fission of ^{252}Es with a kinetic energy release corresponding to the systematics of ref.14. Consistent with the observations for different projectiles [3] the large momentum transfer component cannot be understood in terms of complete fusion followed by statistical decay. For higher projectile energies, smaller fractions of the projectile momentum are transferred to the fissioning nucleus, reflecting the increasing importance of non-equilibrium particle emission.

An upper limit for the contribution from complete fusion reactions to total fission cross-section is obtained by assuming that complete fusion reactions can be represented by a Gaussian distribution in Θ_{AB} with a width given by the measured $\Delta\Phi$ distribution for all fusion-like reactions. The relative contribution of complete fusion to total fission cross-section decreases strongly with increasing beam energy, corresponding to 56 ± 5, 42 ± 4, 26 ± 4, 21 ± 4% for the incident energies of E/A=15, 20, 25 and 30 MeV, respectively. An extrapolation of the present data to higher energies suggests that complete fusion reactions will cease to contribute at incident energies above E/A = 40 - 45 MeV.

Figure 2 shows a compilation of most probable linear momentum transfers measured in reactions induced by various projectiles on actinide nuclei [3,7-9,12,13,15,16]. The energy dependence of the most probable linear momentum transfer measured in units of the projectile momentum is shown in Fig. 2a and the corresponding momentum transfer per projectile nucleon is shown in Fig. 2b. The fractional linear momentum transfer measured for ^{14}N induced reactions is seen to follow the systematic trends established [3] primarily for alpha conjugate projectile nuclei, indicating that the linear momentum transfer per nucleon depends primarily on the relative velocity of target and projectile and much less on the nuclear structure of the two colliding nuclei. At least for strongly absorbed projectiles of mass A=4-20, the individual nucleons appear to have comparable efficiency for transferring their momentum to the composite system.

There is evidence from both light ion and heavy ion induced reactions that the linear momentum transferred to the composite nuclear system reaches a maximum value at intermediate energies. For protons and deuterons maximum linear momentum transfer is achieved at $E/A \simeq 1000$ and 200 MeV, respectively [17]. For strongly absorbed ^{4}He projectile maximum linear momentum transfer is achieved at lower energies, $E/A \simeq 50$ MeV [9,17]. For ^{12}C induced reactions [9] the linear momentum transfer was suggested to reach a limiting value of Δp_{max} = 2GeV/c at bombarding energies above E/A $\simeq$ 15 MeV. For the present system, most probable linear momentum transfers in excess of 2 GeV/c are measured (Δp = 2.7 GeV/c at E/A = 30 MeV) and a limiting value is not reached below E/A = 30 MeV (see Fig. 2b). However, the results of Refs. 9 and 17 suggest that one should expect the linear momentum transfer to saturate at incident energies in the range from E/A=30 to 50 MeV.

In Fig. 3, we compile existing information about the largest values of the most probable, $\Delta p/A$, (full points) and the mean, $\langle \Delta p/A \rangle$, (open points) linear momentum transfer measured up to now for reactions induced by different projectiles on heavy nuclei [3,7-9,13,15-18]. Because of contributions from peripheral reactions, the mean momentum transfer measured with the fission fragment folding angle technique depends on the fissility of the parent nucleus, therefore it is only evaluated for reactions induced on actinide target nuclei, where it can be assumed that the fission and reaction cross sections are nearly equivalent. For strongly absorbed projectiles, A=4-20, the observed maximum values of $\Delta p/A$ and $\langle \Delta p/A \rangle$ do not exceed 200 ± 20 MeV/c and 190 ± 20 MeV/c, respectively. Reactions induced by p, d, ^{4}He and ^{12}C projectiles have been investigated over a sufficiently large range of incident energies to establish limiting values for the linear momentum transfer (shown by the circular symbols in Fig 3). Measurements for ^{6}Li, ^{14}N, ^{16}O and ^{20}Ne reactions, on the other hand, have only been performed up to E/A= 25, 30, 31 and 30 MeV, respectively. The maximum values observed for these reactions (shown by the square symbols) are likely to be close to the limiting values. However, future experiments at higher energies and with heavier projectiles will have to be performed to clarify whether there exists a general upper bound to the linear momentum transfer per nucleon in heavy ion induced reactions as is suggested in Fig 3.

In summary, we have measured linear momentum transfer distributions for the ^{14}N + ^{238}U system over the energy range from E/A = 15 - 30 MeV. Extrapolation of our estimates for the complete fusion cross section indicates that this mechanism becomes a negligible fraction of the total reaction cross section above E/A = 40 - 45 MeV. These data represent the first systematic study of the energy dependence of incomplete momentum transfer processes for heavy ion induced fusion-like reactions above E/A = 20 MeV and support the conclusions of lower energy studies that the linear momentum transfer per projectile nucleon depends primarily on the relative velocity above the Coulomb barrier of the two colliding nuclei. The existing data for strongly absorbed projectiles suggest a maximum value for the most probable linear momentum transfer per nucleon of approximately 200 MeV/c.

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Figure Captions

Fig. 1. Folding angle distributions between coincident fission fragments measured for ^{14}N induced reactions on ^{238}U at E/A = 15, 20, 25, and 30 MeV.

Fig. 2. Systematics of the energy dependence of the most probable linear momentum transfer measured in reactions induced by various projectiles on actinide target nuclei [3,7-9,12,13,15,16]. Part a shows the momentum transfer in units of the projectile momentum and part b shows the momentum transfer per projectile nucleon.

Fig. 3. The largest values of the most probable (open points) and the mean (full points) linear momentum transfer per nucleon measured up to now for reactions induced by different projectiles on heavy nuclei [3,7-9,13,15-18]. The circular symbols are established limiting values while the square symbols are values extracted from experiments performed at the highest bombarding energies available to-date.

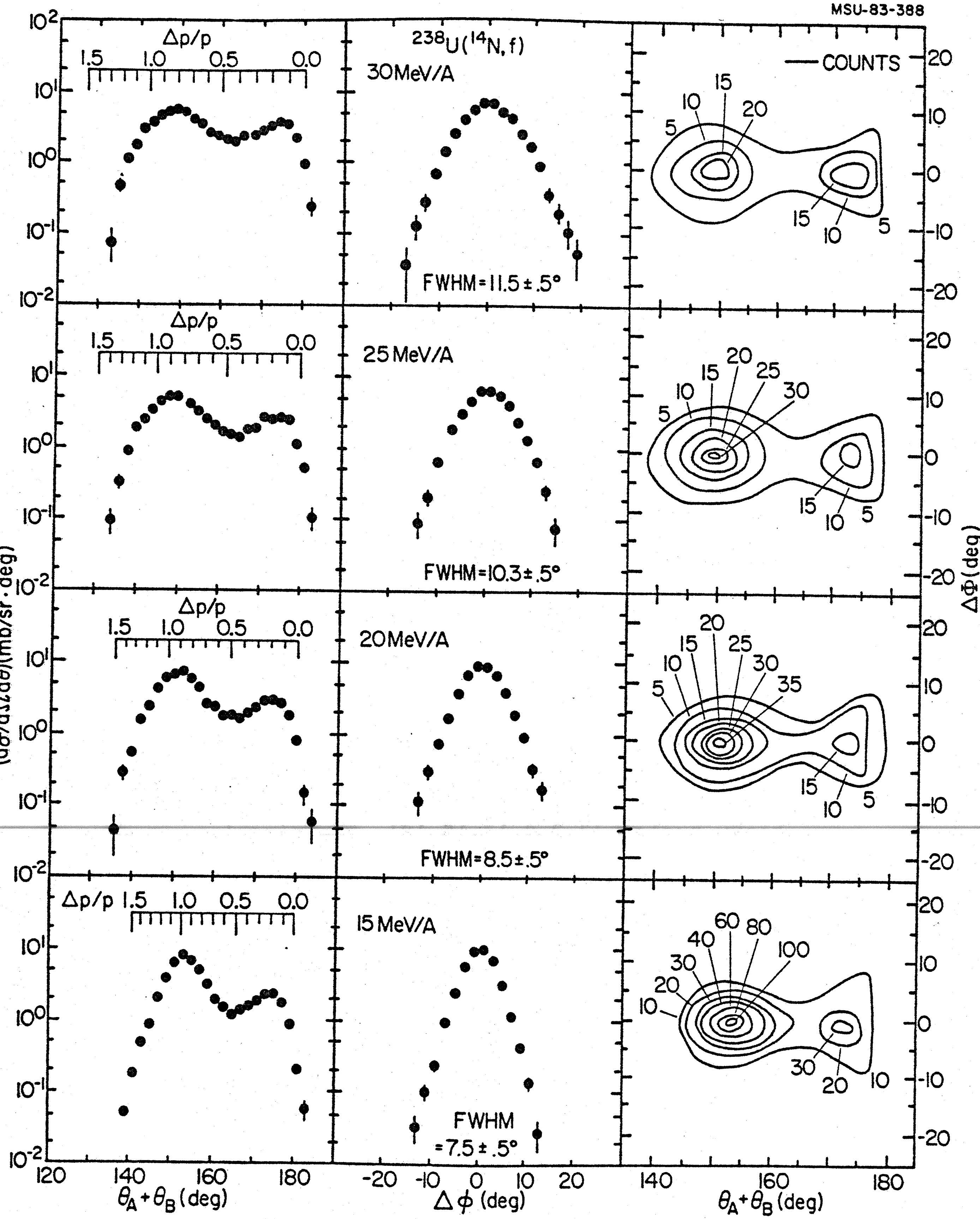
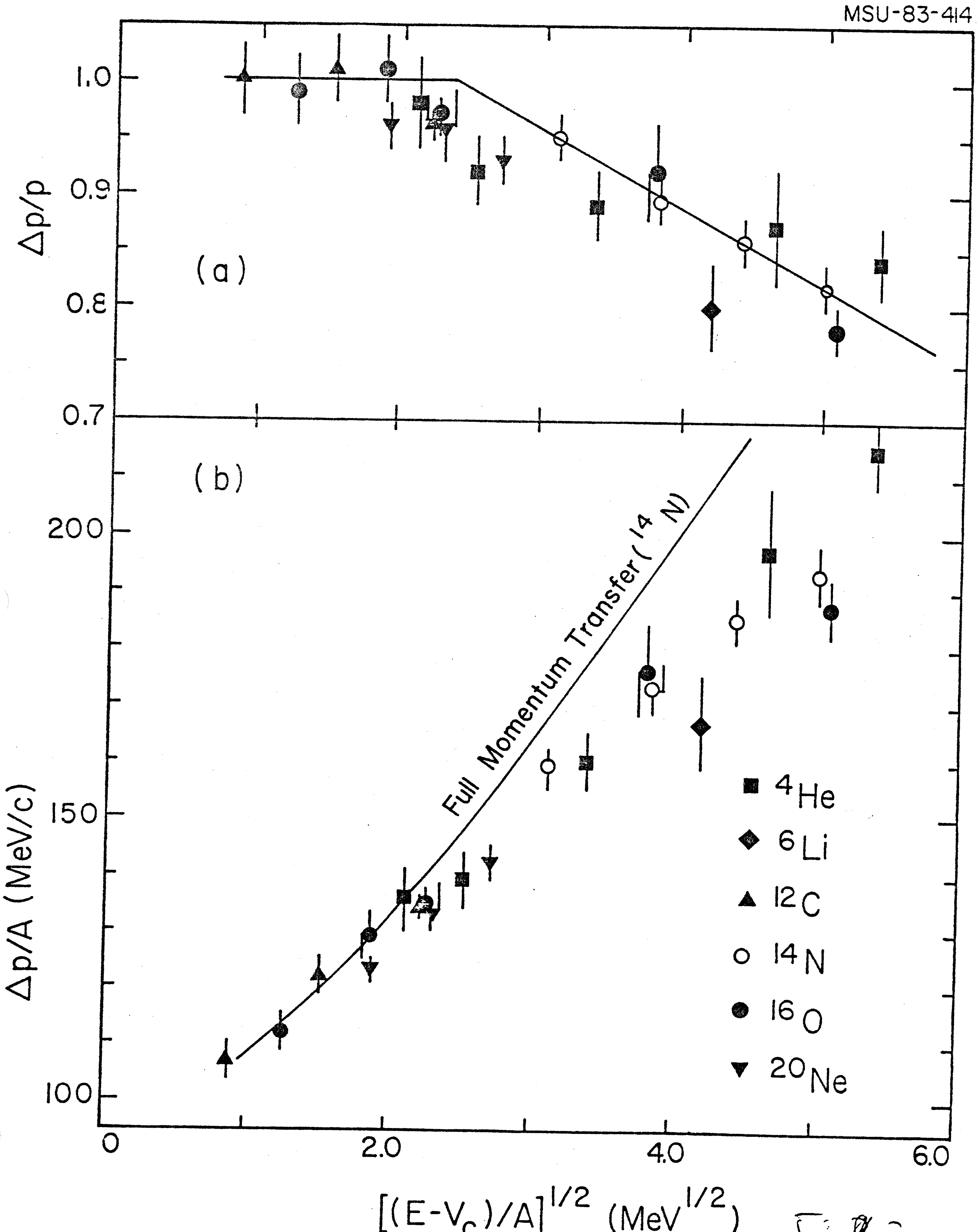

$^{238}U(^{14}N,f)$
30MeV/A
25 MeV/A
20MeV/A
15 MeV/A
FWHM=11.5±.5°
FWHM=10.3±.5°
FWHM=8.5±.5°
FWHM =7.5±.5°
Δp/p
COUNTS
(dσ/dΩdθ)(mb/sr·deg)
ΔΦ(deg)
$\theta_A+\theta_B$ (deg)
Δφ (deg)

Fig 1



MSU-83-414
1.0
0.9
0.8
0.7
Δp/p
(a)
(b)
Full Momentum Transfer (^{14}N)
200
150
100
Δp/A (MeV/c)
0
2.0
4.0
6.0
$[(E-V_c)/A]^{1/2}$ (MeV$^{1/2}$)
^{4}He
^{6}Li
^{12}C
^{14}N
^{16}O
^{20}Ne

Fig 2

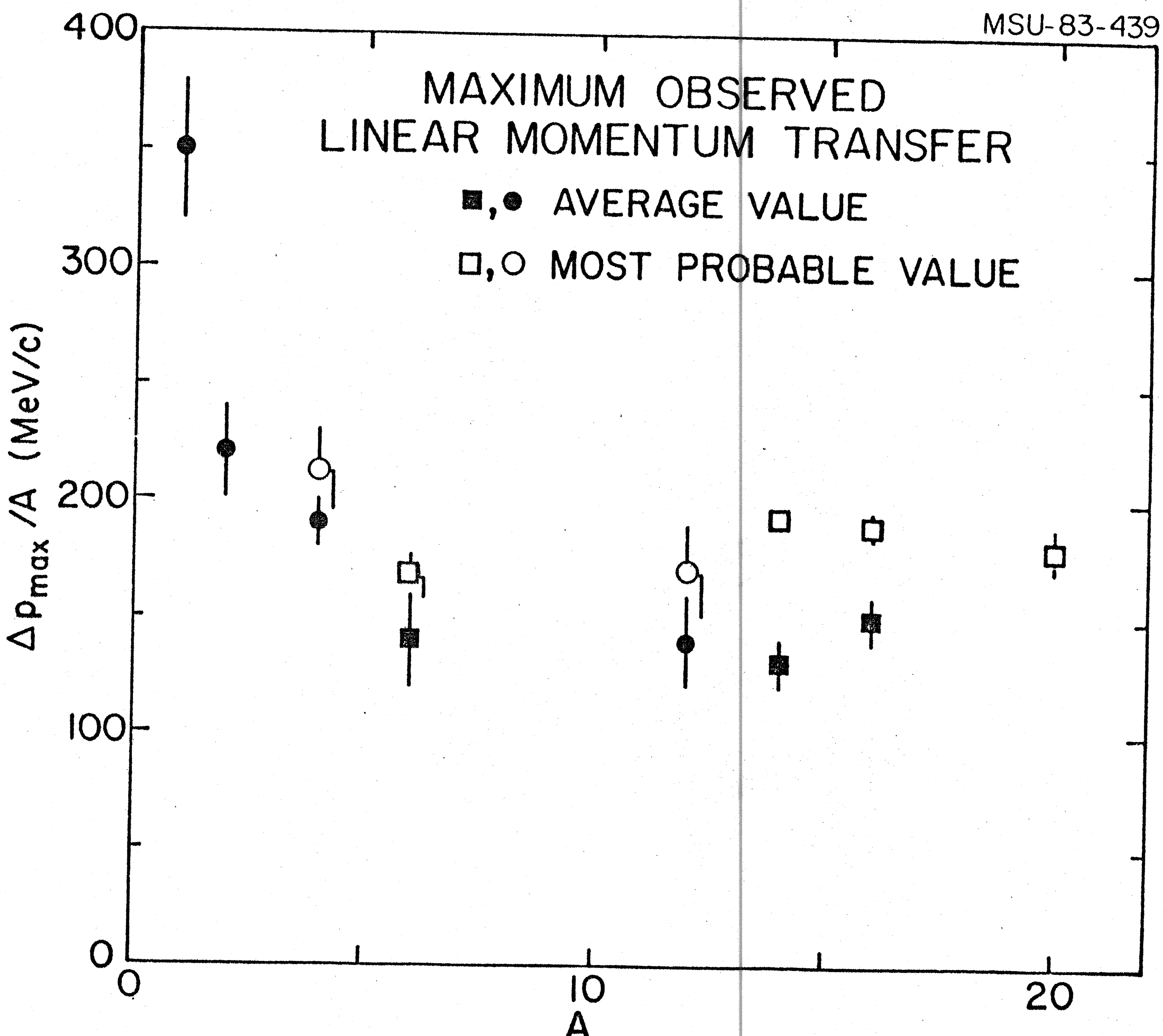

MSU-83-439
MAXIMUM OBSERVED
LINEAR MOMENTUM TRANSFER
■,● AVERAGE VALUE
□,○ MOST PROBABLE VALUE
Δp_max /A (MeV/c)
400
300
200
100
0
0
10
20
A

Fig 3