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STUDIES OF THE $^{32}S + ^{182}W$ REACTION

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Fission-like products from the reaction $^{32}S+^{182}W$ were measured over the entire angular range from theta=10-170° and for bombarding energies of E_{lab}=166, 177, 222, and 260 MeV using an array of eight Si detectors. From the measured energy and flight time the product mass was determined event-by-event by performing the appropriate corrections for the plasma delay and pulse height defect associated with Si detectors. The mass ,angular, and total kinetic energy distributions of fission-like fragments are obtained by assuming two-body kinematics. The angular distributions indicate that a fraction of the observed cross section is associated with quasi-fission reactions as observed previously in several other reactions involving ^{32}S projectiles[1]. Furthermore, we observe an angular dependence of the fragment mass distributions, a feature which is strictly incompatible with compound nucleus decay. Both of these observations indicate that a fraction of fission-like products originate from quasi-fission, a process in which a large degree of mass transfer occurs between the two interaction nuclei in a short time scale[2].

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I. INTRODUCTION

In reactions between heavy ion beams and targets of ^{208}Pb and heavier nuclei it has been found that a significant fraction of the fission-like products originate from a quasi-fission reaction[1,2]. This reaction channel is intermediate between the fission decay of completely fused systems and the deeply inelastic scattering process, which may be characterized by a large degree of dissipation of the kinetic energy without any significant change in the mass asymmetry. The quasifission process is characterized by complete kinetic energy damping (i.e. the fragments emerge with coulomb repulsion energies irrespective of the bombarding energy) but with a substantial or even complete relaxation of the mass asymmetry degree of freedom. Several experimental signatures of the quasifission process have been identified. Among these are the observation of cross section for fission-like products of a magnitude which requires contributions from angular momentum states beyond the limit for stability estimated in the Rotating Liquid Drop Model[3]. Such products were also observed to have abnormally wide mass distributions as compared to the expectations for fission from compound systems[4]. The observation of angular anisotropies of fission-like fragments, which are larger than expected on the basis of the standard transition state fission theory[5,6], as well as the direct observation of angle dependent mass distributions[2,7] have been interpreted as evidence for a separate quasifission channel for the interaction between heavy ions and heavy targets. In the present work, we have studied the reaction products from the $^{32}S + {}^{182}W$ system with special emphasis on the quasifission process. Measurements of the distributions of fragment masses, angular distributions and cross sections were carried out. The results are interpreted in terms of a contribution of quasifission products to the total fission-like yield.

II. EXPERIMENTAL ARRANGEMENT AND DATA ANALYSIS

Reaction products from the interaction between the ^{32}S beam and the ^{182}W target were measured over the angular range from theta=10-170° in 5° steps. Measurements were performed at beam energies of E_{lab}=166, 177, 222, and 260 MeV with beams obtained from the Argonne Superconducting linac. The target consisted of a 175 mug/cm^2 thick layer of metallic W, which was deposited by electron gun bombardment onto a 25mug/cm^2 carbon backing foil. The target was placed such that the carbon backing faced downstream, enabling the slow moving fragments emerging at backward angles to escape from the target with a minimum energy loss. The reaction products were detected in eight 400 mm^2 Si detectors, with four detectors placed at 20° intervals in two opposite quadrants. The distance from the target to the detector surfaces ranged from 40 cm to 53 cm, and the solid angle of individual detectors ranged from 1.0 to 2.4 msr. A monitor detector was placed at 20° on the opposite side of the beam from the forward detectors. This detector was used for the normalization of the cross section by measuring elastically scattered particles at this angle. The time structure of the beam, which has a repetition period of 82.474 ns and a time resolution of about 300 ps, was used as a start signal in a time-of-flight measurement of the velocity of the reaction products. In conjunction with the energy measurement obtained from Si-detectors this feature allows for a determination of product masses. This experimental arrangement facilitates the measurement of single fragments of masses including the target and projectile and energies large enough to emerge from the target and produce a detectable signal in the surface barrier Si detectors.

The masses of the detected fragments were obtained from the measured energy and time-of-flight after correcting for the pulse height defect[8] of the

energy signal and the plasma delay of the time signal. It was assumed that the plasma delay was linear with fragment mass, the mass dependence being calibrated from the observed elestic recoils. The primary masses were obtained by correcting for the the post-scission evaporation of neutrons.

III. ANGULAR DISTRIBUTION OF FISSION-LIKE PRODUCTS

As shown in the example displayed in Fig. 1, the fission-like products are well separated from partially damped scattering processes. This is the case at all the energies and angles studied the present experiment. The differential cross section for such fission-like products is therefore easily obtained by normalizing to the Rutherford scattering cross section detected in the monitor. The transformation to the center-of-mass system is carried out under the assumption of symmetric mass split with kinetic energies according to the Viola systematics[9], which accounts for the measured average fission-like total kinetic energies very well. Angular distributions of fission-like fragments are shown for four beam energies in Fig. 2. The data are represented by solid points with error bars, which represent both statictical errors and estimated systematic errors. This latter contribution to the experimental uncertaincy arises from the fact that only a fraction of the mass distribution was observed at angles near 90°, where large energy losses in the target material resulted in less than 100% detection efficiencies for the heaviest fragments. The solid curves represent the best fits to the data using the standard formula

$$W(\theta) \propto \sum_{I=o}^{\infty} (2I+1)T_I \frac{\sum_{K=-I}^{\frac{I}{2}} e^{-\frac{K^2}{2K_o^2}} |d_{oK}(\theta)|^2}{\sum_{K=-I}^{I} e^{-K^2/2K_o^2}} \qquad (1)$$

Here, I, is the total angular momentum of the system, K its projection onto the separation axis, K_o is the variance of the K-distribution, assumed to be gaussian, $(2I+1)T_I$ represents the partial wave distribution, and $d_{0,K}^{I}(0)$ is the theta-dependent part of the symmetric top wave function (the function). The distribution of partial waves leading to fission-like processes is obtained from calculations which reproduce the excitation function of the angle integrated cross sections. The model used in these calculations is described in detail in Ref. 1. The parameters used in the present case are $\Delta 2=0.50$ and $\sigma 2=0.02$. This choice of parameters give a good reproduction of the near and subbarrier cross section lending credence to the associated spin-distributions. The variance, K_o^2 is varied to obtain the best fit to each angular distribution by minimizing χ^2. We observe that the functional form of eq. 1 provides an excellent description of the experimental data. In addition to the present data we also analyze previous data for the same system measured by Glagola et al.[10] at energies of E_{lab} = 170, 180, 200, 210, 220, and 240 MeV. The resulting values are listed together with other relevant parameters in Table 1 and plotted in Fig. 3 (solid points) as a function of mean spin square (I^2) of the partial wave distribution.

The experimental data are compared with the predictions of the Transition State Model. In this model it is assumed that the K-distribution is determined at the fission saddle point, which represents the point of lowest temperature and consequently the lowest level density on the path to fission. A simple argument based on level density statistics[11] leads to a gaussian K-distribution as used in eq. 1 with a variance of

$$K_o^2 = T^* J_{eff} \hbar^2, \qquad (2)$$

where J_{eff} is the effective moment of inertia for generating axial spin components at the saddle point and T is the nuclear temperature at the saddle point. The quantity, J_{eff}, is related to the moments of inertia for rotations parallel, $J_{\parallel}$, and perpendicular, $J_{|}$, to the nuclear symmetry axis by

$$1/J_{eff} = 1/J_{\parallel} - 1/J_{|}. \qquad (3)$$

The K_o^2 values obtained from the experimental data are compared to the Saddle Point Model using two different predictions of the saddle point shapes. The solid curve in Fig. 3 is based on the prediction of the Rotating Liquid Drop Model[12], whereas the dashed curve is obtained by using the saddle point shapes of the Finite Nuclear Range Model[13]. We observe that the experimental values of K_o^2 fall below the predictions of both of these models. Note that this discrepancy is present also for data points with a spin squared value of $(I^2) < 2500\ \hbar^2$. Above this value the upper tail of the partial wave distribution exceeds the angular momentum, $l_{Bf=0} = 65 - 69\ \hbar$, where the fission barrier vanishes. In an earlier comprehensive study[1] it has been shown that the angular distributions from a system with similar fission properties, namely $^{19}F + {}^{208}Pb$, are well described by the predictions of the Saddle Point Model. We therefore conclude that the deviations from the predictions of the Saddle Point Model observed in the present system arises from a contribution of quasifission processes, which bypasses the step of compound nucleus formation and the subsequent fission decay over the saddle point. In order to test this conclusion, which is based on a quantitative comparison of the measured fission fragment angular anisotropies with the predictions of the Saddle Point Model, we study also the fragment mass distributions over the entire angular range. These are discussed in the following subsection.

V. MASS DISTRIBUTIONS - ANGULAR DEPENDENCE

For a binary decay, such as fission, of a compound system we expect a very specific characteristics. These include forward-backward symmetry in the angular distribution of fragments with a specific mass as well as reflection symmetry of the mass distribution with respect to half the total mass of the system, at any center-of-mass scattering angle. We may express these conditions as follows

$$\sigma(A,\theta) = \sigma(A,\pi-\theta) \tag{4}$$

$$\sigma(A,\theta) = \sigma(A_{tot}-A,\theta)$$

These symmetries are consequences of the assumption of independence of formation and decay for a compound nucleus, i.e. only constants of motions such as the total angular momentum vector I are preserved during the process.

For binary reactions, in general, we note that the following subset of symmetries apply

$$\sigma(A,\theta) = \sigma(A_{tot}-A,\pi-\theta) \tag{5}$$

This condition simply states that e.g. a heavy reaction product observed at a forward angle has a light reaction partner emitted at the complementary angle in the center-of-mass system.

The centroids of the mass distributions of fission-like fragments are shown as a function of the center-of-mass scattering angle in Fig. 4. We note that for the two lowest energies, namely E_{lab}= 166 and 177 MeV the mass

centroids are constant at the symmetric mass of A = 107 u as a function of center-of-mass angle as expected for compound nucleus fission, see Eq. 4. At the two higher beam energies E_{lab} = 222 and 260 MeV we observe, however, a significant angular dependence of the mass centroids. This angle dependence is direct evidence for a contribution from non-compound nucleus reactions to the fission-like processes. A fraction of the observed products must come from reactions in which the intermediate complex rotates less than one revolution while undergoing complete damping of the kinetic energy and an incomplete relaxation in the mass asymmetry degree of freedom. Such a process bears the characteristics expected for the quasi-fission process[14] and we observe that the mass distributions confirm the conclusions obtained from the analysis of the angular distributions, namely that the observed fission-like products contain a component of quasi-fission products in addition to the normal fission products originating from the decay of the ^{214}Th nucleus formed by complete fusion of the ^{32}S beam and the ^{182}W target.

VI. CONCLUSION

Fission-like fragments from the reaction $^{32}S + ^{182}W$ have been studied at beam energies of E_{lab}= 166,177,222,160 MeV. Complete angular distributions were obtained over the angular range θ=10=170°. Fragment mass distributions were also measured over this angular range. From a quantitative analysis of the angular anisotropy in terms of the Saddle Point Model it is concluded that the quasifission process contributes to the fission-like products. This conclusion is strengthened by the angular dependence of the centroids of the mass distribution of fission-like products. This result is model independent and relies only on the assumption of two-body kinematics. The quasi-fission

process, which had earlier been observed only in heavier systems, thus seems to occur also for this lighter system.

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Table 1.: Parameters relevant for the analysis of the fission angular distributions of the $^{32}S + ^{182}W$ reaction.

E_{lab}	S_{fis}	(I_2)	W(0)	K_o^2	T_{Saddle}
(MeV)	(mb)	(h^2)	W(90)	(h^2)	(MeV)
166	180 + 20	1350	4.10	88 + 24	1.42
170	240 + 25	1575	3.78	118 + 42	1.44
177	415 + 40	1850	3.73	144 + 32	1.50
180	440 + 45	1945	4.44	110 + 25	1.55
200	700 + 70	2915	5.64	111 + 32	1.72
210	795 + 80	3380	4.65	186 + 33	1.76
220	950 + 95	4125	5.06	196 + 70	1.82
222	945 + 95	4235	5.03	206 + 49	1.83
240	1135 + 120	5360	4.58	312 + 77	1.92
260	1225 + 125	6065	5.13	288 + 107	2.07

Figure Captions

Fig. 1: Distribution of single fragment masses observed at $\theta=55^{o}$ in the reaction $^{32}S+^{182}W$ at $E_{lab}=222$ MeV after applying the corrections for plasma delay, pulse height defect, energy losses in target, and neutron evaporations.

Fig. 2: Angular distribution of fission-like fragments observed at beam energies of E_{lab} = 166, 177, 222, and 260 MeV. The solid curves represent the best fits to the data using the functional form of Eq. 1.

Fig. 3: Experimental values of K_o^2 (solid points) are plotted as a function of the mean square spin of the fissioning system. Theoretical predictions using the Saddle Point Model are represented by the solid and dashed curves when using the Rotating Liquid Drop Model and the Finite Range Model, respectively. The dot-dashed curve denoted the prediction of the Scission Point Model.

Fig. 4: Centroids of the mass distributions for fission-like products are shown as solid points as a function of center-of-mass angles at four beam energies.

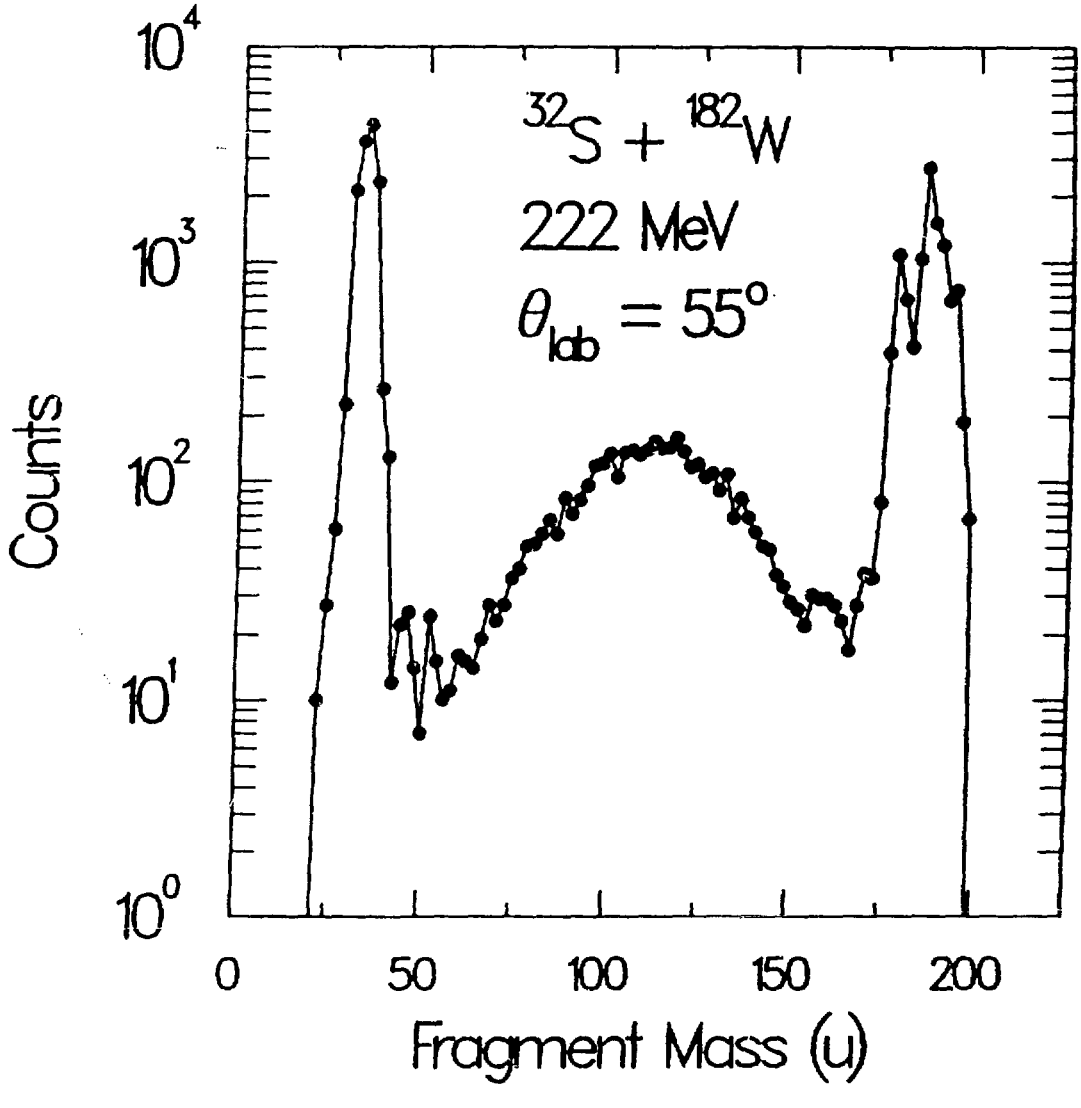
$^{32}S + ^{182}W$
222 MeV
$\theta_{lab} = 55°$
Counts
10^4
10^3
10^2
10^1
10^0
0
50
100
150
200
Fragment Mass (u)

Fig. 1

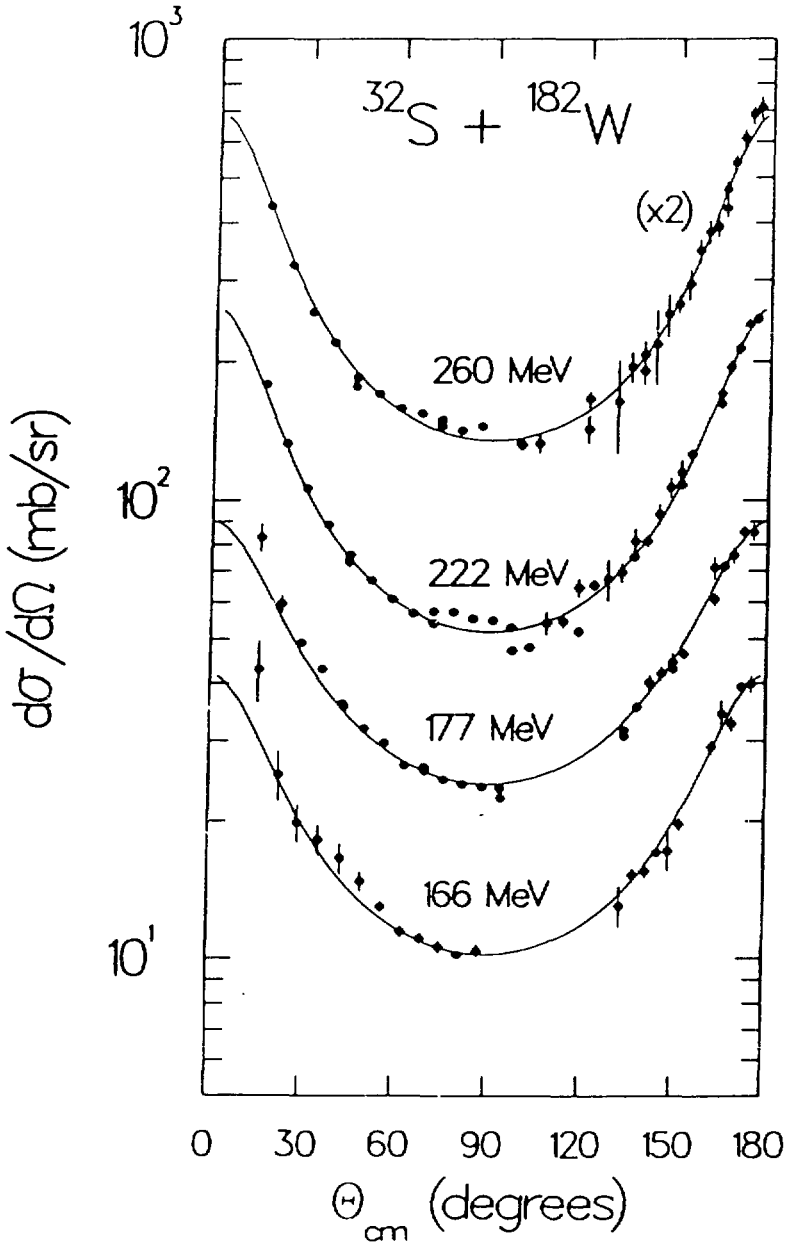
$^{32}S + ^{182}W$
(x2)
260 MeV
222 MeV
177 MeV
166 MeV
10^3
10^2
10^1
$d\sigma/d\Omega$ (mb/sr)
0
30
60
90
120
150
180
Θ_{cm} (degrees)

Fig. 2

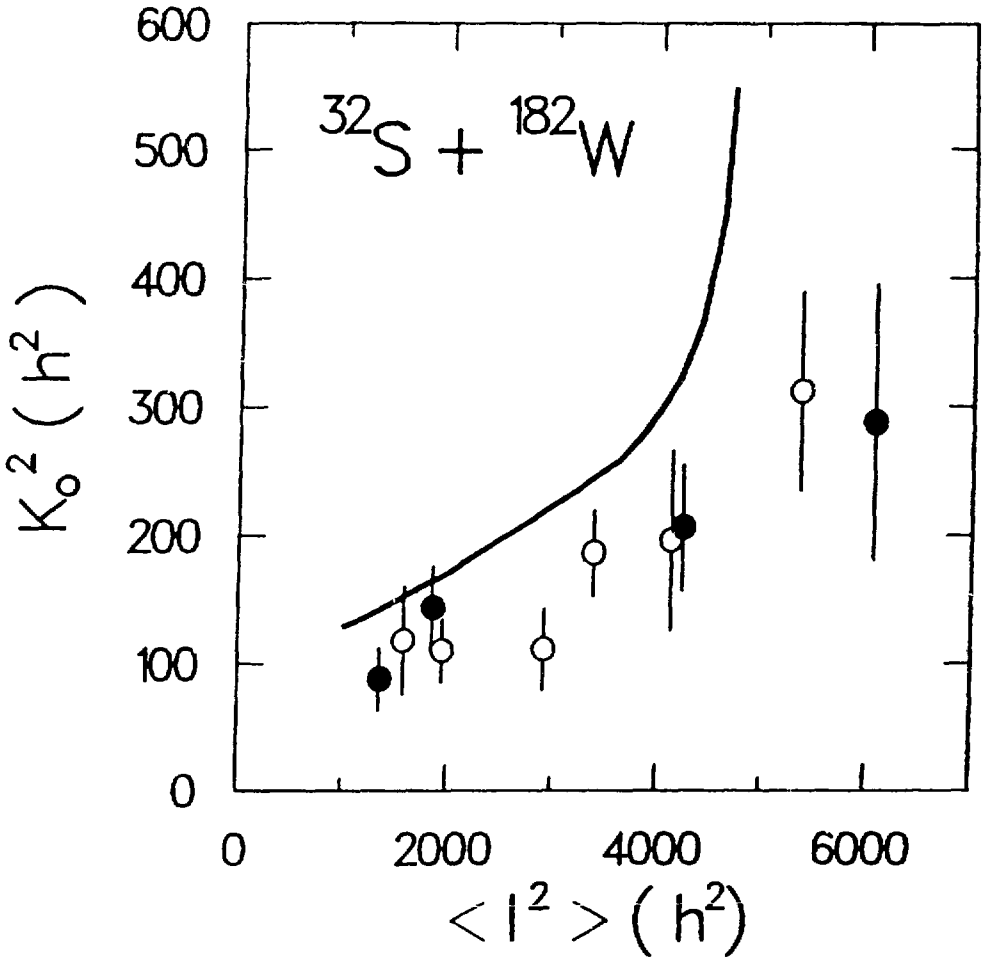

Fig. 3

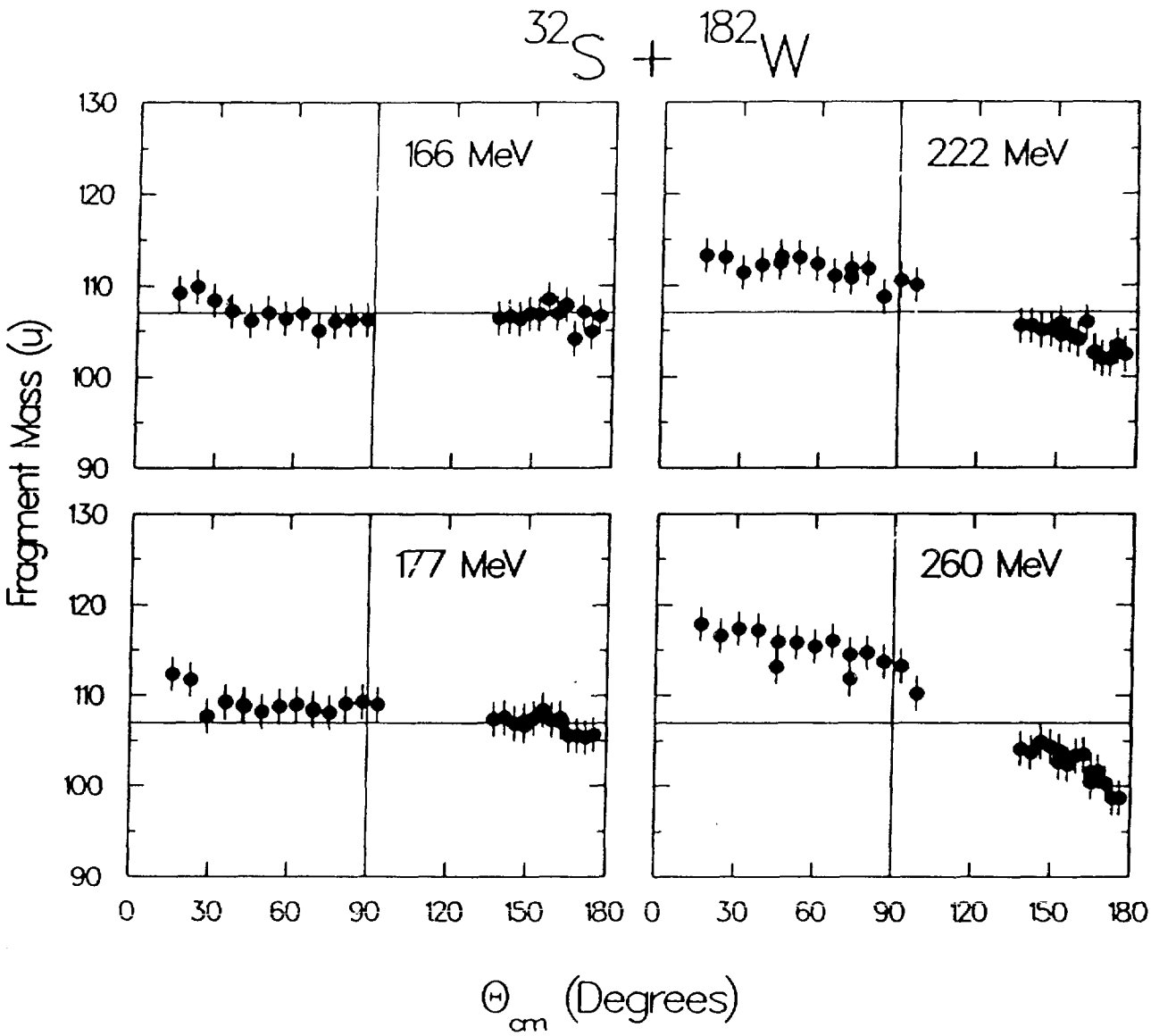
$^{32}S + ^{182}W$
166 MeV
222 MeV
177 MeV
260 MeV
Fragment Mass (u)
130
120
110
100
90
0
30
60
90
120
150
180
Θ_{cm} (Degrees)

Fig. 4