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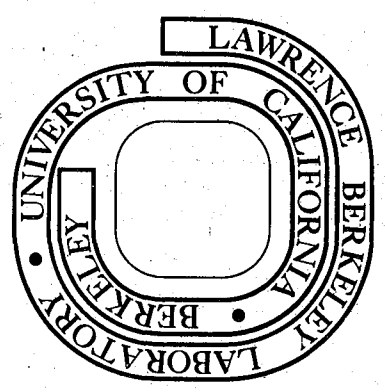
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EVIDENCE FOR ANGULAR MOMENTUM FRACTIONATION IN ^{86}Kr-INDUCED REACTIONS ON ^{107,109}Ag, ^{165}Ho and ^{197}Au

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ABSTRACT:

Gamma-ray multiplicities have been measured as a function of the light-fragment atomic number Z_3 for the above reactions. The events associated with sequential fission of the heavy fragment were distinguished from binary events by means of a triple coincidence. The failure of the measured γ-multiplicities for deep-inelastic collisions to rise with decreasing Z_3, according to the rigid-rotation limit, appears more likely to be associated with a selective population of the low Z fragments by the lower ℓ-waves rather than to an incomplete relaxation of the rotational energy.

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Heavy-ion reaction studies have shown the existence of a rotating "intermediate complex" consisting of a target-like and a projectile-like fragment which undergoes equilibration in its various degrees of freedom.[1] These equilibration processes, like the relaxation of the relative motion, the neutron-to-proton ratio and the mass asymmetry, have been extensively investigated.[1] The angular momentum transfer from orbital to intrinsic rotation, leading to the equilibration of rotational degrees of freedom has been investigated to a lesser degree.[2-5]

Measurements of γ-ray multiplicities M_γ have proven to be a good technique for determining the intrinsic angular momentum in compound nuclei.[6,7] This technique can be applied to deep-inelastic (DI) and quasi-elastic (QE) collisions in order to determine the angular momentum transfer as a function of mass asymmetry as determined from the light-fragment atomic number Z_3. From this dependence it is possible to obtain information on the extent to which rigid rotation has been attained.

In a previous study[2] of the reaction Ag + 175 MeV ^{20}Ne we have shown that: a) for quasi-elastic products, very close in Z to the projectile, M_γ increases linearly with the mass transfer; b) for the deep-inelastic components at backward angles, which show nearly <u>complete</u> kinetic energy relaxation, the rigid-rotation limit has been essentially attained; c) for intermediate degrees of kinetic energy relaxation, and at somewhat forward angles, γ-ray multiplicities smaller than those expected for rigid rotation are observed. The limited data available for heavier systems[4,5] do not show immediately recognizable patterns, and are difficult to interpret because of the lack of systematics and because of experimental limitations. To bridge the gap from relatively light to

heavy systems, we have studied Kr-induced reactions for targets spanning a large mass range (^{107,109}Ag, ^{165}Ho and ^{197}Au).

In contrast to the Ne + Ag system[2] where the deep-inelastic products cover only a narrow angular momentum window, the present systems give rise to DI products over most if not all of the angular momentum range, with small complete-fusion components. The much larger angular momentum range of these reactions (ℓ = 0-300 $\hbar$) opens the interesting possibility of having different ℓ-waves associated with substantially different mass distributions or, in other words, angular momentum fractionation may occur among products of different Z. On the other hand, the possible large transfers of energy and angular momentum to the heavy fragment can also favor decay modes which can efficiently dispose of the angular momentum, like fission and ^{4}He emission. In order to eliminate such a difficulty, we have employed a triple coincidence method, in which the γ-rays were observed in coincidence with the light fragment and with the heavy fragment, or with one of the fission products in the case of sequential fission.

Self-supporting targets (600 μg/cm^2) of ^{nat}Ag, ^{165}Ho and ^{197}Au were bombarded with a 618 MeV ^{86}Kr beam. The atomic number (Z_3) of the lighter fragment as well as its kinetic energy (E_3) was measured with a gas ΔE, solid-state E telescope which was placed in the reaction plane at angles (θ_3) varying from 20° to 70°. In order to detect the heavy fragment from the DI reaction in coincidence, a large solid-angle X-Y position-sensitive detector (PSD) was placed in the reaction plane on the opposite side of the beam axis.

The γ-rays were observed in a set of six 3" by 3" NaI detectors located above the target at 45° with respect to the reaction plane. The number (p-fold) of the NaI detectors in coincidence with a light fragment (Z_3) in the ΔE-E telescope was recorded event-by-event. The γ-ray multiplicities were deduced from the number of counts obtained in the different p-fold coincidences, the solid angle and efficiency of the NaI detectors.[6] Corrections for random events were made, while the contribution from neutrons was neglected (estimated to be less than $\sim$5%).

The γ-ray multiplicities associated with the higher energy events (quasi-elastic) are shown as a function of Z_3 in Fig. 1. A characteristic V-shaped dependence is observed, indicating that the angular momentum transfer is approximately linear with mass transfer. In this feature the present results are similar to those obtained for lighter systems.[2,3]

The results for the multiplicities associated with the DI reactions are shown in Fig. 2 as a function of Z_3 for several lab angles (θ_3). One should notice the slight but systematic increase in multiplicity as one moves from the lighter system (Kr + Ag) to the heavier ones (Kr + Ho and Au). Also, for the lighter system, M_γ is essentially constant with Z_3, while, for the heavier systems an increase in M_γ is observed as Z_3 increases. Furthermore, at the backward angles one observes smaller values of M_γ than at the more forward angles (see the Au + Kr data). This is to be contrasted with results for the Ag + Ne system[2] where the highest multiplicities were observed for the most backward angle.

Estimates of the multiplicity for the DI component have been calculated for both rolling and sticking hypotheses (see Fig. 2). We have assumed that the γ multiplicity was 1/2 the intrinsic angular momentum.[7] Since the systems under study have a very small evaporation residue cross section (< 50 mb) compared to the deep-inelastic cross section, we have assumed an average value of the angular momentum $\langle\ell\rangle = (2/3)\ell_{max}$ (triangular σ_ℓ distribution) for all mass asymmetries. In the rolling limit the intrinsic angular momentum is 2/7 of the total angular momentum independent of mass asymmetry, whereas in the sticking limit this value is obtained only for a symmetric splitting.

The comparison of the data with the rolling limit may not be very significant because of its rather unphysical nature (no rolling friction). However, the comparison with the rigid-rotation limit should be relevant for the trend, if not for the absolute value. It is immediately obvious that the rise in M_γ with decreasing Z_3 predicted by rigid rotation and observed in the Ag + Ne system[2] is not observed here at any angle. The lack of rise in M_γ could be associated with non-rigid rotation, but it would then also be associated with fairly high kinetic energies due to the large amount of angular momentum in orbital motion. (This has been observed at forward angles in the Ag + Ne system.[2]) However, for fragments with Z < 33 the kinetic energy spectra are quite relaxed, with mean values below the Coulomb energies expected for two nearly touching spheres. This last evidence suggests a rigidly rotating intermediate complex.

A possible way out of this dilemma is to assume that, as Z_3 becomes smaller, the complementary heavy fragment disposes of its angular momentum

by fissioning with high probability. This is conceivable in view of its its increased charge, excitation energy, and angular momentum. Our experiment has been specifically designed to test this possibility. In the case of Ag + Kr no fission was observed in coincidence with any fragment. For Ho + Kr some fission was observed in coincidence with the smaller Z_3's, but always in negligible amount. For Au + Kr a very large amount of fission (about 100% for $Z_3 = 30$) was observed as can be seen in the upper part of Fig. 3. However, for this system the γ-ray multiplicities appear to be the same whether or not the heavy fragment undergoes fission as is illustrated in the lower part of Fig. 3. This is somewhat puzzling. It may be possible that the fissioning heavy fragments are those formed with largest angular momentum, which would be mostly lost in orbital motion. On the other hand fission is known to generate 7-8 $\hbar$ units of angular momentum per fragment which may to some extent compensate for the loss of angular momentum in orbital motion.

However, for the cases of Ho and Ag + Kr, the conclusion is that fission is not responsible for the failure of M_γ to rise at low Z_3 values. Another possibility to be considered is that at low Z_3 values the system may lose a progressively larger amount of angular momentum through alpha-particle emission. Indications to the contrary are obtained from the out-of-plane angular widths of the heavy partner which remain essentially constant ($\sim 6°$ FWHM) as a function of Z_3 and completely consistent with nucleon evaporation. In fact as Z_3 decreases, the larger fragment increases

in Z and is less likely to emit alpha particles. Although the light
fragment might emit alpha particles (not borne out by the out-of-
plane widths), the angular momentum carried by it is likely to
become progressively smaller as Z_3 decreases. Therefore, even if
alpha emission occurs, its impact on M_γ is not expected to be large.

In summary, the failure of M_γ to rise as Z_3 decreases is not due to
sequential fission, does not seem to be due to alpha-particle emission,
and, since rigid rotation is indicated by the well thermalized kinetic
energies, does not appear to be due to the failure to achieve rigid rota-
tion. We are then left with the tentative conclusion that M_γ is not rising
because the low Z_3 fragments are preferentially populated by low ℓ-waves.
The analysis of the Z distributions and angular distributions as a function
of Z performed independently by some of us has led to the same conclusion.[1,8]
The explanation for such an effect is simple. The potential energy versus
mass asymmetry depends strongly on angular momentum. In the present case,
at the entrance-channel asymmetry, the potential energy slopes gently
towards symmetry for small angular momentum and it becomes progressively
steeper with increasing angular momentum. Therefore only the lowest ℓ-waves
contribute to the population of fragments substantially lighter than the
projectile. These preliminary conclusions about the fractionation of the
angular-momentum distributions are of interest because of their implica-
tion for the ℓ-dependence of particle, energy and angular momentum trans-
fers. Further studies along the present lines will be needed to clarify
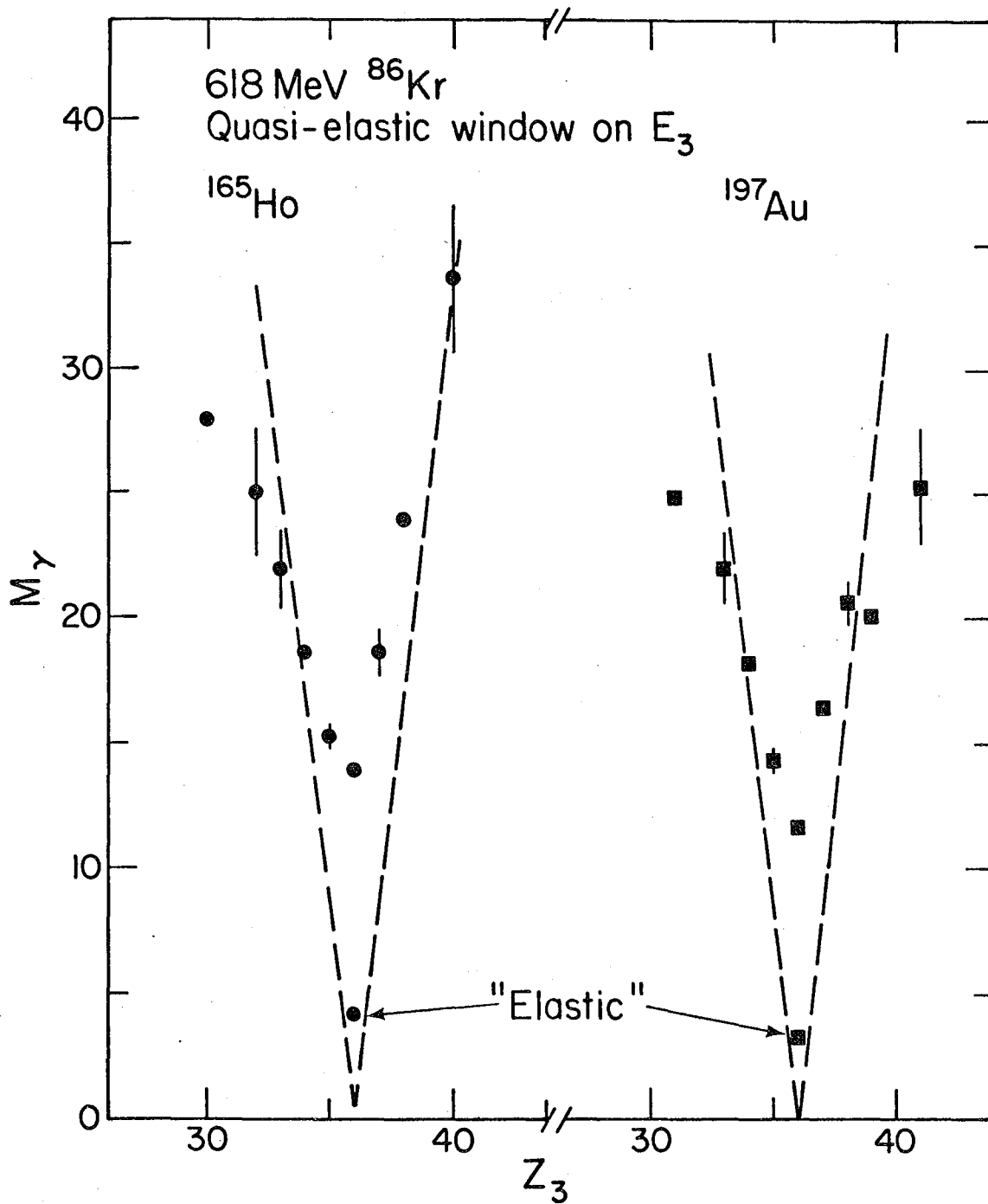these essential aspects of heavy ion reactions.

ACKNOWLEDGMENTS

REFERENCES

1) L. G. Moretto and R. Schmitt, J. Phys. 37, C-5 (1976) 109 and
references therein; J. R. Huizenga and W. V. Schröder, Ann. Rev.
Nucl. Sci. 27 (1977) and references therein.

2) P. Glässel, R. S. Simon, R. M. Diamond, R. C. Jared, I. Y. Lee,
L. G. Moretto, J. O. Newton, R. Schmitt and F. S. Stephens, Phys.
Rev. Letters 38, 331 (1977).

3) M. Ishihara, T. Numao, T. Fukada, K. Tanaka, T. Inamura, Proc. Symp.
on Macroscopic Features of Heavy Ion Collisions, Argonne (1976) 617.

4) M. Berlanger, M. A. Deleplanque, C. Gerschel, F. Hanappe, M. Leblanc,
J. F. Mayault, C. Ngô, D. Paya, N. Perrin, J. Péter, B. Tamain
and L. Valentin, J. Phys. 37 (1976) L 323.

5) H. Sann, A. Olmi, Y. Civelekoglu, D. Pelte, U. Lynen, H. Stelzer,
A. Gobbi, Y. Eyal, W. Kohl, R. Renfordt, I. Rode, G. Rudolf,
D. Schwalm, and R. Bock, preprint (GSI-P-5-77) from Gesellschaft für
Schwerionenforschung MBH, Darmstadt.

6) G. B. Hagemann, R. Broda, B. Herskind, M. Ishihara, S. Ogaza and
H. Ryde, Nucl. Physics A245 (1975) 166.

7) P. O. Tjøm, F. S. Stephens, R. M. Diamond, J. de Boer and W. E. Myerhof,
Phys. Rev. Lett. 33 593 (1974).

8) L. G. Moretto, Lawrence Berkeley Lab preprint No. (LBL-6572), Presented
at the Tokyo International Conference on Nuclear Structure, Sept 1977.

FIGURE CAPTIONS

Fig. 1) M_γ for the reactions $^{86}Kr + {}^{165}Ho$ and ^{197}Au; statistical error bars are shown for representative cases. The dashed lines are obtained by assuming that the fraction of orbital angular momentum associated with the transferred mass is recovered as fragment spin.[3]

Fig. 2) M_γ vs Z_3 for the low energy components (relaxed) of the reactions $^{86}Kr + {}^{197}Au$, ^{165}Ho and $^{107,109}Ag$. The solid lines correspond to the rigid-rotation limit for two touching spheres. The dashed lines correspond to the rolling limit.

Fig. 3) Top. Contour diagrams in the plane $E_4 - Z_3$ for the reaction $^{197}Au + {}^{86}Kr$. The contour lines correspond to values of 20000,2000,200,10 and 5 events for the non fission component and 60,40,10 and 5 events for the fission component.

Bottom. M_γ vs Z_3 for the DI processes with (squares) and without (circles) sequential fission. For comparison, data (triangles) are shown for which no triple coincidence was required.
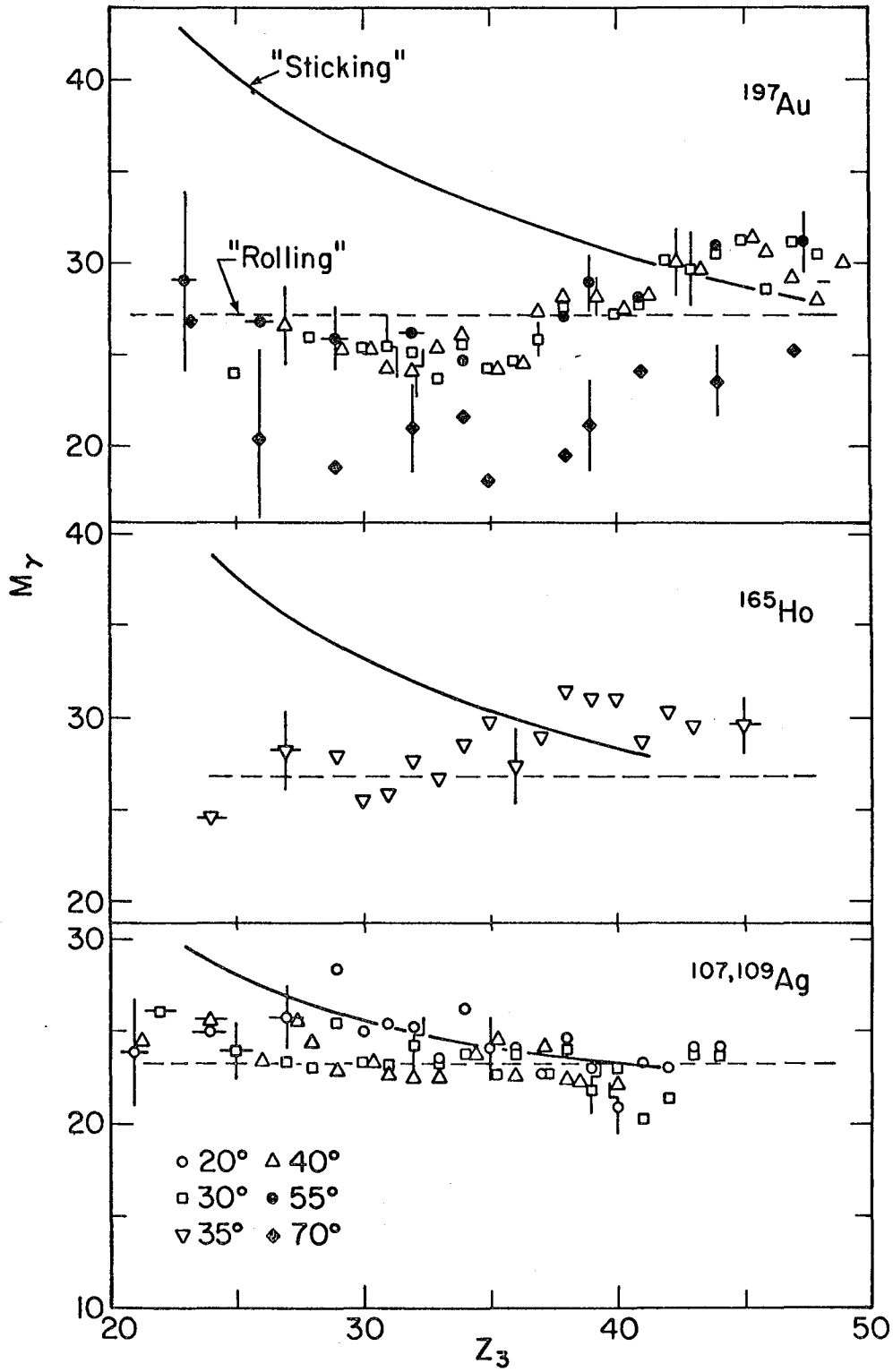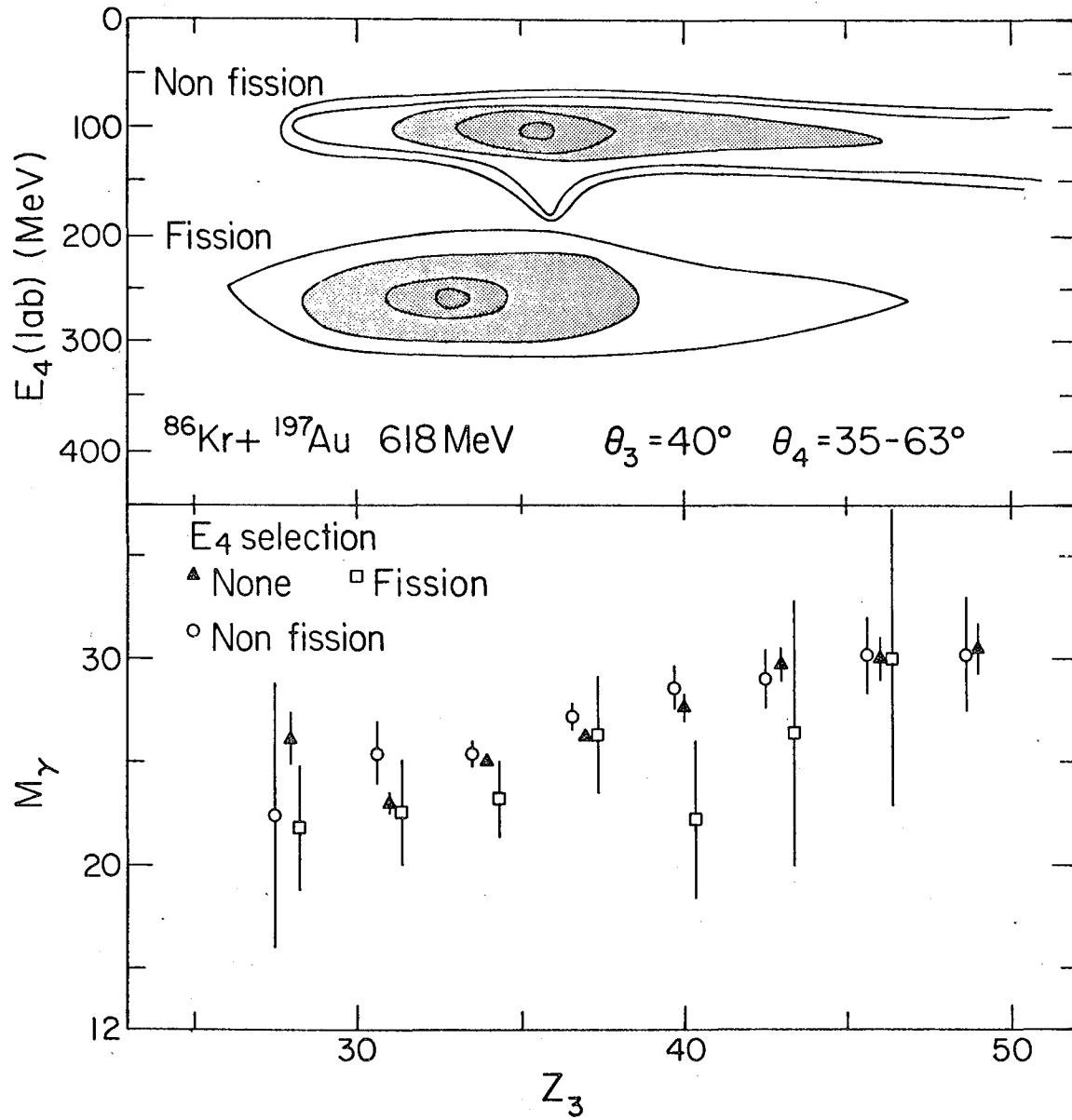
618 MeV ^{86}Kr
Quasi-elastic window on E_3

^{165}Ho

^{197}Au

"Elastic"

M_Y

Z_3

XBL779-2346

Fig. 1

Fig. 2

XBL 779-2345

^{86}Kr + ^{197}Au 618 MeV $\quad \theta_3 = 40°$ $\quad \theta_4 = 35-63°$

XBL 779-2344

Fig. 3