Fission Probability in the Reaction of ^{10}B with ^{197}Au at Projectile Energies of 130 to 320 MeV

by

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ABSTRACT

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Angular distributions of fission fragments for the reaction of ^{10}B + Au at bombarding energies of 130, 180, 225, and 320 MeV were obtained. Integration of these cross-sections was carried out, but problems with the first three energies prevent us from reporting absolute data at this time. The total fission cross-section for the 320 MeV case was 1.2 $\mp$.16 barns which lends evidence to the possibility of a drop in collective character at energies/nucleon comparable to the Fermi energy.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

The study of nuclear matter and the forces that hold nuclei together is one of the most important topics of current interest in physics. The extreme smallness of the atomic nucleus requires that one adopt an indirect approach when seeking to probe its secrets. Most often this involves observing the scattered products of reactions induced by the collision of energetic nuclei. The wide variety of targets, projectiles and incident beam energies available provides a virtually unlimited number of combinations of systems and equally diverse possibilities for the types of physics that can arise.

Heavy ion nuclear physics is the portion of this research that focuses on the reactions of projectiles with atomic number greater than or equal to three. Heavy ions can impart large amounts of linear and angular momentum, and this work has been particularly useful in giving us a look at the behavior of nuclei when subjected to extremes of reaction conditions. The outcome of such reactions depends on several factors including incident projectile energy, angular momentum, and the masses of the reactants. Although the boundaries between mechanisms are seldom well defined, we can gradually begin to put together a picture of the nucleus by trying to understand why some mechanisms are preferred over others.

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II. REACTION MECHANISMS AND THE INTERMEDIATE ENERGY RANGE

At low bombarding energies and small impact parameters, fusion of the nuclei is the dominant mechanism. The resulting nuclear systems will usually be highly excited and tend to undergo subsequent decay to get rid of their excess energy and angular momentum. However, this process is slow enough that an equilibrium state called the compound nucleus is reached. The deexcitation of a compound nucleus can be regarded as independent of path of formation for a nucleus characterized by a particular excitation energy and angular momentum. At larger impact parameters, the deep-inelastic processes are observed. In these reactions the projectile sustains a significant loss of kinetic energy to internal excitation. Although the interaction is strong and some transfer of nucleons between the target and projectile is possible, fusion does not occur, and the scattered particles leave with mass and charge comparable to that of the projectile.

When the bombarding energy is above a few hundred MeV/nucleon, the central collisions can result in the complete shattering of target and projectile. This process is appropriately termed explosion. The more peripheral reactions at these higher energies involve the shearing off of portions of the nuclei. This is known as the participant-spectator mechanism because it gives rise to some highly excited fragments(the participants) and some pieces that are relatively unaffected(the spectators).[1,2,3]

In comparing the heavy ion reaction mechanisms of the low energy and high energy regions, we notice some important differences. In the low energy realm, the nucleus is observed to act as a collective unit with processes that reflect a prevailing equilibrium character. On the other hand, the high energy processes show strikingly non-equilibrium behavior dominated by the influence of the individual nucleons and the localization of the disturbance.[1,4,5]

Consideration of the time scales associated with these reactions may be useful in the explanation of the differences observed. It must be noted that even in the ground state, nucleons inside the nucleus move about with a considerable kinetic energy. The maximum energy of such motion is called the Fermi energy and is typically around 30 MeV/nucleon. We can regard the corresponding velocity, the Fermi velocity, as a measure of the speed with which information can be transferred across the nucleus. In the low energy reactions, the projectile velocity is less than the Fermi velocity. Thus, the reaction time is long enough that the information, that is, the disturbance due to the interaction, can be propagated throughout the nuclear volume, and an equilibrium condition results. In the high energy reactions, the opposite is true. The projectile now interacts on a time scale that is short compared to the time needed for the motion of the nucleons to transmit the information. The result is a localization of the disturbance and a non-equilibrium state of incomplete information distribution.[4,5] We might also talk about the velocity of sound in nuclear matter which is comparable in magnitude to the Fermi velocity and with respect to this point gives rise to similar conclusions.

We may gain further understanding of how the differences in low and high energy reactions come about by considering in more detail the constraints to which the nucleons are subject. The nucleons are spin 1/2 particles or fermions which means that they must obey the Pauli exclusion principle. The effect of the exclusion principle is to inhibit collisions between nucleons. Although the force between these particles is strongly attractive, their mean free path may be on the order of the nuclear radius. The result is that they feel a kind of effective potential or "mean field" environment.[5,6] This picture is consistent with our view of the low energy processes as collective ones; however, when the energy of the system is high enough, the Pauli principle ceases to be effective in preventing these interactions and a new behavior emerges - one that is dominated by individual nucleon character.

It is clear that in the intermediate energy range - roughly defined as 20 to 200 MeV/nucleon - a transition will take place as the collective character declines. The importance of this range has only recently been realized and considerable work is now being done to learn about it. A primary question that concerns scientists is whether or not the transition is a sharp one reflecting an abrupt change in the nature of the forces at work. If such is the case, just where the transition takes place is important.[4] It has been shown that non-equilibrium processes such as fast particle emission are already fairly well developed as reaction components by the time the projectile energy reaches 20 MeV/nucleon.[7] From the standpoint of reaction time scale, we might expect transitional phenomena to arise rather early in the intermediate energy region at energies comparable to the Fermi energy. The diminished effect of the Pauli principle as a contribution to the change in nuclear behavior might also come into play early on.[4,5]

Previous work in the intermediate energy region is somewhat limited, but some interesting things have already been seen and are worthy of note. In experiments designed to measure the efficiency of linear momentum transfer Galin, et al[8] state that a limit is reached above a bombarding energy of 15 MeV/nucleon. Similar studies by Viola, et al[9] show that incomplete momentum transfer can be seen even in central collisions, and the missing momentum is attributed to promptly emitted particles. In the study of projectile fragmentation at a bombarding energy of 43 MeV/nucleon, Natowitz, et al[10] have observed momentum widths analogous to those expected at relativistic energies. This is not the case, however, at 32 MeV/nucleon suggesting that the broadening occurs quite rapidly above this energy.[11]

III. FISSION PROBABILITY

Experiments designed to investigate the transition discussed in the previous section require that there be a measurable quantity which may be affected by a change in the degree of collectiveness or the introduction of non-equilibrium processes. In the present work, the quantity chosen was the tendency of a nuclear system created in such reactions to undergo decay by way of fission, that is, the fission probability.

If we view fission as a characteristically cooperative action involving many nucleons, it seems reasonable that incomplete interaction of projectile and target might not supply a sufficient driving force to cause such a violent outcome. The non-equilibrium, individual nucleon character of high energy reactions would therefore seem to reduce the probability of fission.[4]

The efficiency of angular momentum transfer in these reactions should also have particular importance in determining the tendency to fission. This point can be understood by invoking the rotating liquid drop model(RLDM) where the nucleus is described as a fluid droplet in which the cohesiveness of the nuclear force is opposed by the disruptive effects of electrostatic repulsion and centrifugal force. For the typical nucleus with no angular momentum there is an energy barrier inhibiting fission which is often in the tens of MeV in height. One of the predictions of the RLDM is that the effective fission barrier decreases rapidly with increasing angular momentum and in fact vanishes at very high J.[12] Thus, we see that a reduction in the amount of angular momentum transferred in the reaction can leave a system with a substantial barrier to fission and lower the fission probability.[4]

Both from the standpoint of cooperative modes of deformation and the efficiency of angular momentum transfer, we see that the transition in nuclear behavior from collective/equilibrium character to individual nucleon/non-equilibrium character may cause a reduction in the fission probability. In this experiment, it was our goal to measure the fission probability for some system of target and projectile as a function of incident projectile energy up to a value comparable to the Fermi energy. This would take us through an interesting energy range, and if some sharp transition takes place there we might be able to see it as a rapid drop in the fission probability.

IV. EXPERIMENTAL PROCEEDURE

The facilities of the Texas A & M Cyclotron were used to perform a series of experiments to measure the fission components of the ^{10}B + Au system at four boron projectile energies. In the fall of 1982, measurements for B+Au at 130, 180, and 225 MeV were made. In the spring of 1983, a 320 MeV ^{10}B + Au experiment was performed. The gold targets used ranged from .25 to 2.3 mg/cm^2 in thickness.

The goal of this series of experiments was to obtain the total fission cross section as a function of energy for the B + Au system. The cross-section is a probability that is characteristic of a reaction and is independent of experimental parameters such as detector geometry, beam intensity, and target thickness. Figure 1 shows the beam line set up used in the second experiment. The configuration in the first experiment was similar, but only one monitor was present at that time.

In order to determine the occurrence of a fission event, one of the fission fragments must be detected. The detector used for this consisted of two stages. The front part was a gas-proportional counter to give a ΔE signal. The back part was a large area ($900mm^2$) silicon detector with a depletion depth of 100μ to give the residual energy. The gas used was P-10 at a pressure of about 30 torr. This allowed a healthy signal for fission fragments in both ΔE and E. The window of the gas cell was about 100 $\mu g/cm^2$ polypropylene.[13] In both the fall and spring experiments the detector was positioned so as to subtend roughly 30 msr in solid angle.

The detectors designated as monitors were used to measure the Rutherford elastic scattering of the beam. This information was needed

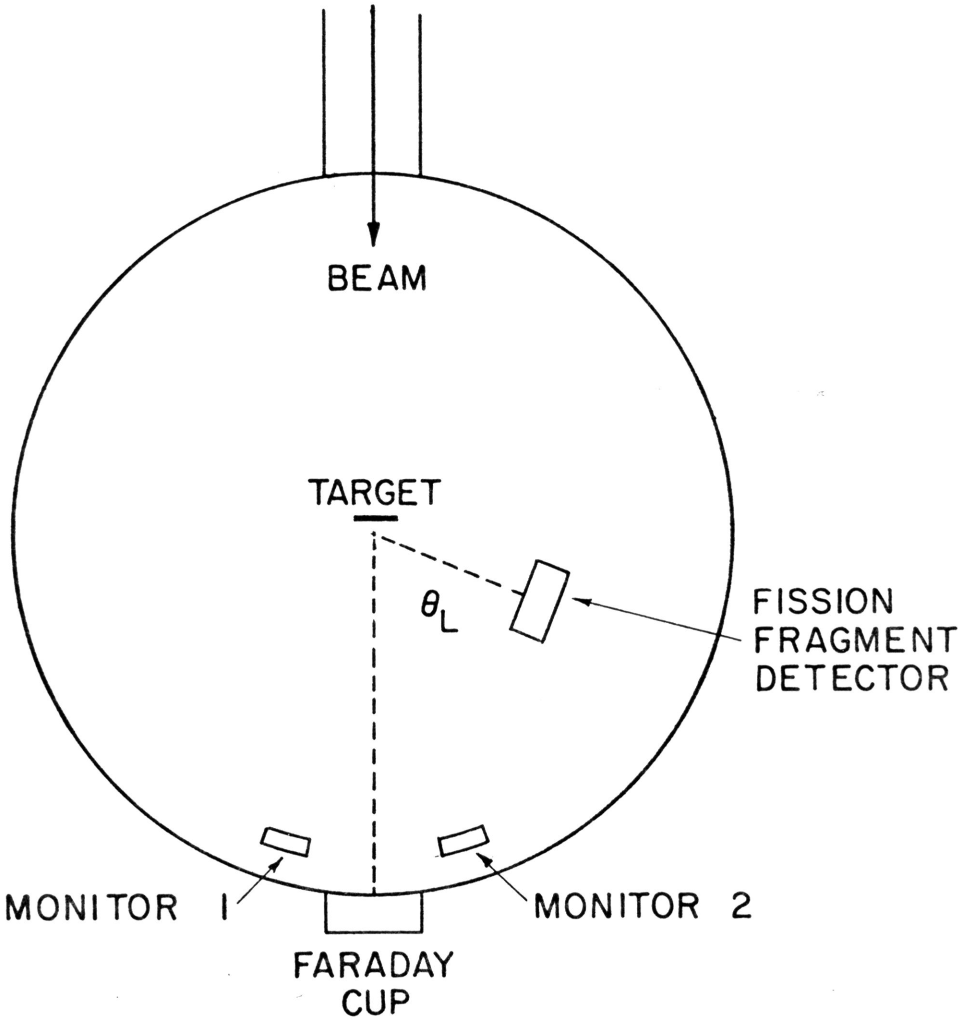

Figure 1. Target Chamber Configuration

in order to determine the beam intensity for cross-section purposes. Also shown in Fig. 1 is the Faraday Cup. The undeflected portion of the beam strikes the cup, and the reading taken from it can be related to the beam intensity.

Figure 2 shows a block schematic of the experimental electronics used. The detector signals were pre-amplified in the experimental area and then sent to the computer room. The signal from the fission fragment silicon detector (E) provided the event trigger from which logic pulses were derived. These gated the ADCs and provided an interrupt for the computer. Linear energy signals were amplified and then sent into the aquisition computer - a Digital VAX 11/780 - via the CAMAC ADC interface. An existing acquisition program allowed us to monitor the experiment on-line through the display of raw spectra on a graphics terminal. Event-by-event data was stored on magnetic tape for subsequent off-line analysis. The number of elastics detected by the monitor was recorded by a scaler after a suitable window had been set on the particle energy to exclude other reaction components.

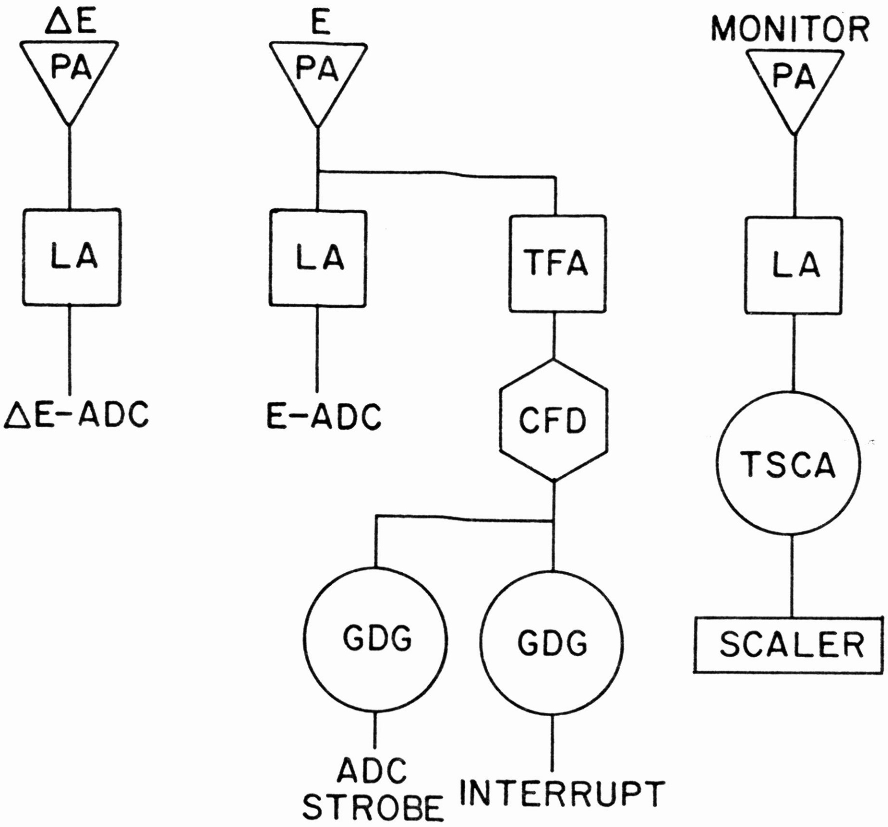

Figure 2. Electronics Schematic

Definition of symbols: PA pre-amplifier, LA linear amplifer, TFA timing filter amplifier, CFD constant fraction discriminator, GDG gate and delay generator, TSCA timing single channel analyzer, ADC analog-to-digital converter.

V. DATA ANALYSIS

For the present work, an operational 'data run' included the following information: (1)an event-by-event file stored on magnetic tape, (2) scaler readings for the monitors and Faraday cup, and (3) data regarding such things as detector geometry and target thickness as they existed at acquisition time. The subsequent value of the data set depends on an accurate account of the prevailing conditions.

The fission fragments were distinguished from the other reaction components seen in our detector by standard $\Delta E - E$ techniques. In many cases, it was possible to identify these events by looking at either the ΔE or E spectrum individually.

Simply knowing the number of fission fragments detected in a data run is not sufficient to say anything about the fission probability. The other pieces of information associated with the run must be employed to remove dependencies on experimental parameters so that we can talk in terms of cross-sections. We define a quantity known as the differential cross-section :

$d\sigma/d\Omega$ = number of particles of a given type scattered in the a differential solid angle $d\Omega$ per number of incident beam particles per number of target nuclei per unit area

From this formal definition a mathematical expression for the differential cross-section of fission fragments can be obtained by supplying thepertinent experimental data:

$$d\sigma/d\Omega(\text{fission}) = \frac{(\text{\# of fission fragments})(\text{Mt})(\cos(\theta\text{t})(\lambda)}{(\text{cup reading})(\text{Tt})(\text{Na})(\Delta\Omega)}$$

where Mt, θt, and Tt are the target atomic mass, angle and thickness (mg/cm^2) respectively, Na is Avagodro's divided by 1000, and $\Delta\Omega$ is the solid angle subtended by the detector. The multiplicative constant λ in the above expression amounts to a calibration for the Faraday cup, so that we can convert the cup readings to the number of incident beam particles. When the differential cross-section defined by these equations is integrated over the polar and azimuthal angles relative to the beam direction and the result is divided by two to account for the two fission fragments resulting from one fission event, we arrive at the total fission cross-section:

$$\sigma t(\text{fission}) = 1/2 \int\int (d\sigma/d\Omega)\sin(\theta)d\phi d\theta \ .$$

It should be noted that $d\sigma/d\Omega$ is a function of the detector angle θ and that this quantity must be measured at several values of θ to get an angular distribution suitable for integration. In the present case, the fission fragment detector was placed at eight equally spaced angular positions, and a data run exists for each setting.

The cup calibration depends on the beam energy and must be done separately for each case studied. This proceedure requires that the intensity of a reaction of known cross-section be compared with a corresponding cup reading for a data run. In this case, the elastic scattering observed in the monitors and the well-known Rutherford cross-section were used. It should be noted that the strong dependence of the elastic scattering cross-section on angle requires that one know the spatial relation of the monitor, target and beam accurately to obtain the correct λ. The absence of a second monitor ,some problems with the beam optics, and uncertainties in the spatial positioning of the monitor resulted in our being unable to faithfully extract the normalization constants for the three beam energies studied in the fall experiment. The spring experiment involving the 320 MeV ^{10}B beam did not suffer from these problems.

VI. RESULTS AND ERROR ANALYSIS

The angular distributions-$d\sigma/d\Omega$ for the four boron energies studied here are plotted in Fig. 3 and Fig. 4. The forward and backward peaking of the angular distributions can be viewed as a carry over to the lab frame of the $1/\sin(\theta c.m.)$ shape of the high angular momentum limiting case. The error bars are due to the statistical uncertainty of the fission fragment counts as well as an estimated systematic uncertainty arising in the calculation of the normalizing constant, λ. The statistical errors never amounted to more than a few percent even in the case of the 320 MeV boron experiment where the beam intensity was exceedingly low. The uncertainty in the normalization constant contributed between 13 and 20 per cent to the overall uncertainty depending on the particular energy for which λ was computed.

In the course of the analysis, it became apparent that some of the values of λ, though the best we could get, cannot be trusted to give us absolute cross-sections. Within the distributions for a single energy, the relative cross-section may be compared with no problems. However, to make comparisons between distributions, one must have absolute data which at this point is not available. This problem carries over in the integration to the total fission cross-section σt(fission).

Figure 5 is a plot of the total fission cross-section as a function of incident projectile energy using the suspect normalization constants. The problems in finding the correct λ show up in the first three energies but are not expected to exist in the 32 MeV/nucleon case. Early work[14,15] at 10 MeV/nucleon for C + Au and O + Au would

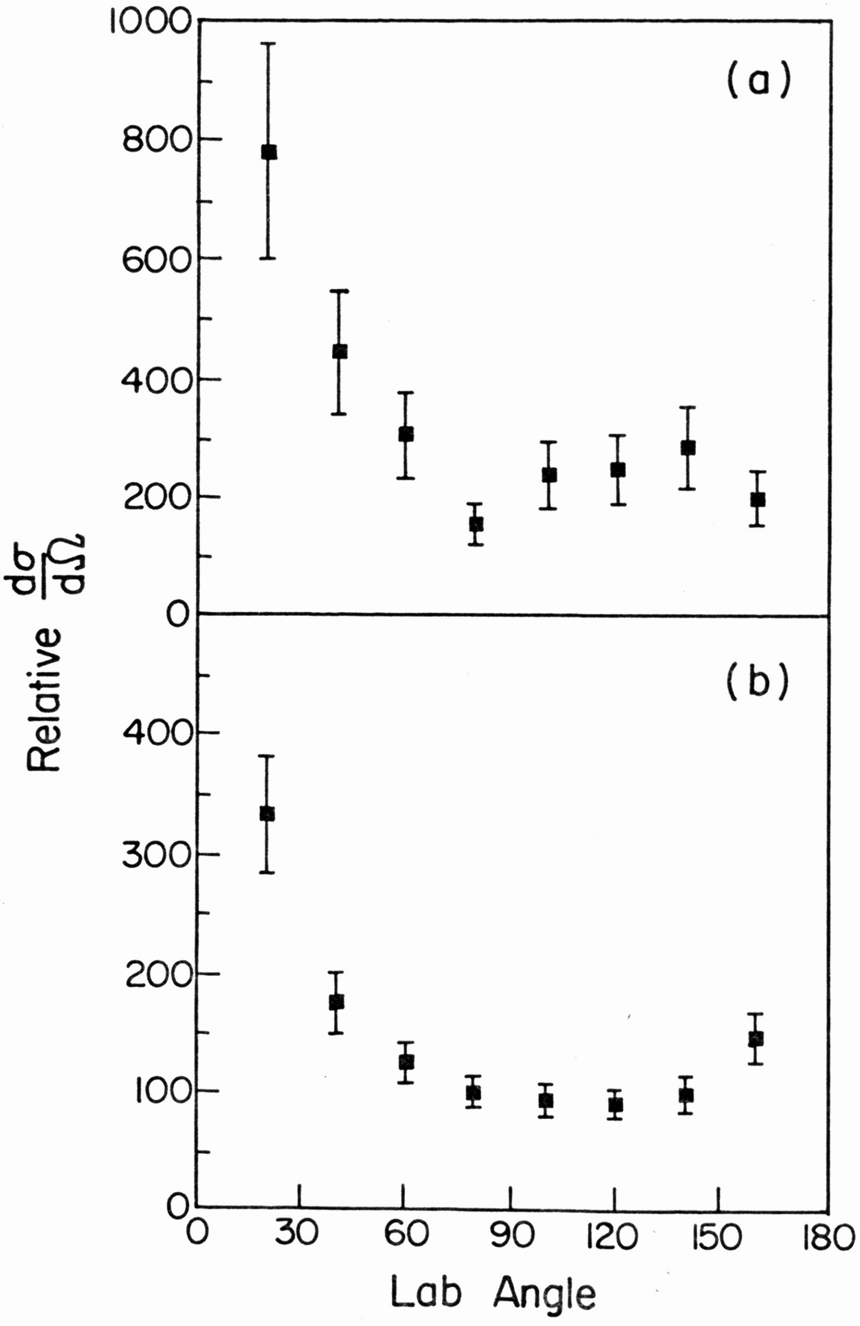

Figure 3. Relative fission fragment angular distributions for (a) 130 MeV B + Au and (b) 180 MeV B + Au

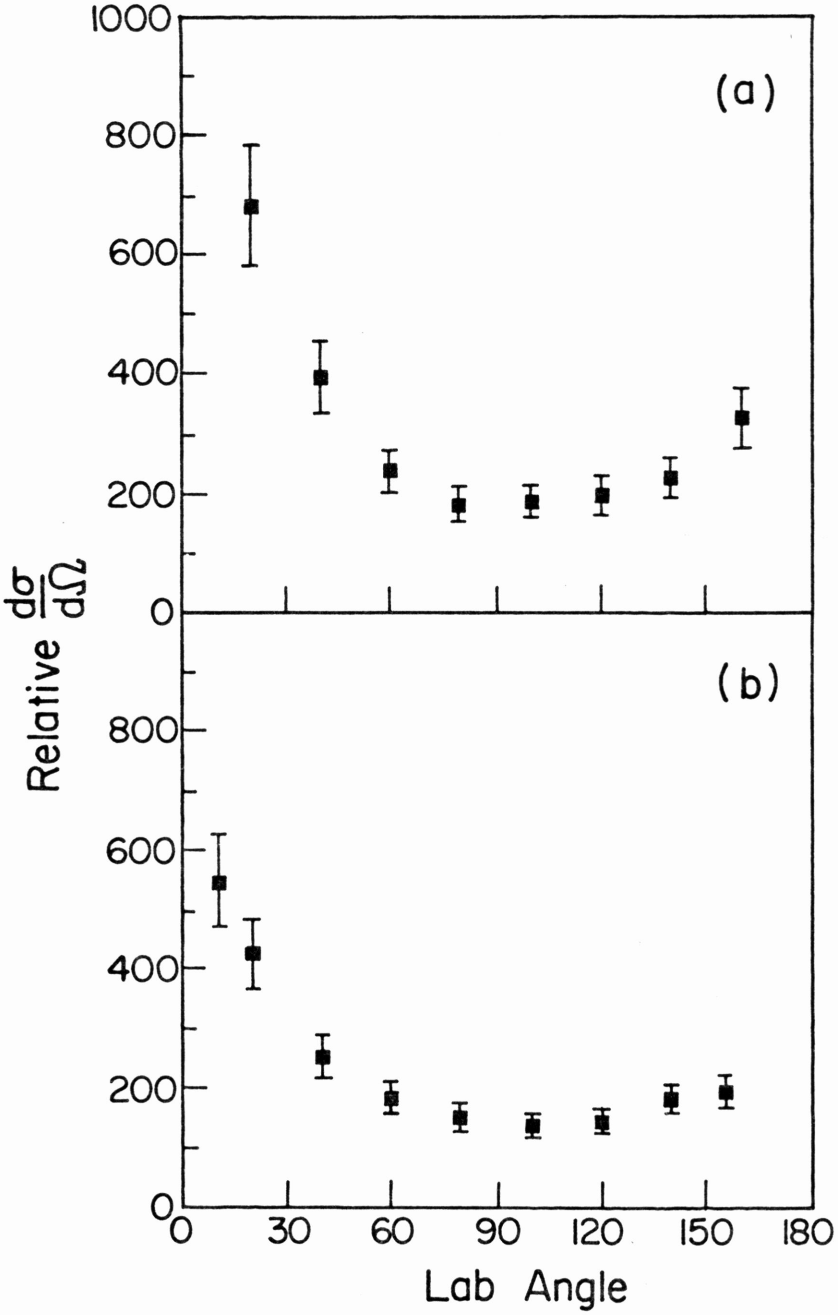

Figure 4. Relative fission fragment angular distributions for (a) 225 MeV B + Au and (b) 320 MeV B + Au.

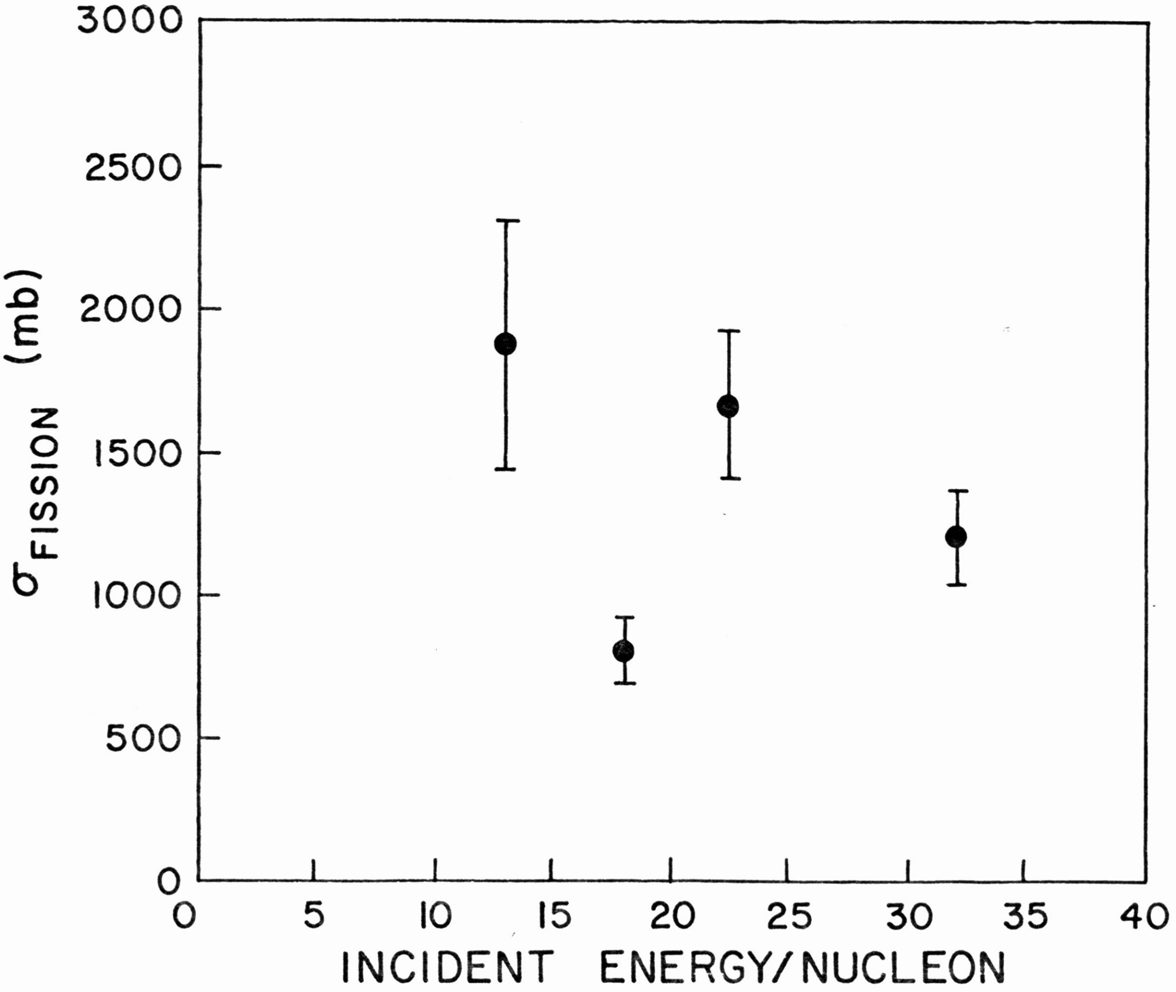

Figure 5. Absolute fission cross-section for B + Au as a function of incident projectile energy.

lead us to believe that the fission cross-section for our system should level out in this range somewhere around 1.3 to 1.6 barns. Of the three that are thought to have normalization trouble, the 13 MeV/nucleon and 22.5 MeV/nucleon cases are somewhat high with values of 1.8 and 1.6 barns respectively. The 18 MeV/nucleon case with a value of only 0.8 barns is substantially lower than expected.

A solid set of cross-sections to establish the fission probability trend in the 10 - 25 MeV/nucleon range is not available. However, we are probably justified in assuming the fission cross-section for 32 MeV/nucleon B + Au of 1.2 barns is a good estimation of the true value. Better certainty in the spatial position of the monitors with respect to the beam is the main argument behind this assertion.

VII. CONCLUSIONS

The limitations of the data presented in the last section though surely disappointing must not be allowed to completely overshadow the useful information that one can reasonably extract from it. If we believe that the fission cross-section for B + Au is on the order of 1.5 barns through the 15 to 25 MeV/nucleon range in projectile energy, our 1.2 barn value at 32 MeV/nucleon seems to indicate that the fission probability does in fact go down at energies comparable to the Fermi energy. Our interpretation would be that this quantity is changing due to a drop in collective behavior. That a drop is occuring as early as 32 MeV/nucleon is certainly interesting. However, without further measurements above and below this energy, we are still lacking the necessary information to say how sharp the change is.

It should also be mentioned that the information contained in the angular distributions can still be used in this study even though some cross-sections were not known in absolute terms. Another experiment would be required in which the absolute $d\sigma/d\Omega$ is accurately measured for one or two of the original detector angles. This will fix the distributon in absolute terms and effectively give us the total fission cross-sections we had hoped to get in the first place.

Our experience in this study can contribute to future work where this same approach is employed. It is clear that a number of accurate cross-sections are needed at rather close energy intervals before one can discuss transition sharpness. Further, it would be useful to attempt a series of measurements on different targets where the degree of importance of fission varies.

In summary, the information generated in the course of this project was not sufficient to offer concrete evidence of a drop in collective behavior at projectile velocities comparable to the Fermi velocity though there were indications to that effect. These will have to wait for future experiments to be confirmed.

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