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Fission Fragment Anisotropy in Reactions of 24-MeV ^{2}H and 48-MeV ^{4}He with ^{238}U*

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Abstract

The angular distributions of gross and specific fission fragments from bombardment of ^{238}U by 24-MeV ^{2}H and 48-MeV ^{4}He have been measured. These data are analyzed in terms of the Bohr angular distribution theory and the results are found to be consistent with previous interpretations based on this model. It is found that for 24-MeV ^{2}H bombardment the anisotropy increases with increasing mass ratio of the fragments, whereas, for 48-MeV ^{4}He, the anisotropy is nearly independent of mass ratio. For values of the fissionability parameter x greater than 0.68, the experimentally derived values for the effective moment of inertia are substantially greater than the theoretical predictions of the liquid drop model. The dependence of the effective moment of inertia on angular momentum is found to be small within the range investigated here.

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Introduction

One aspect of charged-particle-induced fission reactions that has received infrequent attention is the dependence of the anisotropy on the mass ratio of the fragments. It has been reported that the anisotropy of the products increases with increasing mass asymmetry for ^{238}U + 22-MeV ^{1}H and ^{232}Th + 45-MeV ^{1}H.[1,2] However, for ^{232}Th + 42-MeV ^{4}He and ^{238}U + 45-MeV ^{1}H the anisotropy is essentially independent of mass ratio.[2,3]

This behavior has been qualitatively explained within the Bohr theory of fission fragment angular distributions,[4] as developed by Halpern and Strutinski,[5] and Griffin.[6,7] According to their predictions, the anisotropy varies directly with square of the angular momentum of the fissioning nucleus and inversely with its nuclear temperature and effective moment of inertia (see Section IV).

The previous experimental results have been explained as follows.[5] Fission products for which the yields increase rapidly with increasing excitation energy (e.g. low energy symmetric fission of uranium) most probably result from fission prior to neutron evaporation; hence, the initial temperature of the compound nucleus is appropriate. For products with yields that are rather insensitive to excitation energy (e.g. asymmetric fission of uranium), a significant fraction of the fission may occur after neutron emission, and thus at relatively low temperature. Applied to the case of medium energy fission of uranium, a larger anisotropy would be expected for the asymmetric fragments because of their lower average T. For fission reactions in which the temperature is in all cases only negligibly decreased by pre-fission neutron emission, or uniformly decreased independent of the final fragment mass, the anisotropy is expected to be the same for all products. The above argument assumes no dependence of the yield mass pattern on angular momentum.

We have extended the investigation of this problem by measuring angular distributions of several products from fission of ^{238}U induced by ^{2}H and ^{4}He. By means of techniques developed in other experiments,[8,9] we were equipped to measure angular distributions with good precision. The techniques included well-standardized chemical procedures[8] plus the use of a chamber for recoil collection that permitted much improved angular resolution compared to previous measurements.[9]

Our results follow the general trends of the previous studies.[1-3] We correlate the various results and discuss the dependence of the effective moment of inertia on angular momentum. A comparison with calculations of the liquid drop model is presented.[10]

Experimental Procedure

Beams of 48-MeV alpha particles and 24-MeV deuterons were accelerated at the Crocker 60" cyclotron. After collimation through three 0.2-inch diameter collimators, the beam was passed into a fission recoil-collection chamber that is described elsewhere.[9] Typical bombarding times were from 8 to 24 hours at beam currents of 0.5 to 1.0 μA.

Targets were prepared by vaporizing 150 to 200 μg/cm^2 of UF_4 onto a nickel backing foil of thickness 220 μg/cm^2. In contrast to previous experiments of this type, these thin targets permitted measurement of the angular distribution in both the forward and backward hemispheres, simultaneously. At angles of less than 60 deg to the target normal, the thickness of such targets is substantially less than the range of the fission fragments.

Catcher foils of 3/4 in. diameter were placed radially 5 inches from the target center at 15° intervals with mean angles at 15° to 90° and from 195° to 270°. The target plane coincided with the 135°-315° diameter. The size of the catcher foils gave a spread of about ± 4° in the width of the collecting angle. For the small anisotropies encountered in these experiments, angular resolution corrections were negligible.

Two types of measurements were performed: (a) gross product studies, and (b) studies of individual products. First, in order to check the reliability of the system, the gross fission fragment angular distribution for 24-MeV deuterons incident on ^{238}U was measured by a differential range technique. The products were stopped in stacks of 0.00025 in. mylar catchers. After the bombardment these catchers were mounted on Al backing plates and the gross beta activity was measured with a group of end window proportional counters. The radiation from each catcher foil was measured systematically with each detector, and from the gross decay data, both the range characteristics and the angular distribution were determined. These experiments revealed the presence of three groups of products: (a) a short-range group observed in the first mylar catcher, (b) the fission products with average range of approximately 2 mg/cm^2 mylar, and (c) ^{11}C, ^{13}N etc. from the activation of the mylar itself (observed only in the forward hemisphere). In subsequent experiments that involved radiochemical processing, a stack of three foils was used (1) a mylar cover which was discarded (2) an Al foil of 0.001 in. which was radio-chemically processed, and (3) an Al guard foil. Previous studies had shown negligible production of the products studied due to activation of impurities in the Al.

The second set of measurements involved separation of the fragments 7.5 day ^{111}Ag, 9.7 hour ^{91}Sr, 12.8 day ^{140}Ba, and 8.1 day ^{131}I. The Al catcher foils were dissolved, inactive carrier was added, and analysis was performed by standard procedures for one or two of the above products. The yields were quite uniform and usually greater than 80 percent. The samples were mounted and the β radiation measured as in the gross experiments. Initial counting rates ranged from about 600 cpm for ^{91}Sr down to 100 cpm for ^{140}Ba.

Due to the high beam intensities and tight collimation required for the experiments, the possibility existed that neutrons from reactions originating in the collimation system might have induced an appreciable amount of fission. This was investigated by focusing a deuteron beam on the chamber and then inserting a $\frac{1}{2}$ inch carbon plug in place of the last collimator. The beam was monitored by means of the comparitive intensities on the second collimator, first with the collimator out, and then with it in. After a representative bombarding time, the foils were counted for gross activity. Only at the extreme forward angles were the counting rates appreciable, and the range characteristics indicated the activity to be the result of activation of the catcher foils by secondary particles. This radioactivity could be removed by chemical processing and therefore did not affect the fission product studies.

Results

Various studies have shown that fission is preceded by full momentum transfer of the projectile to the target nucleus in the reactions considered here.[2,11-12] With this knowledge, the angular distributions in the lab system can be easily transformed into the center of mass system. The transformation parameter η was calculated from the relationship

$$\eta^2 = \frac{E_b A_b A_f}{E_f A_c^2} . \qquad (1)$$

Here, E_b and A_b are the laboratory kinetic energy and mass of the projectile, and A_f and A_c are masses of the fragment and the compound nucleus. The kinetic energy of the fragment in the c.m. system is given by E_f. Values of E_f were obtained in a previous study.[8]

The center-of-mass angular distribution obtained from the measurements of the gross fission products (^{238}U + 24-MeV ^{2}H) is shown in Fig. 1. The angular distribution exhibits symmetry about 90°, and is in good agreement with other measurements of the gross anisotropy for this reaction.[12]

In Figs. 2 and 3 we show the angular distributions for selected fragments from deuteron and alpha fission of uranium respectively. In Fig. 2 the discrepancy between measurements at forward angles and those at backward angles for ^{111}Ag and ^{140}Ba is attributed to an error in target positioning. In the subsequent experiments this error was removed and no such discrepancy was observed. We conclude that the average of the results at forward and backward angles gives a good representation of the angular distributions.

Our experimental results are summarized in Fig. 4 where the anisotropy (i.e., the differential cross section at 0° divided by that at 90°) is plotted against the mass ratio (M_H/M_L). Also shown here are similar data for 22-MeV proton bombardment of ^{238}U measured by Cohen, et al.[1] The ratio M_H/H_L represents the masses of the fragments before neutron emission.

For 48-MeV ^{4}He bombardments, it is observed that the anisotropy is very nearly independent of mass ratio. In the case of 24-MeV deuterons, on the other hand, there appears to be an increase in anisotropy with increasing mass-ratio similar to that observed by Cohen for ^{238}U + 22 MeV ^{1}H.[1]

Discussion

Theoretical description of the angular distribution of fission fragments involves summation over the angular momentum states which describe the orientation of the fissioning nucleus in space, usually with respect to a beam axis.[7] These states are described by (1) the total angular momentum vector I of the fissioning nucleus, arising from the coupling of the target spin I_o, projectile spin S, and orbital angular momentum generated in the reaction ℓ, and (2) the projection of I on an assumed nuclear symmetry axis K. For reactions where the most probable value of ℓ is large ($\langle \ell \rangle \sim 8$), one can take I to be approximately equal to ℓ and replace the sums by integrals.[5-6] This treatment characterizes the anisotropy by the parameter p which is given by

$$p = \frac{\hbar^2 \langle I^2 \rangle}{2 K_o^2} \approx \frac{\hbar^2 \langle \ell^2 \rangle}{2 K_o^2} . \qquad (2)$$

The quantity K_o^2 is the mean square value of the quantum number K. It is related to the effective moment of inertia $\mathfrak{J}_{eff}$ of a nucleus of cylindrical symmetry as follows:

$$K_0^{\,2} = T\mathcal{J}_{eff} = T\left(\frac{\mathcal{J}_{\parallel}\ \mathcal{J}_{\perp}}{\mathcal{J}_{\perp} - \mathcal{J}_{\parallel}}\right) \tag{3}$$

where $\mathcal{J}_{\parallel}$ and $\mathcal{J}_{\perp}$ denote moments of inertia about axes parallel and perpendicular to the symmetry axis. The temperature T of the fissile nucleus is given approximately as

$$T = \left[(E^* - E_{rot} - E_{th})/a_f\right]^{\frac{1}{2}} \tag{4}$$

where E*, E_{rot}, and E_{th} are the excitation, rotational, and fission threshold energies respectively, and a_f is the corresponding nuclear level density parameter. The experimental angular distributions fix the value of p, and Eqs. (2, 3 and 4) are employed to gain information about the fissile nuclei.

It is clear that our experimental results, even when supplemented by many other studies, cannot test the separate effect of I, T and $\mathcal{J}_{eff}$ on fission anisotropy. We must make certain assumptions before the theoretical framework can be used. From our results and those of others using protons and heavy ions[1-2,9], we attempt to estimate the dependence of $\mathcal{J}_{eff}$ on Z^2/A and angular momentum. In making these estimates we use angular distribution data from several reactions leading to fissile nuclei with almost identical values of Z^2/A. We use calculated values of T and $\langle I^2 \rangle$ along with Eqs. (2 and 3) to estimate $\mathcal{J}_{eff}$. The implicit assumption is that E* is the only quantity that is related to the mass of the final product. In other words, we assume that the angular distributions are "decided independent of the mass distributions".

In the calculation of T we must insert a value of the excitation energy (E*) of the fissile nucleus.[14] Therefore, we must consider the competition between fission and neutron emission. Since T is proportional to $(E^* - E_{rot} - E_{th})^{\frac{1}{2}}$, this problem is most important at lower values of E*. For ^1H, ^2H, and ^4He we consider only the anisotropies of the near symmetric products (Ag). This is because the probability of symmetric fission decreases so rapidly with decreasing E*, we are justified in assuming no neutron emission before fission. For systems at high E* (^{12}C and ^{16}O)[9], we also assume "first chance" fission because even a rather large error in E* will not cause much error in T. Recent calculations by Plasil[21] also indicate this is probably a good assumption.

Values of E_{th} were calculated from Huizenga, et al.[15], and E_{rot} was taken as $\hbar^2\langle I^2\rangle/2\mathcal{J}_o$ where $\mathcal{J}_o$ is the moment of inertia of a rigid sphere of radius $1.2A^{1/3}$ F. The fission level density parameter a_f was taken to be A/8 MeV^{-1}.[15] Errors in T stemming from the possibility that E_{th} may decrease for large angular momentum are small because $E^* \gg E_{th}$ for such systems.

As a test of these assumptions, we may cite the results of the mass ratio dependence of the anisotropy (see Fig. 4 and Ref. 2). For fission of ^{238}U with 22-MeV ^1H or 24-MeV ^2H the anisotropies for asymmetric products appear to be greater than those for symmetric products. This effect has been attributed to the lower E* values for asymmetric fission due to neutron emission before fission. For fission induced by ^{1}H or ^{4}He at higher energies this effect is much smaller presumably because changes in E* lead to a much smaller change in T. Hence, our results substantiate previous observations. It should be pointed out, however, that an increase in Γ_n/Γ_f will also lower T, so that for less fissionable nuclei, the anisotropy will not become independent of mass ratio until higher values of E* are reached (e.g. ^{232}Th + 45-MeV p, Ref. 2). The magnitude of the experimental errors, as well as insufficient information about Γ_n/Γ_f as a function of mass division, preclude a more quantitative discussion of the mass ratio dependence for $^{238}U + {}^{1}H$ or ^{2}H.

In calculating $\langle I^2 \rangle$, we usually make the approximation that $\langle I^2 \rangle$ can be replaced by $\langle \ell^2 \rangle$. The validity of this approximation has been checked by carying out the exact summations over ℓ and S prescribed by Griffin in Ref. 7. Only for the cases 22-MeV ^{1}H + ^{238}U and 24-MeV $^{2}H + {}^{238}U$ is a difference observed. In subsequent calculations the results of the summations are used for these two systems. For the remaining systems, we use

$$\langle I^2 \rangle \approx \langle \ell^2 \rangle = \sum_{\ell=0}^{\ell} \ell^2 (2\ \ell + 1)\ T_\ell \Big/ \sum_{\ell=0}^{\ell} (2\ell + 1)\ T_\ell\ . \qquad (5)$$

The transmission coefficients T_ℓ were calculated from the optical model for ^{1}H, ^{2}H and ^{4}He, and a parabolic potential was used for

^{12}C and ^{16}O (see Table I for parameters). We do not expect the values of $\langle \ell^2 \rangle$ to be very sensitive to the model chosen for heavy ions.

These values of $\langle \ell^2 \rangle$ can be identified with $\langle I^2 \rangle$ of the fissile nuclei only if (a) compound nucleus formation (total momentum and energy transfer) precedes all fission events, and (b) the fission cross section is equal to the total reaction cross section. Angular correlation studies and analysis of the angular distribution symmetry have shown that the first condition is satisfied for all reactions considered here.[2,11,16] Agreement between the measured fission cross sections and the calculated total reaction cross section gives evidence that the second condition is very nearly satisfied for ^{1}H and ^{4}He.[17] Direct reactions between ^{238}U and various projectiles at ~10 MeV/nucleon account for 11% of the total reaction cross section for ^{2}H,[18] 14.5% for ^{12}C,[19] and 25% for ^{16}O.[19] We assume these effects to be the same with ^{209}Bi as a target and correct the calculated values of $\langle \ell^2 \rangle$ for these reactions, with the assumption that direct interactions at the nuclear surface consume the highest possible ℓ-waves. This correction is described in more detail in Ref. 19.

In Table I we list the values of the various parameters used in the calculations and the resulting values of the effective moment of inertia divided by the rigid body moment ($\mathcal{J}_{eff}/\mathcal{J}_0$). These values are shown as a function of $x = (Z^2/A)/50.13$ in Fig. 5 and agree well with similar results measured by Chaudhry, et al.[20] Liquid drop model calculations of $\mathcal{J}_{eff}/\mathcal{J}_o$ by Cohen and Swiatecki are also plotted as a continuous curve in Fig. 5.[10] Our experimental points deviate substantially from the liquid drop values, although the trend is in the same direction. As x decreases, experiment and theory appear to converge. The liquid drop saddle shapes undergo rapid deformation near $x \sim 0.67$, and as a result, Cohen and Swiatecki predict the nature of fission should differ markedly across this region. The trend of the data may be a reflection of this difference.

Fig. 6 shows the ratio of the experimental to theoretical effective moment of inertia as a function of $\langle \ell^2 \rangle$ for $x \sim 0.72$. We observe this ratio to be on the average about 60 percent greater than unity and to be essentially independent of $\langle \ell^2 \rangle$. The deviation from unity may possibly be explained by the choice of parameters (e.g. $a_f = A/8\ \text{MeV}^{-1}$). Preliminary calculations of the effect of rotational energy on liquid drop shapes, carried out by Plasil[21] indicate that $\mathcal{J}_{eff}/\mathcal{J}_o$ should increase with angular momentum. However, this increase is significant only for very large angular momentum. For $x \sim 0.72$, theory predicts an 8% increase in $\mathcal{J}_{eff}/\mathcal{J}_o$ between $\langle \ell^2 \rangle =$ 0 and 2800, the range of values studied here. The data of Fig. 6 are consistent with such behavior.

It should not be concluded that the near independence of $\mathcal{J}_{eff}/\mathcal{J}_o$ on $\langle \ell^2 \rangle$ means that the shape of the nucleus at the saddle point is constant. In no sense does $\mathcal{J}_{eff}/\mathcal{J}_o$ fix the shape of the nucleus; it only permits one to compare with shapes predicted by a given nuclear model. Hence, arguments concerning the distortions created by rotational and vibrational forces set up within the nucleus under the influence of angular momentum and excitation energy are not altered by our data.

One further consequence of the experimental dependence of $\mathcal{J}_{eff}/\mathcal{J}_o$ on x should be noted. This regards the "target spin anomaly" in the Bohr angular distribution theory. Specifically, it is observed that the anisotropy from 1-5 MeV neutron induced fission of ^{235}U ($I_o = 7/2$) is greater than that from fission ^{240}Pu ($I_o = \frac{1}{2}$). Theory predicts lower anistropy for high spin targets at the same angular momentum and excitation energy. This effect has been discussed by Leachman and Sanmann[22] using liquid drop values of $\mathcal{J}_{eff}/\mathcal{J}_o$.

Examination of the results in Fig. 5 indicate that the ^{235}U - ^{239}Pu comparison is not a good test of the theory because $\mathcal{J}_{eff}/\mathcal{J}_o$ increases about 25% between these two nuclei ($\Delta x \sim 0.02$). If one inserts these values into the theory, making consistent assumptions about nuclear temperature, it is observed that the experimental anisotropies are reproduced within the limits of error. Such a calculation is discussed in Appendix I. From the results of these considerations, it appears that the "target spin anomaly" arises in part from the rapid change in $\mathcal{J}_{eff}/\mathcal{J}_o$ that occurs in the region $x \sim 0.70$.

To summarize this study, we have extended the previously reported information on the angular distributions of fission products. From our work and that of others, it appears that the effective moment of inertia for fissile nuclei of $x \approx 0.72$ is essentially independent of angular momentum between $\langle \ell^2 \rangle \cong 0$ and 2800. Our results compare well with a plot of $\mathcal{J}_{eff}$ versus Z^2/A presented by Huizenga, et al.[20] Further, they indicate that the "target spin anomaly" in the Bohr fission theory probably does not exist.

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Figure Captions

Fig. 1 Center of mass angular distribution for gross products from 24-MeV ^{2}H bombardment of ^{238}U. (□ - backward hemisphere; o - forward hemisphere).

Fig. 2 Center of mass angular distributions for various products from 24-MeV ^{2}H bombardment of ^{238}U. Symbols are as in Fig. 1.

Fig. 3 Center of mass angular distributions for various products from 48-MeV ^{4}He bombardment of ^{238}U. Symbols are as in Fig. 1.

Fig. 4 Anisotropy $[\sigma(0^{\circ})/\sigma(90^{\circ})]$ as a function of mass ratio (M_H/M_L) for ^{238}U bombarded with 22-MeV ^{1}H - ⊡; 24-MeV ^{2}H - ⊙ ; and 48-MeV ^{4}He - o.

Fig. 5 Effective moment of inertia $\mathfrak{J}_{eff}$ divided by the rigid sphere moment $\mathfrak{J}_0$ as a function of the fissionability parameter x. Symbols are as follows: this work - o; Ref. 20 - Δ; Ref. 1 - ◊ ; Ref. 2 - ▽ ; Ref. 9 - □. The dashed curve represents the experimental points; the solid curve is from the liquid drop model (Ref. 10).

Fig. 6 The ratio of the experimental $\mathfrak{J}_{eff}$ to the liquid drop value (Ref. 21) is a function of average angular momentum $\langle \ell^2 \rangle$. Solid line represents theoretical value for angular momentum dependent $\mathfrak{J}_{eff}$ divided by $\mathfrak{J}_{eff}$ for case of no angular momentum with x = 0.72.

Fig. 7 Plot of anisotropy versus neutron energy for bombardment of ^{239}Pu, ^{237}Np, ^{233}U, ^{235}U and ^{238}U with low energy neutrons. The data are those of Ref. 26 - o and Ref. 27 - o. The solid curve assumes fission independent of angular momentum and the dashed curve assumes fission occurs from the highest possible ℓ-waves.

Table I Parameters involved in analysis of angular distribution data and results for $\mathcal{J}_{eff}/\mathcal{J}_o$. The quoted values for $\mathcal{J}_{eff}/\mathcal{J}_o$ obtained from 22-MeV ^1H and 24-MeV ^2H bombardments were derived using power series expansion of Ref. 7.

Table I

			$\frac{(Z^2/A)}{50.13}$	$\langle \ell^2 \rangle$	E* (MeV)	E_{rot} (MeV)	E_{th} (MeV)	Psym.	$\mathcal{J}_{eff}/\mathcal{J}_o$
22 MeV	p+	^{238}U	0.722	20.7[a]	27.2	0.1	6.4	0.15 ± 0.05	$0.72 {+0.36 \atop -0.19}$
45 MeV	p+	^{238}U	0.722	79.0[a]	50.1	0.4	6.4	0.26 ± 0.04	$0.97 {+0.18 \atop -0.12}$
24 MeV	d+	^{238}U	0.719	61.0[b]	32.0	0.3	7.9	0.30 ± 0.06	$0.90 {+0.21 \atop -0.17}$
48 MeV	He^4+	^{238}U	0.728	276[b]	42.2	1.1	4.9	0.94 ± 0.06	1.02 ± 0.07
125 MeV	C^{12}+	^{209}Bi	0.717	1765[c]	85.0	8.0	6.6	5.3 ± 0.3	0.91 ± 0.06
166 MeV	O^{16}+	^{209}Bi	0.734	2768[c]	107	12.0	5.0	6.0 ± 0.3	1.09 ± 0.06

a Optical model calculations of B. Wilkins, Lawrence Radiation Laboratory, private communication. The parameters were: V = -54 MeV and W = -9 MeV for the respective real and imaginary parts of the nuclear potential, r_o = 1.30 F for the nuclear radius, and a = b = 0.52 F for the real and imaginary potential diffuseness parameters.

b Optical model calculations of J. R. Huizenga, Argonne National Laboratory, Argonne, Illinois; private communication. The nuclear parameters for the deuterons were: V = -57.2 MeV, W = -9 MeV, r_o = 1.40 F, and a = 0.63 F. Those for ^4He are based on J. R. Huizenga and G. Igo, Nuclear Physics 29, 462 (1962).

c Calculations based on the parabolic approximation to the diffuse nuclear potential, described by T. D. Thomas, Phys. Rev. 116, 703 (1959), using parameters derived for ^{238}U by V. E. Viola, Jr. and T. Sikkeland, Phys. Rev. 128, 767 (1962).

UCRL-10686

Appendix I

In order to investigate the dependence of the anisotropy on target spin it is convenient to consider fission induced by low energy (1-5 MeV) neutrons. The analysis of such compound systems is quite complicated due to difficulties in defining quantities such as the nuclear temperature and moment of inertia as well as knowing the energy gap parameter applicable to the fissioning states of such nuclei.

We have performed an approximate calculation based in part on superconductivity considerations and using experimental values of $\mathcal{J}_{eff}/\mathcal{J}_o$ derived in this work. The theoretical anisotropies have been calculated according to Ref. 7 using optical model transmission coefficients[24] under two extreme assumptions about the ℓ-dependence of fissionability: (1) that fission occurs with equal probability from all ℓ-waves, and (2) that fission results only from the highest possible ℓ-waves. Neutron fission cross sections were taken from Ref. 25 and the compound nucleus cross section was based on Ref. 24.

The nuclear temperature is defined by

$$E_f^* = \frac{1}{8} T^2 - T$$

where

$$E_f^* = E^* - E_f - \epsilon\Delta_f .$$

The gap parameter Δ was arbitrarily taken to be 1.0 MeV and $\epsilon = 1$ for e-e; 0 for e-o and o-e; and -1 for o-o nuclei. The reduction of the rigid body moment of inertia due to pairing effects at low energies was calculated according to the pairing model of Lang.[23] In general, for these excitations $\mathcal{J} \sim \frac{1}{2} \mathcal{J}_0$.

The results of these calculations are compared with the data[26-27] in Fig. 7. It is observed that the experimental data are well bracketed by the theoretical curves representing the two assumptions regarding fissionability as a function of angular momentum. Hence, within the limitations of this model, the so-called "anomaly" in the Bohr theory of fission anisotropies is not apparent if one includes the experimentally derived differences in $\mathcal{J}_{eff}/\mathcal{J}_0$ with nuclear species, and permits ℓ-dependent fission.

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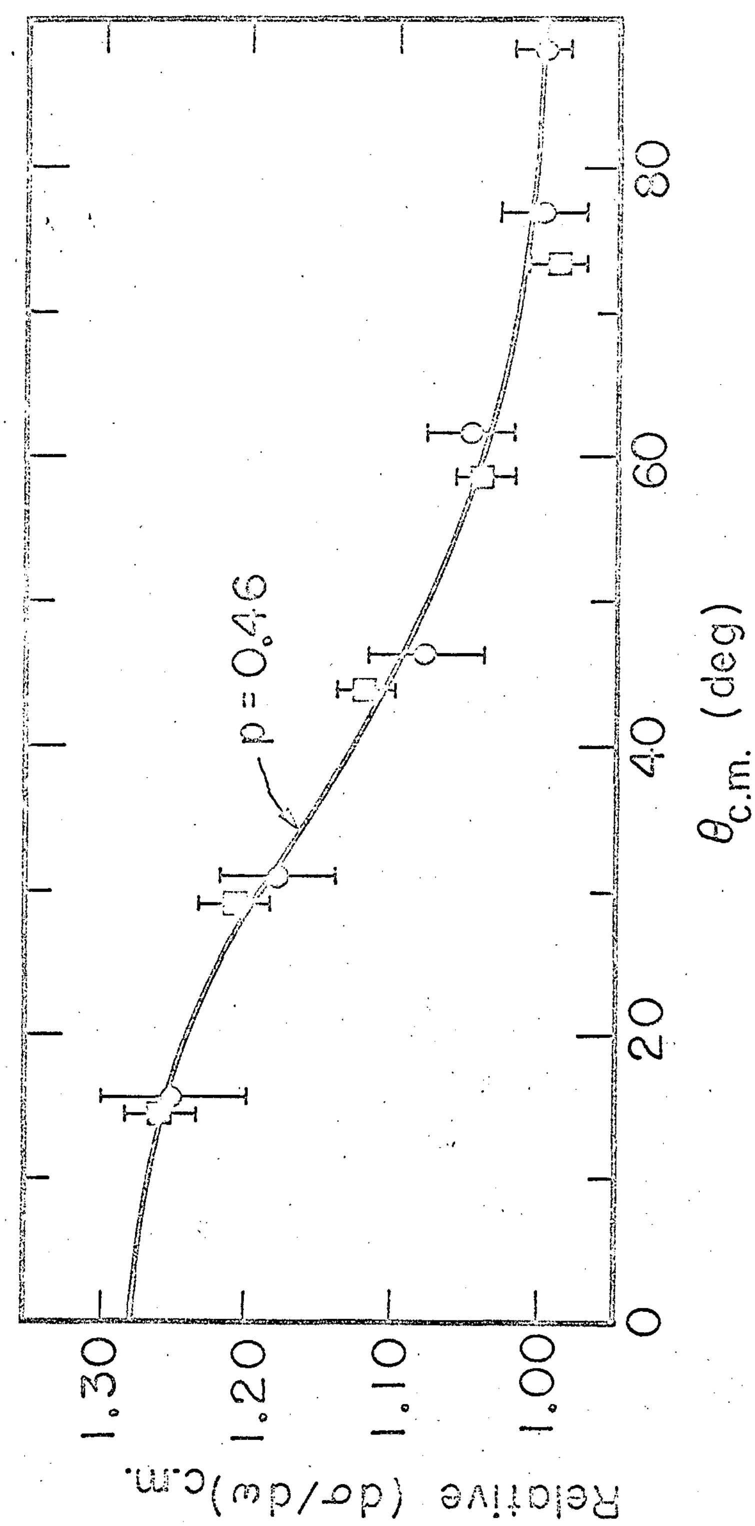


MU-25759

Fig. 1

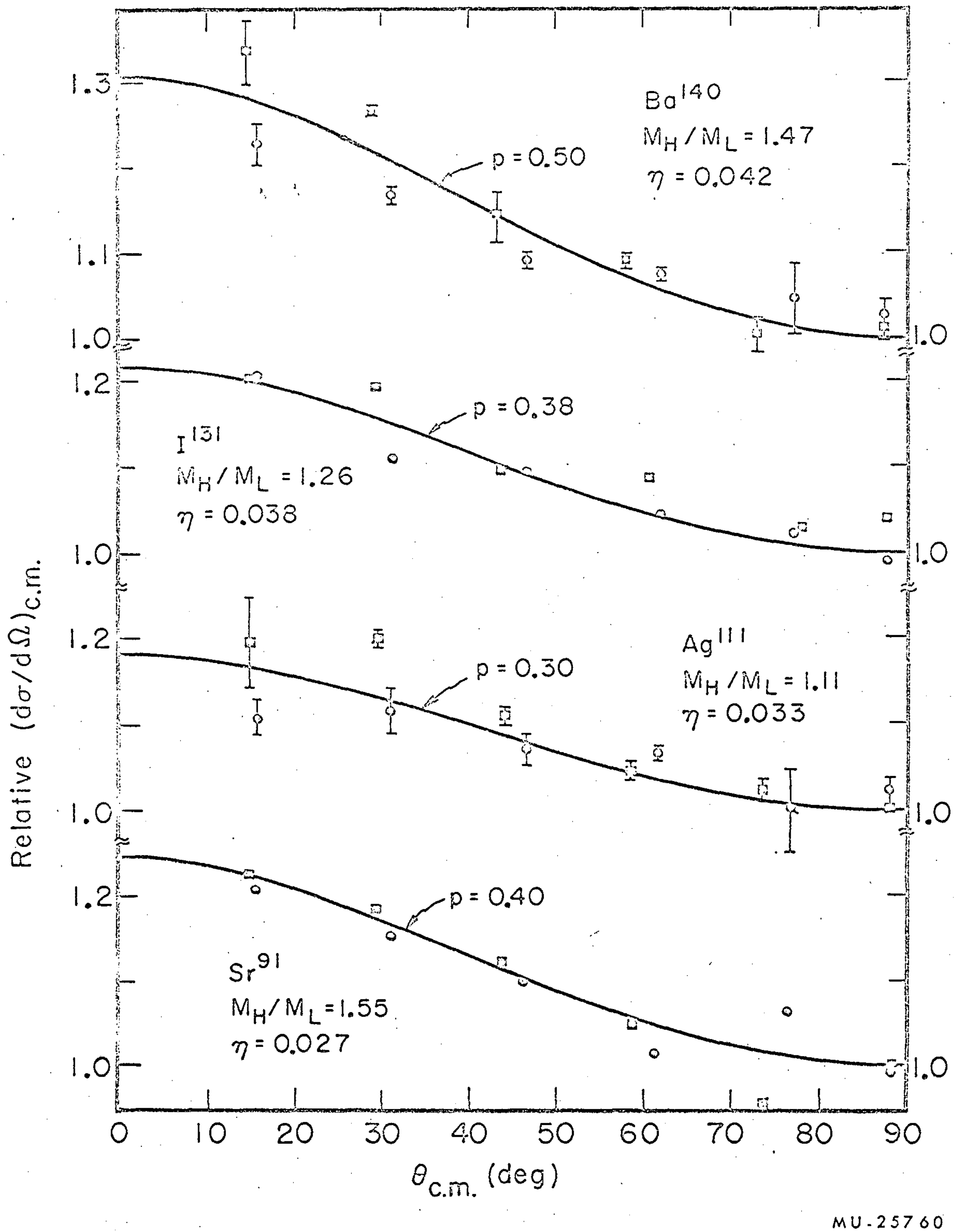
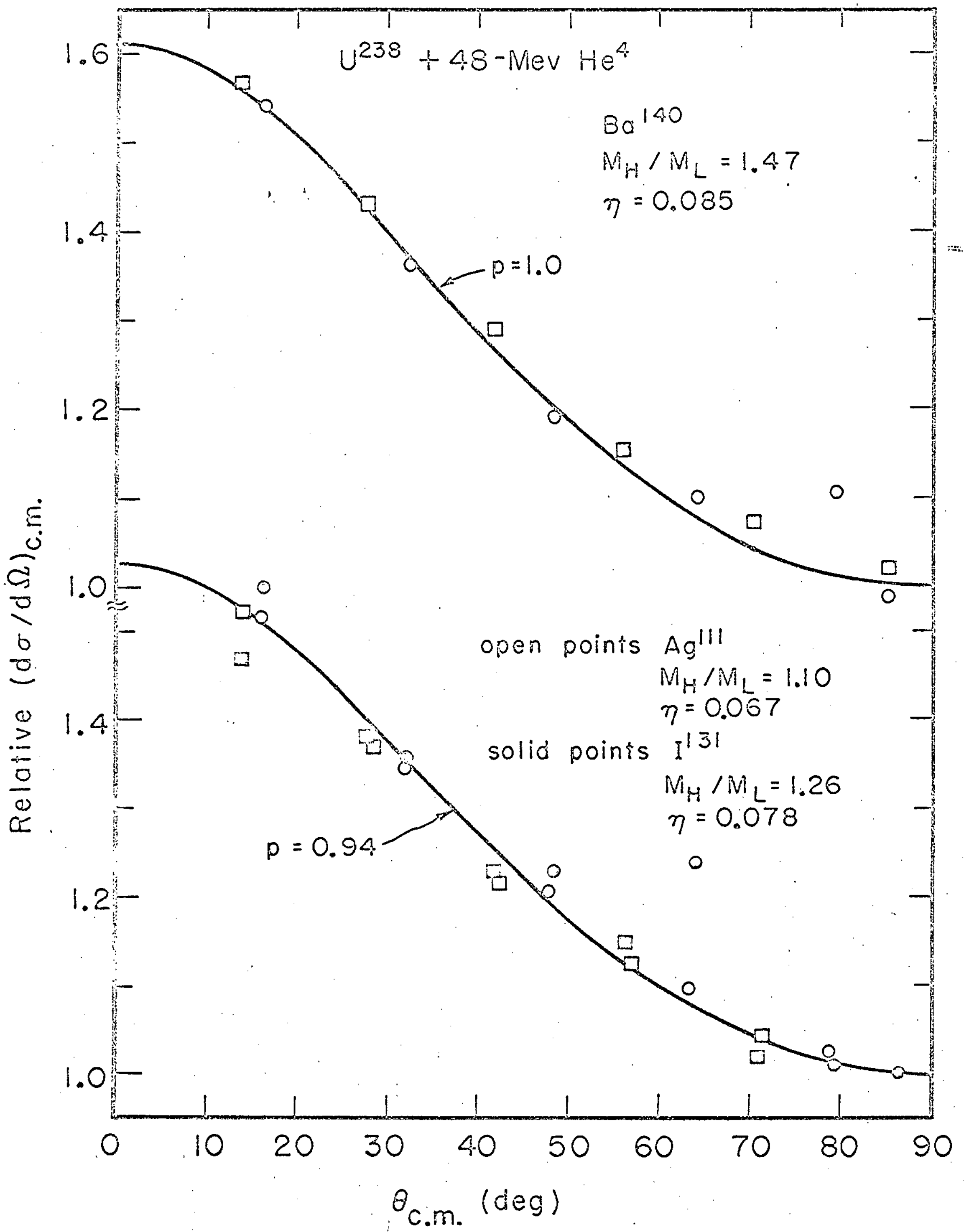

Ba140
MH / ML = 1.47
η = 0.042
p = 0.50
I131
MH / ML = 1.26
η = 0.038
p = 0.38
Ag111
MH / ML = 1.11
η = 0.033
p = 0.30
Sr91
MH / ML = 1.55
η = 0.027
p = 0.40
Relative (dσ/dΩ)c.m.
θc.m. (deg)
1.3
1.1
1.0
1.2
0
10
20
30
40
50
60
70
80
90
MU-25760

Fig. 2



MU-25761

Fig. 3

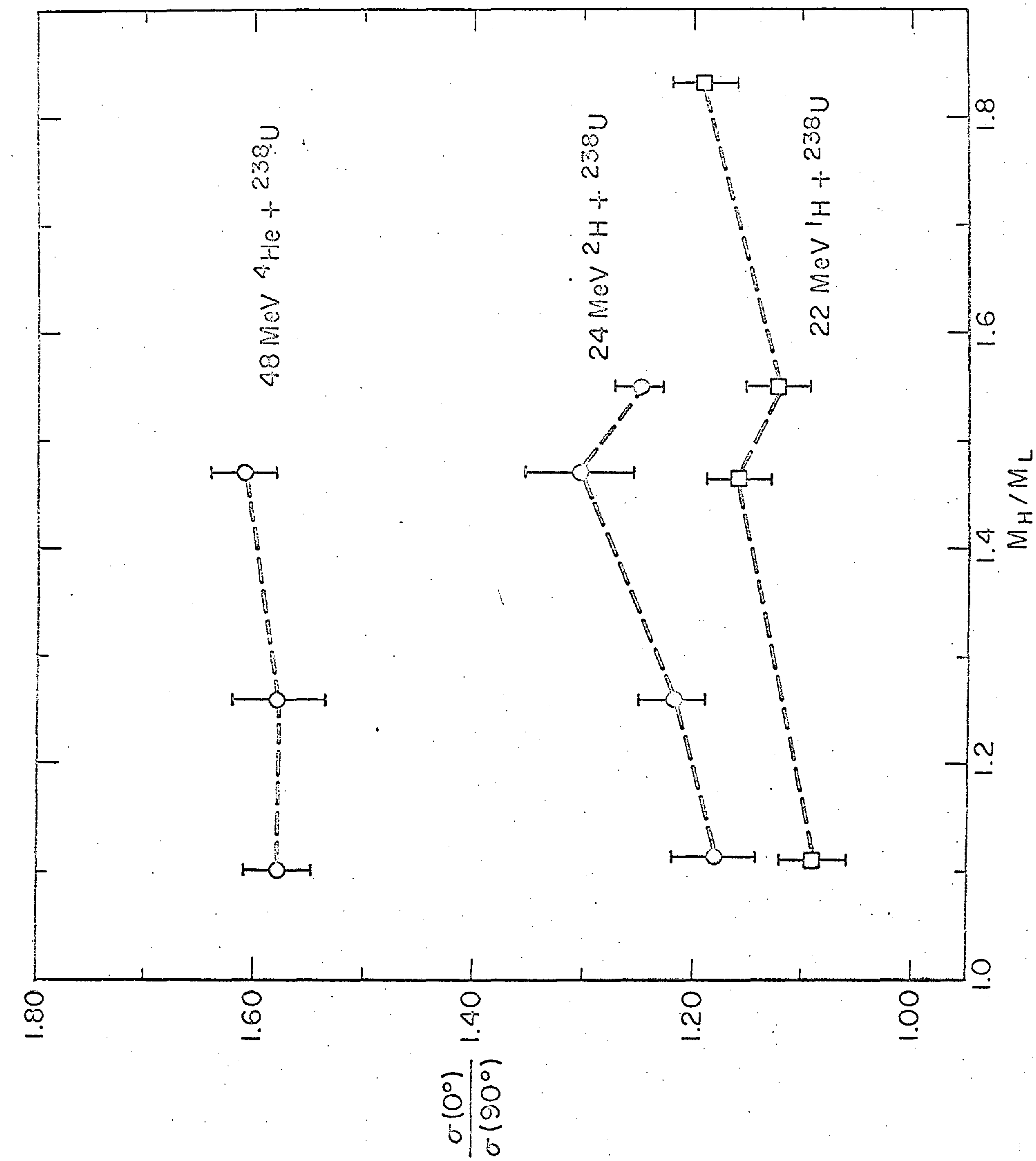

48 MeV $^4He + ^{238}U$
24 MeV $^2H + ^{238}U$
22 MeV $^1H + ^{238}U$
$\frac{\sigma(0°)}{\sigma(90°)}$
1.80
1.60
1.40
1.20
1.00
1.0
1.2
1.4
1.6
1.8
M_H / M_L

Fig. 4

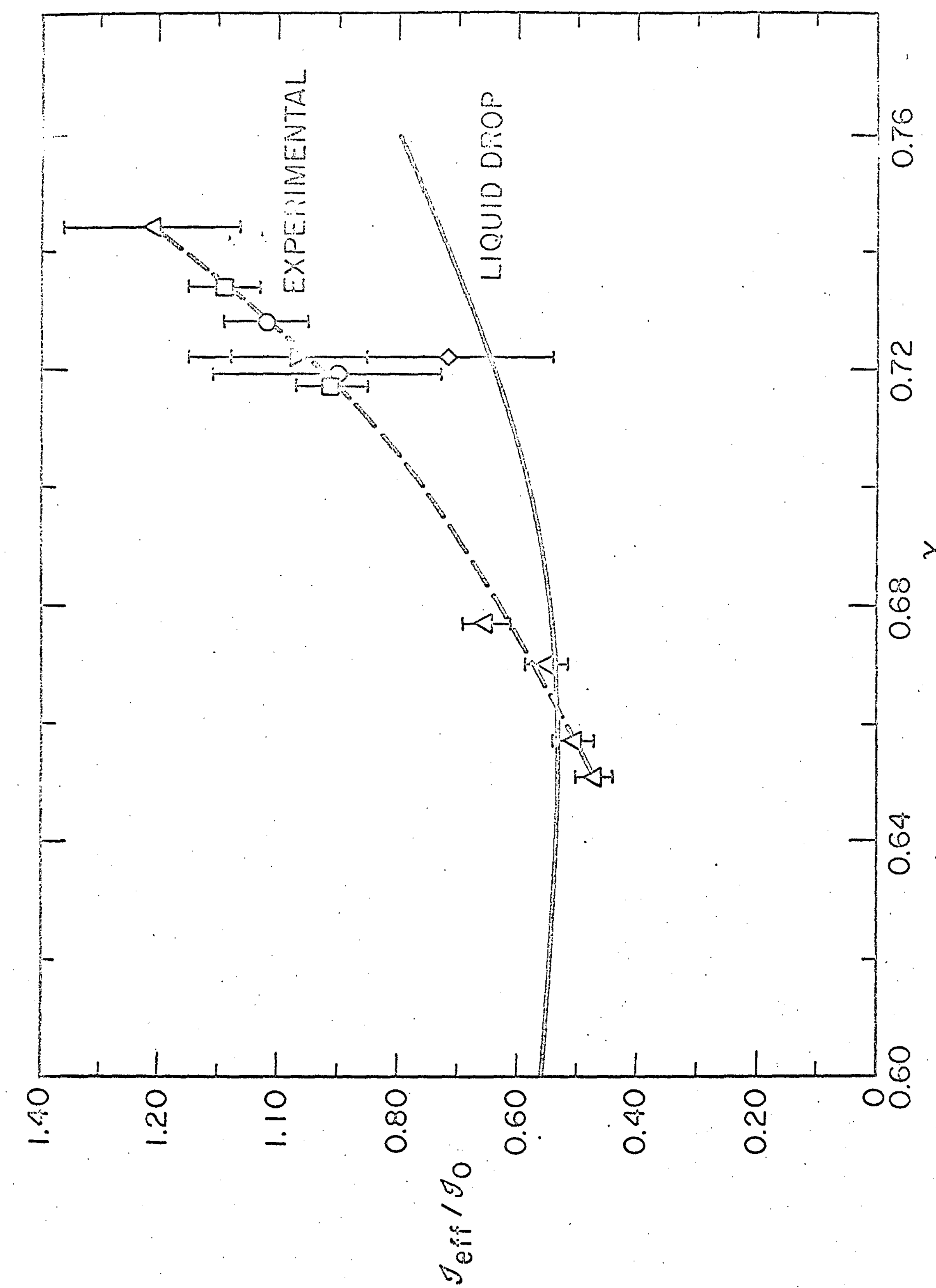

EXPERIMENTAL
LIQUID DROP
1.40
1.20
1.10
0.80
0.60
0.40
0.20
0
0.60
0.64
0.68
0.72
0.76
X
$\mathcal{J}_{eff}/\mathcal{J}_0$

Fig. 5

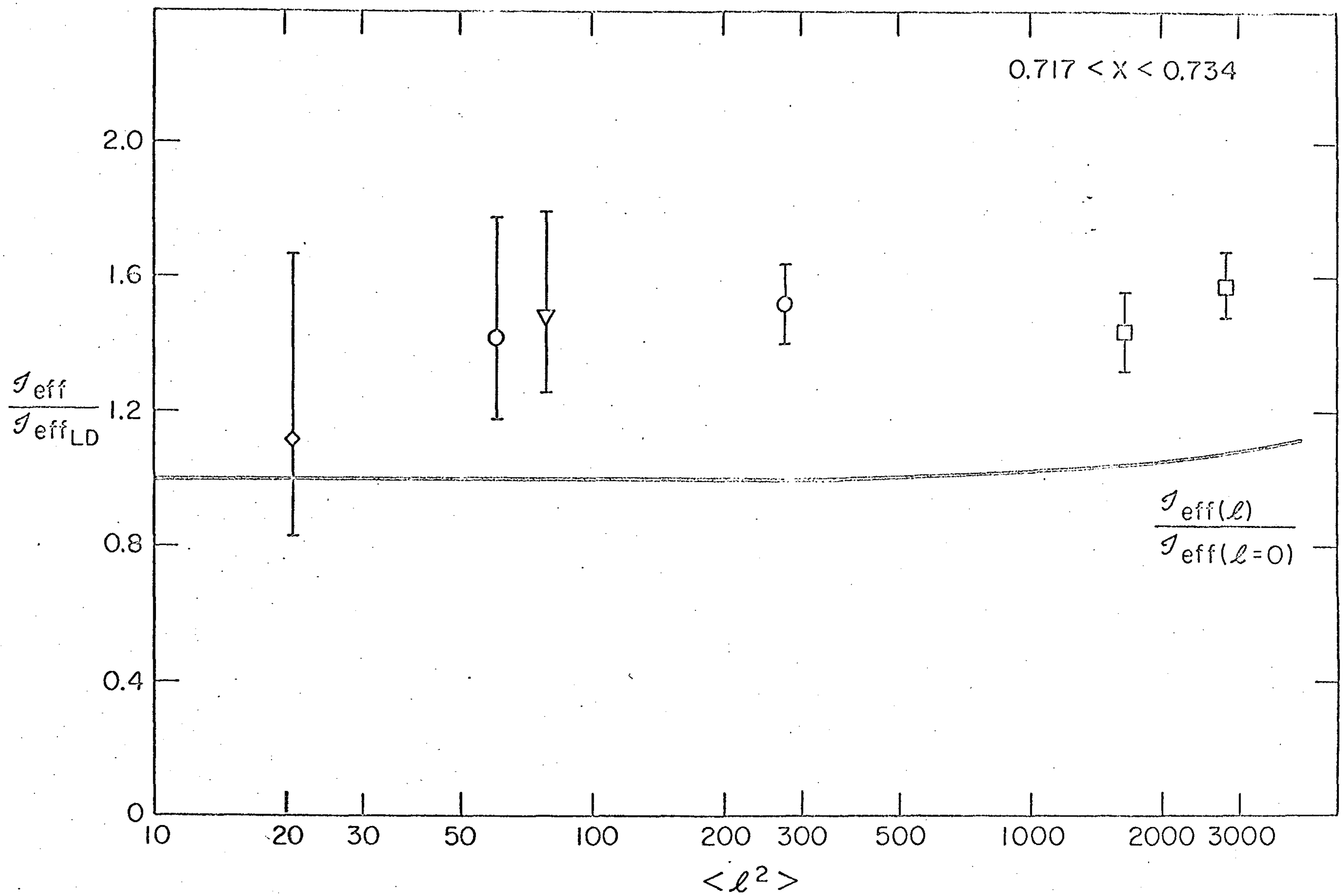

0.717 < X < 0.734
2.0
1.6
1.2
0.8
0.4
0
$\frac{\mathcal{I}_{eff}}{\mathcal{I}_{eff_{LD}}}$
$\frac{\mathcal{I}_{eff(\ell)}}{\mathcal{I}_{eff(\ell=0)}}$
10
20
30
50
100
200
300
500
1000
2000
3000
$<\ell^2>$

Fig. 6

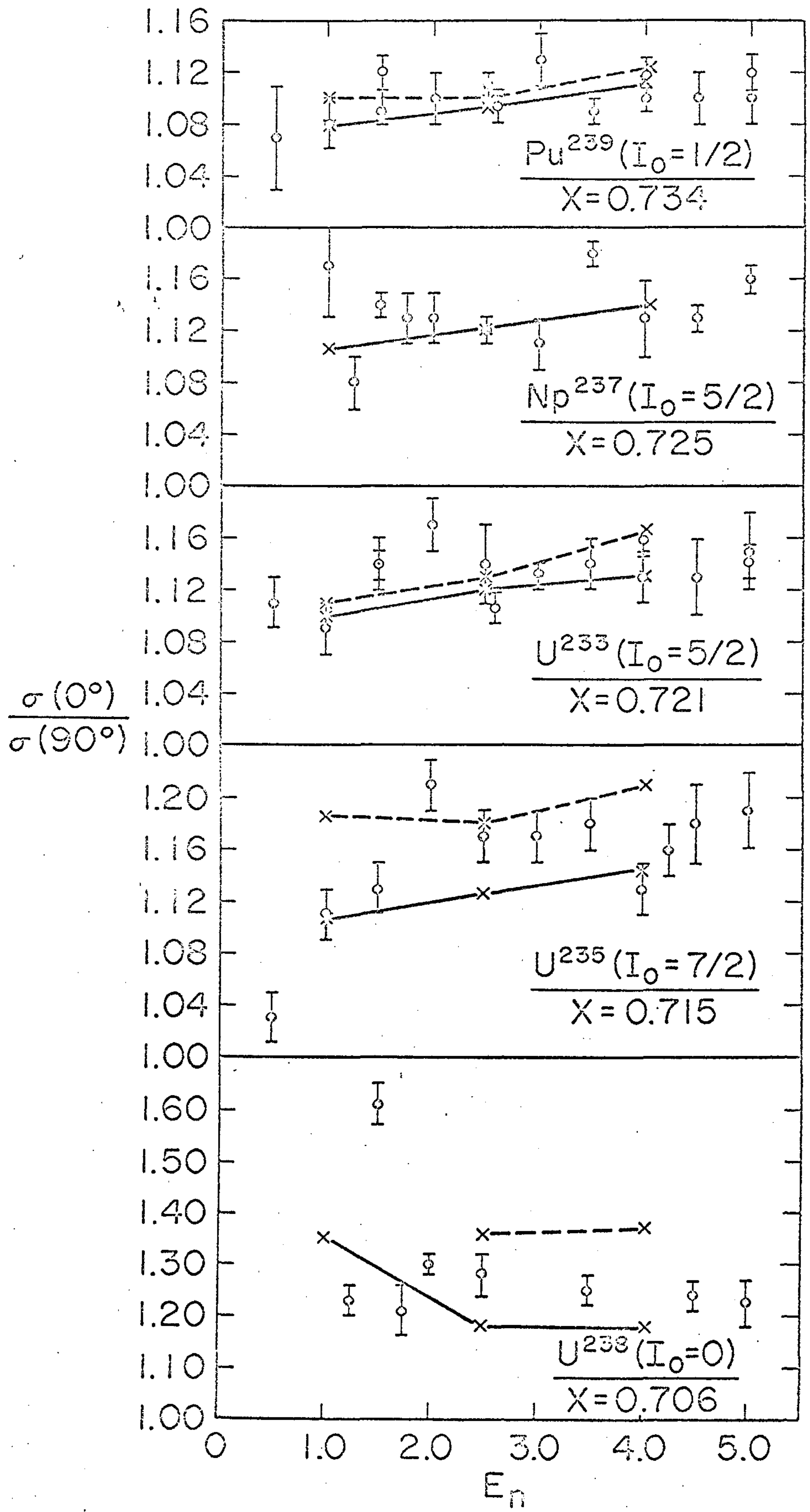

Pu239 (I0=1/2)
X=0.734
Np237 (I0=5/2)
X=0.725
U233 (I0=5/2)
X=0.721
U235 (I0=7/2)
X=0.715
U238 (I0=0)
X=0.706
σ(0°) / σ(90°)
1.00
1.04
1.08
1.12
1.16
1.20
1.10
1.30
1.40
1.50
1.60
0
1.0
2.0
3.0
4.0
5.0
En

Fig. 7