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FISSION MECHANISMS OF 0.2 TEV URANIUM BEAMS

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In this paper we examine first the contributions of various reaction mechanisms to "clean" fission of ^{238}U projectiles incident on nuclear emulsion at $E/A \approx 1$ GeV. "Clean" fission designates events in which fission occurs but no other charged particle tracks are observed. The examined reaction mechanisms are able to account for only about half of the observed cross section for clean fission. Evidently, charged-particle emission is more strongly suppressed in grazing collisions than our modified soft spheres model can account for. Also examined are the mechanisms for F_1 type events in which fission is accompanied by a small-angle singly or doubly charged particle. We present results of a Monte Carlo code yielding angular and linear momentum distributions following hot-spot nucleon emission or following a nucleon-nucleon quasielastic collision in the grazing passage of the heavy nuclei.

Key words:
NUCLEAR REACTIONS, fission of $E/A = 1$ GeV ^{238}U in nuclear emulsion, reaction mechanisms, clean fission PACS numbers 21.85-W, 25.70 Bc

I. INTRODUCTION

The work of Friedlander, Heckman, and Karant[1] and Jain, Aggarwal, El-Nagdy and Ismail[2] on 0.1-0.9 A · GeV uranium beam reactions in nuclear emulsion poses intriguing new challenges for theory. There have been related heavy ion studies with etchable track detectors, for example, Hudis *et al.*[3] with 2.6 A · GeV ^{14}N beams on uranium and other targets and Tarle *et al.*[4] with 0.96 A · GeV beams incident on CR-39 plastic stacks. However, the emulsion studies offer the additional classification of reactions into "dirty" and "clean" (F_0) fission, according to whether fission is or is not, respectively, accompanied by other tracks. Jain *et al.*[2] have also classified F_1 events, with one or two singly or doubly charged particles. We think that a careful study of these events can shed more light on the details of the reaction mechanisms at work, and we shall suggest some angular correlation measurements that need to be made to help with this analysis.

Bayman, Ellis, Fricke and Tang[5] have attributed a significant role to their impulsive collective nuclear excitation mechanism in the clean fission phenomenon. We shall here estimate contributions of this and various other conventional reaction mechanisms. We find they can account for less than half the observed events, which leaves considerable room for the existence of new processes.

II. THE CLEAN FISSION CROSS-SECTION

In this section we consider different reaction mechanisms which are expected to contribute to clean fission and estimate the cross-section in each case.

A. Reaction mechanisms

1. Coulomb excitation of Giant Modes

Modes like the Giant Dipole Resonance (GDR) and Giant Quadrupole Resonance (GQR) may play an important role as intermediate states leading to clean fission. The Coulomb excitation of such states in Relativistic Heavy Ion Collisions has been studied by Winther and Alder,[6] and expressions for GDR and GQR cross-sections are available.

The GDR cross-section is given by

$$\sigma_{GDR} = \left(\frac{Z_1 e^2}{\hbar c}\right)^2 \sum_{\mu=-1}^{1} \frac{B_2(E1, 0 \to 1^-)}{e^2} \times$$

$$|G_{E1\mu}(1/\beta)|^2 g_\mu(\xi(R)) \qquad (II.1)$$

Above, and in what follows, we adopt the usual notation $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$ and use the subscripts 1 and 2 for quantities (N,Z,A,...) associated to the target and the projectile, respectively. The adiabaticity parameter is

$$\xi(r) = \left(\frac{\hbar\omega}{\hbar c}\right) \frac{r_0}{\beta\gamma} \left(A_1^{1/3} + A_2^{1/3}\right) \quad , \qquad (II.2)$$

and we adopt the value $r_0 = 1.18$ fm. The energy $\hbar\omega$ of the ^{238}U GDR is[7]

$$\hbar\omega \approx 80\, A_2^{-1/3}\ \mathrm{MeV} = 12.9\ \mathrm{MeV} \quad , \qquad (II.3)$$

and we assume that the dipole sum rule is exhausted and

$$B_2(E1, 0 \to 1^-) = \frac{0.19\, N_2 Z_2}{A_2^{2/3}}\, e^2 \mathrm{fm}^2 \quad .$$

$$= 66.4 e^2\ \mathrm{fm}^2 \quad . \qquad (II.4)$$

The quantities G and g are given in Ref. 6.

The GQR cross section is given by[8]

$$\sigma_{GQR} = \left(\frac{Z_1 e^2}{\hbar c}\right)^2 \left(\frac{\hbar\omega}{\hbar c}\right)^2 \sum_{\mu=-2}^{2} \frac{B_2(E2, 0 \to 2^+)}{e^2}$$

$$\times |G_{E2\mu}(1/\beta)|^2 g_\mu(\xi(r)) \quad . \qquad (II.5)$$

In Eq. (II.5) the GQR energy[7] and the reduced transition probability[8] are

$$\hbar\omega = 62\, A_2^{-1/3}\ \mathrm{MeV} = 10.0\ \mathrm{MeV}$$

$$B_2(E2, 0 \to 2^+) \approx \frac{50\, Z_2 \left(r_0 A_2^{1/3}\right)^2}{\hbar\omega}\, e^2\ \mathrm{fm}^4$$

$$= 2.54 \times 10^4 e^2\ \mathrm{fm}^4 \quad . \qquad (II.6)$$

The total Coulomb excitation (COULEX) cross-section σ^{COULEX} can be approximated by the sum $\sigma_{GDR} + \sigma_{GQR}$, and the clean fission cross-section is

$$\sigma_{CF}^{COULEX} = \sigma^{COULEX} \cdot \frac{\Gamma_f}{\Gamma} \quad . \qquad (II.7)$$

The branching ratio (Γ_f/Γ) was obtained from the photofission work of Veyssiere *et al.*[8]:

$$(\Gamma_f/\Gamma) \cong 0.25 \quad .$$

While the ratio of GDR to GQR may not be the same in photofission and Coulomb fission, the former is dominant, so we assume the Γ_f/Γ ratio the same. We have calculated the Coulomb fission cross-section for a 1 GeV · A ^{238}U beam colliding with nuclear emulsion. We have considered the main target nuclei (Ag, Br, N, O, C, H) in the emulsion. We have also estimated the M1 contributions using eqn (3.1) of ref. 6. From J. Arruda Neto *et al.*[9] we take for ^{238}U $\hbar\omega = 6.5$ MeV and $B(M1, 0 \to 1) = 16\mu_0^2 = 0.177 e^2 \mathrm{fm}^2$. The result is $\sigma_{M1} = 0.0033 Z_1^2$ mb. Numerical results are given in Table I.

2. Clean fission (CF) induced by nuclear forces in grazing collisions

We consider here CF induced by nuclear forces through two mechanisms. The first are incoherent collisions involving nucleons in the target and nucleons in the projectile. The second is the coherent action of target nucleons on the projectile, producing a pulse of field of short duration. In both cases quantum effects are neglected.

In a classical collision with impact parameter b the CF probability can be written as a product of two factors. These factors are (1) a fission probability P(b) and (2) a transparency factor T(b), for emission of light charged particles, which would make the fission "dirty." The CF cross section is then given by the integral

$$\sigma_{CF} = 2\pi \int_0^\infty db\, b\, T(b) P(b) \qquad (II.8)$$

a. Incoherent nucleon-nucleon collisions.

If one assumes that the CF cross-section can be expressed in terms of incoherent free collisions between projectile nucleons and target nucleons, a simple estimate with the help of Karol's soft spheres model[10] (SSM) can be made. Karol and others have used his model mainly to calculate total reaction cross sections. For our application we need to consider 8 types of collisions, as listed in Table II.

The basic quantities in our calculation are the transparencies with respect to the collision types listed in Table II. They can be written as functions of experimental nucleon-nucleon cross sections $\sigma_i(E)$ as

$$t_i(b) = \exp\left[-\chi_i e^{-\frac{b^2}{a^2}}\right] \qquad \text{(II.9a)}$$

with

$$\frac{1}{a^2} = \frac{1}{a_1^2 + a_2^2} \qquad \text{(II.9b)}$$

and

$$\chi_i = \frac{\pi^2 \rho_1(0)\rho_2(0) a_1^3 a_2^3}{a^2}\, \sigma_i(E) \quad . \qquad \text{(II.9c)}$$

In the above equations a_1 and $\rho_1(0)$ (a_2 and $\rho_2(0)$) are parameters appearing in a Gaussian parametrization[10] of the target (projectile) density at its surface. They can be associated with proton or neutron densities, according to the collision type [Table II.2].

Equations (II.9a,b,c) are trivial generalizations of Karol's SSM for the total reaction cross-section.

To use the SSM in the calculation of the CF cross-section we have to determine which types of collision, and what fraction of each, contribute to clean fission and to "dirty" processes. For this purpose we make the following assumptions:

1) Any inelastic collision leads to "dirty" events.
2) Whenever a target nucleon suffers a collision it is ejected from the target. Thus, if the nucleon is a proton, a dirty event is produced.
3) When a ^{238}U nucleon suffers a collision it has equal probabilities of acquiring momentum towards the center of the ^{238}U nucleus or away from it. In the former case it is reabsorbed while in the latter it is ejected. (Thus, a struck proton can lead to clean fission if it travels into the uranium being reabsorbed.)
4) In an n-p collision the charge exchange probability is 50%.
5) The cross-sections for clean fission (F_0) as calculated above will, of course, be reduced by the fraction of charged particle evaporation from the uranium compound nucleus. This is expected to be small but not negligible, as later discussion of F_1 events brings out. In spite of the oversimplifications, these assumptions are qualitatively right and should be appropriate for an estimate of the contributions from this mechanism to σ_{CF}.

The fission probability and the "dirty events" transparency can be written

$$P(b) = \sum_{i=1}^{8} (1 - t_i^P(b)) \qquad \text{(II.10)}$$

$$T(b) = \prod_{j=1}^{8} (t_j^T(b)) \qquad \text{(II.11)}$$

In Eqs. (II.10) and (II.11) we have distinguished between nucleon-nucleon transparencies t^P and t^T, appearing in the calculation of P and T. They are both given by Eq. (II.9a) but with the replacement of $\sigma_i(E)$ by the effective cross sections $\sigma_i^P(E)$ or $\sigma_i^T(E)$. These cross-sections are products of $\sigma_i(E)$ with the factors α_i^P and α_i^T, expressing the fraction of $\sigma_i(E)$ contributing to fission and dirty events, respectively. These factors are specified by the assumptions a-d and are given below

$$\begin{array}{llll} i=1 & (n_1n_2) & \alpha_i^P = 1 & \alpha_i^T = 0 \\ i=2 & (n_1p_2) & \alpha_i^P = .25 & \alpha_i^T = .75 \\ i=3 & (p_1n_2) & \alpha_i^P = .25 & \alpha_i^T = .75 \\ i=4 & (p_1p_2) & \alpha_i^P = 0 & \alpha_i^T = 1 \\ i\geq 5 & (\text{inel.}) & \alpha_i^P = 0 & \alpha_i^T = 1 \end{array} \qquad \text{(II.12)}$$

Using Eqs. (II.9) in Eqs. (II.10) and (II.11) and evaluating the integral in Eq. (II.8) we get*

$$\sigma_{CF} \cong \pi a^2 \sum_{i=1}^{3} \ln\left[1 + \frac{\chi_i^P}{\chi^T}\right] \quad , \qquad \text{(II.13)}$$

with

$$\chi_i^P = \chi_i \cdot \alpha_i^P \qquad \text{(II.14)}$$

and

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*In the derivation of Eq. (II.13) we used the fact that $\chi_i^P, \chi^T >> 1$.

$$\chi^T = \sum_{j=1}^{8} \chi_j \cdot \alpha_j^T \qquad \text{(II.15)}$$

We have performed numerical calculations for a 1 · A GeV ^{238}U beam on the main target nuclei in the nuclear emulsion. In the evaluation of the nuclear densities and diffuseness, we used the nuclear parameters of Myers.[1]

The CF cross-section varies slowly with mass number and we got:

heavy elements (Ag,Br) : $\sigma_{CF} \cong$ 180 mb

light elements (N,O,C) : $\sigma_{CF} \cong$ 130 mb (II.16)

b. CF induced by a short pulse of nuclear field.

Bayman, Ellis, Fricke, and Tang[5] developed a simple model which provides an estimate of the energy transferred to the projectile (target) in a collision where the target (projectile) nucleons act coherently as a rapidly moving potential in a classical trajectory with impact parameter ***b***.

If the collision time is short enough, the nuclear matter in the projectile does not have time to respond. While the projectile density is frozen during the collision, each nucleon receives a transverse impulse, and the projectile is excited through absorption of kinetic energy.

The momentum transferred to a nucleon N is represented in Fig. II.1, in the x-y plane containing N. The trajectory, a straight line parallel to the z-axis, is represented by the point Q. Due to the symmetry with respect to the point of closest approach, the nucleons get no net momentum transfer along the z-direction.

The calculation of the momentum transfer $\vec{\Delta} p(\vec{r})$ and the kinetic energy transfer $\Delta\epsilon(\vec{r},\vec{p})$ is straightforward. The momentum transfer depends exclusively on the nucleon location and on the nucleon-target optical potential. The kinetic energy transfer depends also on the nucleon Fermi motion before the collision. The total kinetic energy transferred to the projectile, E*(b), is obtained by integrating $\Delta\epsilon(\vec{r},\vec{p})$ with the initial nucleon distribution in phase-space.

Calculations along these lines have been performed in Ref. 5 for several nuclei, with dominantly attractive nucleon-nucleus optical potentials derived from the interaction of Greenlees *et al.*,[12] and including also Coulomb interaction.

To estimate the importance of this mechanisn in the CF problem we approximate the fission probability P(b) by the step function

$$P(b) = 1 \quad \text{for} \quad b \le b_B \qquad \text{(II.17a)}$$

$$P(b) = 0 \quad \text{for} \quad b > b_B \ . \qquad \text{(II.17b)}$$

The critical impact parameter b_B is determined by the condition that the excitation energy equals the ^{238}U fission barrier V_B

$$E^*(b_B) = V_B \cong 6 \text{ MeV} \ . \qquad \text{(II.18)}$$

This approximation is based on the assumption that the only condition for fission is that enough excitation energy is available.

Our numerical calculations were based on the results of Fricke and Bayman[13] presented in Fig. II.2. There, average projectile excitation energies and numbers of nucleons abraded are given for collisions of 1 · A GeV ^{238}U with Ag, Br, O and C, with different impact parameters. Applying the condition (II.18) on E*(b) we have determined the critical impact parameters, as indicated in Fig. II.2.

To avoid possible inconsistencies in the choice of parameters for T(b) and P(b), we chose to use results of Fig. II.2 in the calculation of T(b), rather than keeping the values of the previous section. For this purpose it is necessary to estimate the fraction β of N, the average total number of nucleon-nucleon collisions, that leads to "dirty" events. This can be done with the help of the α_i^T coefficient [Eq. (II.12)] and, approximating $\sigma_{np} \approx \sigma_{pp}$ and $\sigma_{el} \approx \sigma_{inel} \approx \sigma_T/2$, we get

$$\beta \approx \frac{1}{2} + \frac{1}{2}\left[0.75\left(\frac{Z_1}{A_1}\frac{N_2}{A_2} + \frac{N_1 Z_2}{A_1 A_2}\right) + \frac{Z_1 Z_2}{A_1 A_2}\right] \qquad \text{(II.19)}$$

Using Eq. (II.19) we find

$\beta \cong$ 0.71 for heavy (Ag,Br) targets

$\cong$ 0.80 for heavy (C,O,N) targets (II.20)

The transparency is given in terms of the average number of "dirty" events $\beta\tilde{N}$ as

$$T(b) = \exp[-\beta \tilde{N}(b)] \ . \qquad \text{(II.21)}$$

The resulting cross-sections are given below

$\sigma_{CF}^{Ag} \approx$ 400 mb $\sigma_{CF}^{O} \approx \sigma_{CF}^{C} \approx \sigma_{CF}^{N} \approx$ 80 mb

$$\sigma_{CF}^{Br} \approx 280 \text{ mb} \qquad (II.22)$$

B. Emulsion averaging—comparison to experimental data

1. Emulsion averaging

Before we make any comparison with the experimental data we have to average the cross-sections of the previous section, with respect to the emulsion composition given in Table III.

The emulsion averaging should be performed for the CF cross-sections predicted by each of the three mechanisms in the previous sections. We will use the notation < > to represent emulsion averaged cross-sections.

a. Coulomb excitation ($<\sigma_{CF}^{COULEX}>$).

In performing emulsion averaging for the CF cross-section induced by COULEX in ^{238}U, we neglected contributions from collisions with I and S, which appear in the emulsion in very small amounts, and with H, due to its low charge. We obtained

$$<\sigma_{CF}^{COULEX}> \cong 115 \text{ mb} \quad \text{or}$$

$$<\sigma_{CF}^{COULEX}> = 3.1\% \ \sigma_R \quad , \qquad (II.23)$$

where σ_R is the total reaction cross section[2] ($\sigma_R \sim 3.7$ b).

The above result agrees with the estimate of Ref. 1, made on the basis of the Weizsacker-Williams method.

b. Incoherent nucleon-nucleon collisions

Also in this case we neglected collisions involving S and I. Collisions with H, on the other hand, were considered more carefully.

The contribution of emulsion hydrogen to the clean fission cross section can best be estimated from experiment. That hydrogen contributes is due to the charge-exchange collision with a neutron in uranium. A fast neutron escapes, and the excited uranium fissions. On a less fissionable target the fast charge exchange would lead to (p,xn) residues. Hunter and Miller[15] in 1959 measured $^{209}Bi(p,xn)^{210-x}Po$ reaction cross-sections with 380 MeV protons. For unmeasurable Po cross-sections we can use the Monte Carlo cascade calculations they show to fit the measured cases.

With the help of Table IV we estimate

$$\sigma[U(p,CF)] \approx \sum_x \sigma[Po(p,xn)] \approx 72 \text{ mb} \qquad (II.24)$$

It does not seem worthwhile to try to refine this estimate of the hydrogen contribution, as corrections are of both signs. Uranium is larger than bismuth, a positive correction. Not all the compound nucleus will go to fission, a negative contribution. Contributions lighter than ^{201}Po estimated, a positive contribution. Cross-sections could change in going from 380 MeV to 1 GeV.

Parenthetically, we note that these old experiments tell us about the distribution of excitation energy after the simplest cascade, a single charge-exchange collision. The measured distribution between 3 and 8 neutrons evaporated is quite broad. This is consistent with average excitation energies in Table X of Metropolis *et al.*[16] Monte Carlo cascade studies. For Bi(P,N) cascades $\bar{E}^*$ is 116 ± 77 MeV for 286 MeV protons and is similar for (P,2N), (P,3N) and (P,4N) cascades. Preliminary detailed kinematics analysis by Heckman *et al.*[17] for uranium clean fission in emulsion does seem to show a similar broad range in neutron loss.

With the cross-sections of Eqs. (II.16) and (II.24) we got the emulsion averaged CF cross-section resulting from incoherent N-N collisions

$$<\sigma_{CF}^{N-N}> = 120 \text{ mb} \quad \text{or}$$

$$<\sigma_{CF}^{N-N}> = 3.2\% \ \sigma_R \quad . \qquad (II.25)$$

We should have in mind, however, that this estimate relies upon our assumptions (a-d of the previous section) about which collision-types contribute to fission or "dirty" processes. These assumptions are based on qualitative arguments which allow for some changes. For the purpose of getting an upper limit, $<\sigma_{CF}^{N-N}>_{MAX}$, for the CF cross-section we introduced some changes in our basic assumptions, so as to include other effects which might favor clean fission. Firstly, we took into account that approximately 30% of inelastic collisions would produce an uncharged pion and, consequently, not necessarily lead to dirty events. Secondly, we assumed that Ag or Br protons suffering collisions would be reabsorbed whenever the momentum transfer pushed them towards the center of the nucleus. Finally we considered a "limiting" neutron skin in ^{238}U, in the sense that collisions involving ^{238}U-protons should be neglected. After all these modifications we got the upper limit

$$< \sigma_{CF}^{N-N} > \sim 6\% \ \sigma_R \ . \qquad (II.26)$$

Any evaporation of charged particles from the compound nucleus will shift some of this estimate over into F_1 type events.

c. Short pulse of nuclear field

As in the case of COULEX we will neglect contributions to CF resulting from collisions involving S, I and H. The emulsion averaging was performed with the cross-sections of Eqs. (II.22), and we found

$$< \sigma_{CF}^{N-field} > \cong 115 \text{ mb} \quad \text{or}$$

$$< \sigma_{CF}^{N-field} > \cong 3.1\% \ \sigma_R \ . \qquad (II.27)$$

Assessing the reliability of the above estimate is, however, a difficult task, firstly because it is based on the knowledge of the N-target optical potential for 1 A · GeV collisions, about which very little is known. In the calculations of Refs. 12 and 13, which we used for our estimate, the N-target optical potential was obtained by folding a predominantly attractive N-N interaction with the target density. This choice is questionable, as one would expect that the repulsive part of the interaction would dominate at these energies. A second problem in the estimate of Eq. (II-27) is the classical assumption that fission requires $E^* \geq V_B$. This should be unrealistic in situations where the uncertainty ΔE^* is of the order of E^*. Using the Heisenberg uncertainty relation for a 1 A · GeV collision and considering the nuclear interaction active along a length of 5-10 fm in the trajectory by the point of closest approach we find

$$\Delta E^* \sim 20-40 \text{ MeV} \qquad (II.28)$$

Equation (II.28) shows that one should be careful when using classical approximations in such fast collisions. On the other hand, the inclusion of quantal effects in the model of Ref. 5 presents several difficulties which will be considered in a separate paper.

3. Comparison with experimental data

The CF cross-section for 1 A · GeV ^{238}U ions on nuclear emulsion has been measured by Heckman *et al.*[1] and Jain *et al.*[2] These works agree about the value

$$< \sigma_{CF}^{Exp} > \cong 20\% \ \sigma_R \ . \qquad (II.29)$$

It is clear that none of the mechanisms considered in the previous sections comes close to it. Even summing all mechanisms together (and in that case the effects of the electric field would be double counted), and considering the most favorable possibilities in $< \sigma_{CF}^{N-N} >$ would not produce more than 12%.

This comparison allows us to rule out the possibility that either COULEX or incoherent collisions between nucleons plays a major role in Clean Fission. On the other hand, the comparison of $< \sigma_{CF}^{N-field} >$ would not produce more to the data is still inconclusive, as important quantal effects were neglected in the theory. For the purpose of assessing the importance of such coherent effects more theoretical work is needed. On the other hand, one should also look at other aspects of the experimental data, such as the angular distirubtion, to be considered in the next section.

III. THE CLEAN FISSION ANGULAR DISTRIBUTION

In the laboratory frame the fission fragments continue forward with only a small opening angle. If these angles are transformed to the velocity frame of the excited fissioning compound nucleus, the resulting angular distribution is a further test of theory. Jain *et al.*[2] have presented results showing anisotropic fission favoring 0° over 90° by a factor of ~ 2.3, but the Berkeley group finds an isotropic distribution.[17]

By Aage Bohr's theory the fission angular distribution is determined by the spin I, its projection M on the beam axis, and its projection K on the long axis of the nucleus in the saddle-point transition state.[8,18]

$$W(\theta) = \sum_{IMK} \frac{2I+1}{2} \alpha_{IMK} \, | D_{MK}^{I}(\theta) |^2 \, . \qquad (III.1)$$

where D is a symmetric top function and α_{IMK} is the weight function for the distribution.

For even-even nuclei the lowest fission channel for any spin of either parity likely has K = 0. Hence, the formula simplifies to

$$W(\theta) \approx \sum_{IM} \frac{2I+1}{2} \alpha_{IM0} \, | P_I^M(\theta) |^2 \quad . \qquad (III.2)$$

with P an associated Legendre function.

The general rule for direct nuclear reactions is that $M_r = 0$ along the recoil axis of the compound nucleus. For low energy fusion reactions the recoil axis is the beam axis, but for the very high energy peripheral reactions the recoil axis is nearly perpendicular to the beam axis.

A. Angular distribution in COULEX induced CF

Let us now calculate the angular distribution for giant dipole Coulomb excitation. In this case I = 1. For the M distribution we use a rotation matrix to transform the recoil axis distribution (0 1 0) to the beam axis. (See p. 57 of Ref. 19.) We want the I = 1 rotation matrix for rotation of $\beta = \pi/2$.

$$\begin{pmatrix} \frac{1}{2} & \frac{1}{\sqrt{2}} & \frac{1}{2} \\ -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{\sqrt{2}} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}} \\ 0 \\ -\frac{1}{\sqrt{2}} \end{pmatrix} \qquad \text{(III.3)}$$

Thus, the distribution of $M_r = 0$ along the recoil axis transforms to $M = \pm 1$ on the beam axis. The fission angular distribution is then

$$W(\theta) = |P_1^1(\theta)|^2 = \text{const} \cdot \sin^2\theta \quad . \qquad \text{(III.4)}$$

This GDR Coulomb excitation is thus of opposite sign to the anisotropy reported by Jain *et al.*[2]

Likewise, for GQR going through K = 0 saddle states the anistropy is small but again negative.

$$(W_{GQR}(0)/W_{GQR}(\pi/2)) = 16/19 \qquad \text{(III.5)}$$

However, as R. Vandenbosch pointed out to us, the temperature at saddle may be so high that a statistical mixture of K-states is populated, giving isotropy.

B. Angular distributions in CF induced by nuclear forces

The fission anisotropy contributions from N-N collisions and from impulsive excitation are harder to estimate. To that end we have made some Monte Carlo calculations, extracting not only fission angular distributions but also linear and angular momentum distributions.

First, we consider the impulsive excitation as giving a "hot spot" on the uranium surface. If no nucleon is evaporated before fission, the anistropy is expected to be small. The classical impulsive excitation is like a sharp hammer blow at the grazing point on the uranium surface. This disturbance can be expanded as a set of surface waves with $M_r = 0$ along the recoil axis. To the extent that Coulomb or other isovector terms are present, the expansion includes isovector as well as isoscalar modes. We have already showed that dipole and quadrupole give negative contributions to anisotropy, and that is expected also of higher multipolarities.

We should probably recognize that "hot spots" can decay on a range of time scales. Here the simplification will be to consider (1) instantaneous decay as might come from break-up of an alpha mother cluster (or nucleon pair in the related Feshbach-Zabek[20] peripheral process) and (2) nucleon evaporation from a uranium compound nucleus on a slower time scale.

Suppose the hot spot instantaneously ejects a neutron. If that neutron is reabsorbed in the light collision partner, it will usually give a target track and not contribute to clean fission. (Similar considerations apply to an ejected proton, which may give rise to what Jain *et al.*[2] call an F_1 event, with one singly-charged track associated with the projectile. We defer discussion of F_1 events until later.)

In our Monte Carlo code (in BASIC for PCs) we take a Boltzmann distribution of momentum of the hot spot ejectile neutron and consider the probability, neglected in the previous section, that this neutron interacts with the target. The neutron leaves the point of tangency of the two spheres at time zero, as they touch. The path length (chord) within the light partner is calculated non-relativistically, and a mean-free path is computed from the average experimental nucleon-nucleon cross-section at $E/A \sim 1$ GeV (~ 30 mb), taking a constant nuclear density. The various components of linear and angular momentum of recoil into the uranium are recorded with a weight factor of the survival of the neutron without interaction.

For a neutron ejected from the point A with velocity components v_x, v_y and v_z, as indicated in Fig. III.1, the path lengths through the target are

$$S = 2R_T \cos\theta \quad . \qquad \text{(III.6)}$$

and

$$\tan\theta = [v_y^2 + (v_z + V)^2]^{1/2} / v_x \quad . \qquad \text{(III.7)}$$

The survival probability is $\exp(-S/\lambda)$, where λ is the mean free path.

Table V gives results for various average quantities weighted with survival probabilities at different assumed "hot-spot temperatures"* and collision velocities. Note that the average a_2 coefficient of the Legendre expansion of fission anistropy, $W(\theta)(=1 + a_2P_2(\cos\theta) + ...)$, is always small and negative.

We then modify the code to handle the problem of nucleon-nucleon collisions (soft-spheres mechanism). Instead of assuming the nucleon traversing the light partner comes from a uranium hot spot, we assume the nucleon came from the light partner itself in a nucleon-nucleon collision. We neglect Fermi motion, rationalizing that the local density in the surface region is small, and hence Fermi motion is small. We assume the energy regime of 1 GeV to give predominantly forward (and backward) scattering, so that we can select v_x and v_y to make $P_\perp$ of the order of observed ~ 200 MeV/c in high energy nucleon-nucleon elastic scattering, and we neglect the momentum transfer along the beam. We assume the struck nucleon moving into uranium is always absorbed, and we do a Monte Carlo calculation for the chord length and hence survival of the neutron to pass through the light partner. The assumption of a uniform density and sharp surface is made, giving a mean free path independent of position on the chord for the struck nucleon. The mean free path depends on energy ($\lambda = 1/\rho\sigma_{NN}(E)$).

Table VI summarizes the resulting average quantities for a few values of input parameters. Notice that the results are, in this case, independent of the beam velocity. This is a consequence of the small (neglected in our calculation) momentum transfer along the beam. The coefficients a_2 are larger than those associated with hot spot emission but they are, again, negative.

The average total angular momenta are sizable, but it is hard to think how this could be measured experimentally. The average perpendicular momentum is small compared to the total momentum of the uranium beam, so that may also be hard to measure.

We have seen that all mechanisms so far have given negative contributions to fission anistropy in contrast to the positive values of Ref. 2. The recent analyses of the Heckman group[17] disagree and show isotropy. However, we have not been consistent in considering the uranium hot spot ejecting one neutron. The fissioning system would then be odd-mass ^{237}U, and there is a chance that the low states at fission saddle have large K values K ≈ I, rather than small. Such channels could give positive contributions to anisotropy.

IV. F_1 TYPE EVENTS, ONE LIGHT FORWARD TRACK (p,d,t,($\pi^\pm$) ACCOMPANYING FISSION

Jain *et al.*[2] also classify and study so-called F_1 events, those in which the uranium fission is accompanied by one or more lightly ionizing particle in the forward cone. They speak of (p,d,t or α) and give a further breakdown of this class. They find F_1 events are 8% of all interactions, compared to 20% for F_0 events. Of this 8%, 3% are a single a, 3% are a single p, d, or t, and 2% are more than one. Presumably, the emulsion only distinguishes between charge | 2| and charge | 1| , so ^3He and other bound He species could be admixed with alphas. Also charged pions could be admixed in charge | 1| .

Of the various mechanisms we considered Coulomb excitation of giant resonances should not give F_1 events, since the energy deposition is too low.

That part of F_1 events coming from excitation and instantaneous break-up of alpha clusters in the surface will contribute to singly charged vs. doubly charged in the ratio of $^3He/(p + d + t)$ as observed in alpha break-up studies on nuclei at comparable energies.

Budzanowski and colleagues in two papers[21] have studied a-particle break-up on nickel targets at E_α^{lab} of 172.5 MeV. They see substantial break-up into ^3He + n and into ^3H + p. Their beam energy is too low to make quantitative use of their cross sections, however. If this instantaneous break-up component can be neglected, we then have an evaporation alpha/proton ratio governed by standard Hauser-Feshbach theory. Evaporated alphas and protons may be expected to be nearly equal, since the Coulomb barrier height above the binding energy is comparable for alphas and protons in the heavy elements. That such charged-particle evaporation can compete at all with neutron evaporation implies large excitation energies to give pre-equilibrium emission.

*The term "temperature" here is merely a parameter for the Boltzmann distribution of velocities from instantaneous break-up, as in pre-equilibrium emission. Presumably a lower temperature prevails in the nucleon evaporation on a longer time scale.

The experimenters have not reported on the angular distribution of the doubly- and singly-charged particles in F_1 events. Such a measurement would be of interest to give an effective temperature for the pre-equilibrium emission.

It would be valuable to remeasure emulsions to determine azimuthal correlations of the F_1 light particle(s) with respect to the plane of the fission fragments.

There is an extensive literature on the angular and energy distributions of alphas accompanying fission. We cite the work of Radi *et al.*[22] as one of the more recent theoretical studies, and it gives references to contemporary work and earlier work. A general conclusion is that the Coulomb field of the outgoing fission fragment strongly steers the alpha in the perpendicular direction. Anticorrelations between uranium beam fission fragments and the light particles in F_1 events would signify that the particle emission and fission occur in the same time frame. If the light particles are direct reaction products and the fission occurs on a slower time frame from a compound nucleus, the azimuthal anticorrelation may be weak or absent.

V. SUMMARY

Adding up contributions of all the clean fission mechanisms we know leaves us a factor of two short of explaining the observed 20% F_0 and 8% F_1 events.

It seems unlikely that the ~ 3% contribution of Coulomb excitation to the giant electric dipole and quadrupole resonances can be of such uncertainty that would affect the overall discrepancy. Inclusion of electromagnetic excitation of higher electric multipoles and of magnetic multipoles seems unlikely to have a significant effect, particularly since much of the isoscalar E3 strength lies below the fission threshold.

Likewise, the nucleon-nucleon knock-out processes give too small a fraction (3%) for their uncertainties to significantly affect the shortfall. We have varied parameters to give uranium a "neutron skin" but find the clean fission cross-section only slightly increased.

There is uncertainty in the impulsive collective excitation by nuclear force field. We have used the double-folded attractive nuclear potential calculations kindly supplied to us by Fricke and Bayman.[13] In principle this classical calculation sums over all modes, isoscalar and isovector. Their calculation takes into account Fermi motion and both Coulomb and nuclear forces. It is not clear that their static attractive potential without a repulsive core is appropriate to the GeV/u energy range. Their Coulomb nuclear interference is destructive, whereas Coulomb-core interference would be constructive. The uncertainty that deserves further theoretical study is the classical approximation. The needed 5 MeV for fission is comparable to or smaller than the participating nuclear modes. A mode-by-mode quantum mechanical treatment would much smear the sharp cut-off impact parameter giving 5 MeV excitation. Larger impact parameters than the classical critical value could contribute, but it still seems unlikely that the quantum corrections could double the overall cross-section of F_0 events. However, as discussed in the next paragraphs, the unexplained cross section may be to highly excited uranium, where the impulsive mechanism contributes little.

Before responding to the referee's requirements of early 1986, we decided to wait for further analysis by the Berkeley emulsion group.[17] They have taken angle and range measurements of clean fission to compute various distributions with the assumption that Z/N of both fragments is the same.

In order to get colinearity of fission fragments in the beam velocity frame, they assume a loss of mass in the form of unobserved neutrons. This loss is quite large, averaging 20 neutrons, implying that most fission is from rather highly excited (> 100 MeV) uranium. The other distributions determined are consistent with such high excitation. That is, the fragment mass distribution is peaked for symmetric fission and the fission fragment angular distribution in the beam velocity frame is isotropic. The fission kinetic energy Q_f is quite ordinary (~ 200 MeV), but Q_f is known not to vary much with excitation energy. Both the determined distribution of fragments mass ratios and the fission fragment angular distribution differ somewhat from those of ref. 2, which seemed to point to fission of low excitation energy. In ref. 2 there was no report of apparent momentum (i.e., neutron) loss. The forward momentum loss could be due in part to a systematic "frictional" loss in the collision as well as to neutron loss.

The excitation energy distribution in clean fissioning uranium is crucial to the theoretical interpretation.[1] If excitation is high (> 100 MeV), then our soft-sphere model for nucleon-nucleon collisional contributions needs to be corrected to suppress knock-on proton emission. Perhaps the combined Coulomb fields of target and projectile nuclei act somehow to suppress proton emission. Perhaps collisions involving neutrons rather than protons are enhanced for reasons we do not understand, such that more deeply scraping collisions can occur without proton or alpha emission from either partner.[2] If excitation of the fissioning uranium is low, as the work of ref. 2 indicates, then we must seek to explain the 10% of geometric cross section in terms of new mechanisms transferring modest excitation at large impact parameters.

Until the questions of experimental analysis are resolved we believe it better simply to present our model calculations of the December, 1985, submission, rather than develop modifications to account for missing cross section assuming correctness of one or the other experimental group.

While emulsions have an almost unique advantage in showing what happens in both grazing collision partners, it may be that uranium beam interactions in gas or thin targets of streamer chambers could be useful. Streamer chamber measurements would avoid the emulsion averaging over different elements, and the magnetic curvature of F_1 light particles could better dissect such events.

We believe there is much valuable to be learned from further exclusive measurements of peripheral heavy ion collisions.

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FIG. II.1. The momentum transfer in a projectile nucleon, according to the mechanism of Ref. 5. For details see the text.

FIG. II.2. Average excitation energy (a) and number of nucleons abraded in ^{238}U vs. impact parameter, for several target nuclei. The results are from Ref. 13.

FIG. III.1. Neutron evaporation from a hot spot in the ^{238}U surface.

TABLE I. Calculated Coulomb fission cross sections of ^{238}U at 1 GeV/u.

Target element	Ag	Br	N	O	C	H
σ_{CF}^{COULEX}(mb) (E1+E2)	550	305	15	20	11	0.3
σ_{F}^{COULEX} (M1)	7	4	0.2	0.2	0.1	0.003
σ_{F}^{COULEX} (Total)	557	309	15.2	20.2	11.1	0.3

TABLE II. Types of nucleon-nucleon collision.

1. Elastic n_1 - n_2 collisions	5. Inelastic n_1 - n_2 collisions
2. Elastic n_1 - p_2 collisions	6. Inelastic n_1 - p_2 collisions
3. Elastic p_1 - n_2 collisions	7. Inelastic p_1 - n_2 collisions
4. Elastic p_1 - p_2 collisions	8. Inelastic p_1 - p_2 collisions

TABLE III. Composition of the nuclear emulsion used in the experiments.

Target nucleus	Ag	Br	I	C	N	S	H	O
composition (atomic %)	12.78	12.71	0.07	17.30	3.92	0.16	40.82	12.23

TABLE IV. Bi(p,xn) cross-section from Hunter and Miller.[11]

A	207	206	205	204	203	202	201
x	3	4	5	6	7	8	9
σ_{exp}(mb)	12(theor.)	8	13	9	12	5	13

TABLE V. Average quantities from our Monte Carlo calculation for ejection from a hot spot, with 15000 events. $\langle E_n \rangle$ is the average energy of the ejected neutron and a_2 is described in the text.

V/c	Hot spot temp. (MeV)	p_z (MeV/c)	$p_\perp$ (MeV/c)	$L/\hbar$	$L_z/\hbar$	E_n (MeV)	a_2 (× 100)
0.0	5	113	123	6.1	4.3	15.1	-2.0
	15	196	213	10.5	7.5	45.5	-3.0
	25	254	275	13.6	9.6	75.3	-3.3
0.4	5	96	119	5.2	3.7	12.5	-1.6
	15	166	202	9.2	6.7	36.7	-3.1
	25	221	264	12.2	8.9	63.8	-5.7
0.6	5	95	121	5.1	3.7	12.8	-1.5
	15	164	203	9.0	6.5	36.6	-2.8
	25	215	259	11.7	8.4	60.7	-3.2

Linear and angular momentum values above are root mean square averages.

TABLE VI. Monte Carlo calculations in the Soft Spheres model. E_0 is an energy parameter specifying the momentum distribution and E_n is the average kinetic energy of the ejected nucleon, weighted with survival probabilities. Owing to the neglect of the momentum transfer along the beam $p_\perp = p$ and $L_z = L$.

V/c	E_0 (MeV)	p_z (MeV/c)	$L/\hbar$	E_n (MeV)	a_2
0.0	5	160	4.8	13.7	-0.10
	15	266	7.6	37.9	-0.12
	25	338	9.5	61.5	-0.13
0.4	5	159	4.7	13.6	-0.10
	15	266	7.6	38.0	-0.12
	25	340	9.5	61.9	-0.13
0.6	5	159	4.8	13.7	-0.10
	15	267	7.6	38.1	-0.12
	25	338	9.5	61.3	-0.13

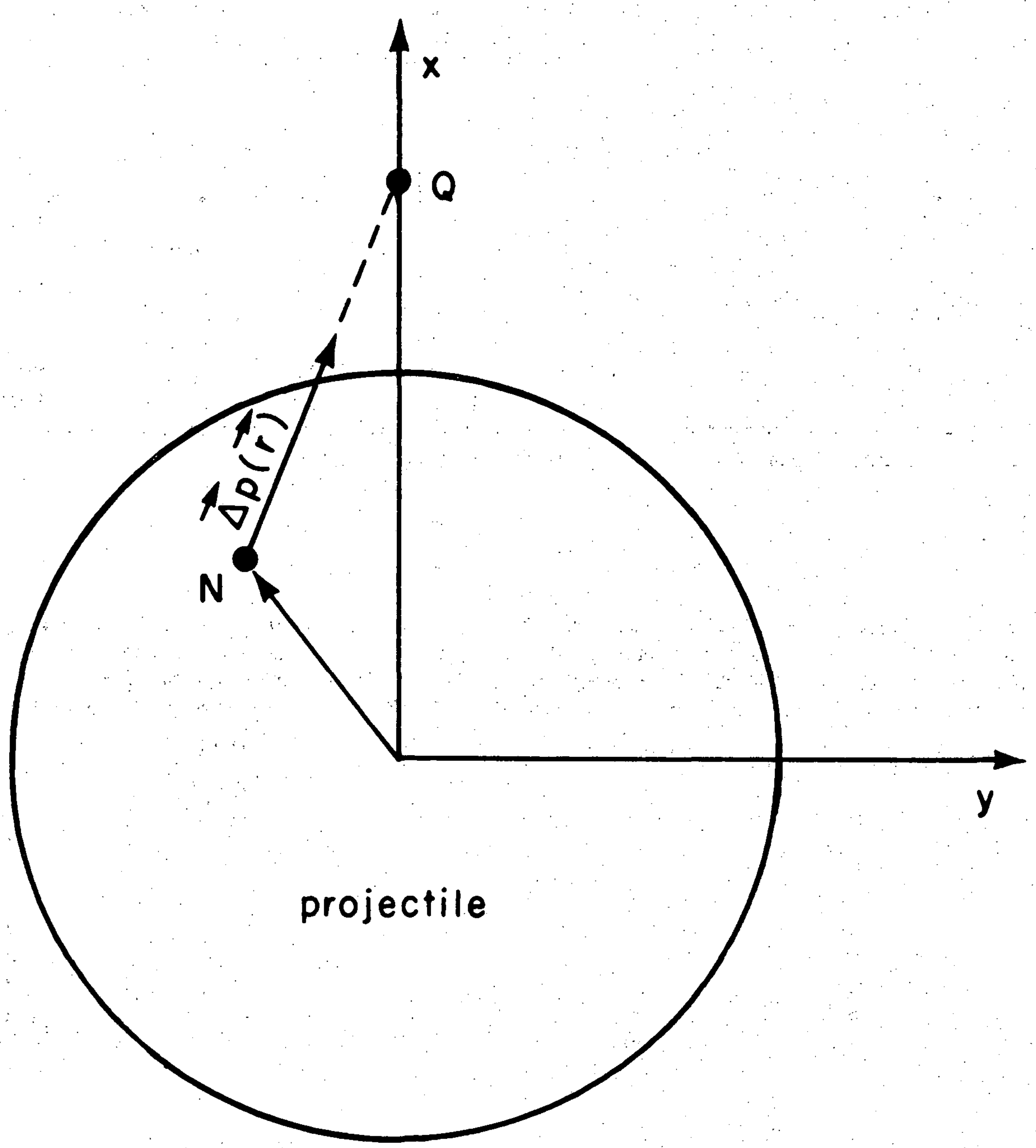

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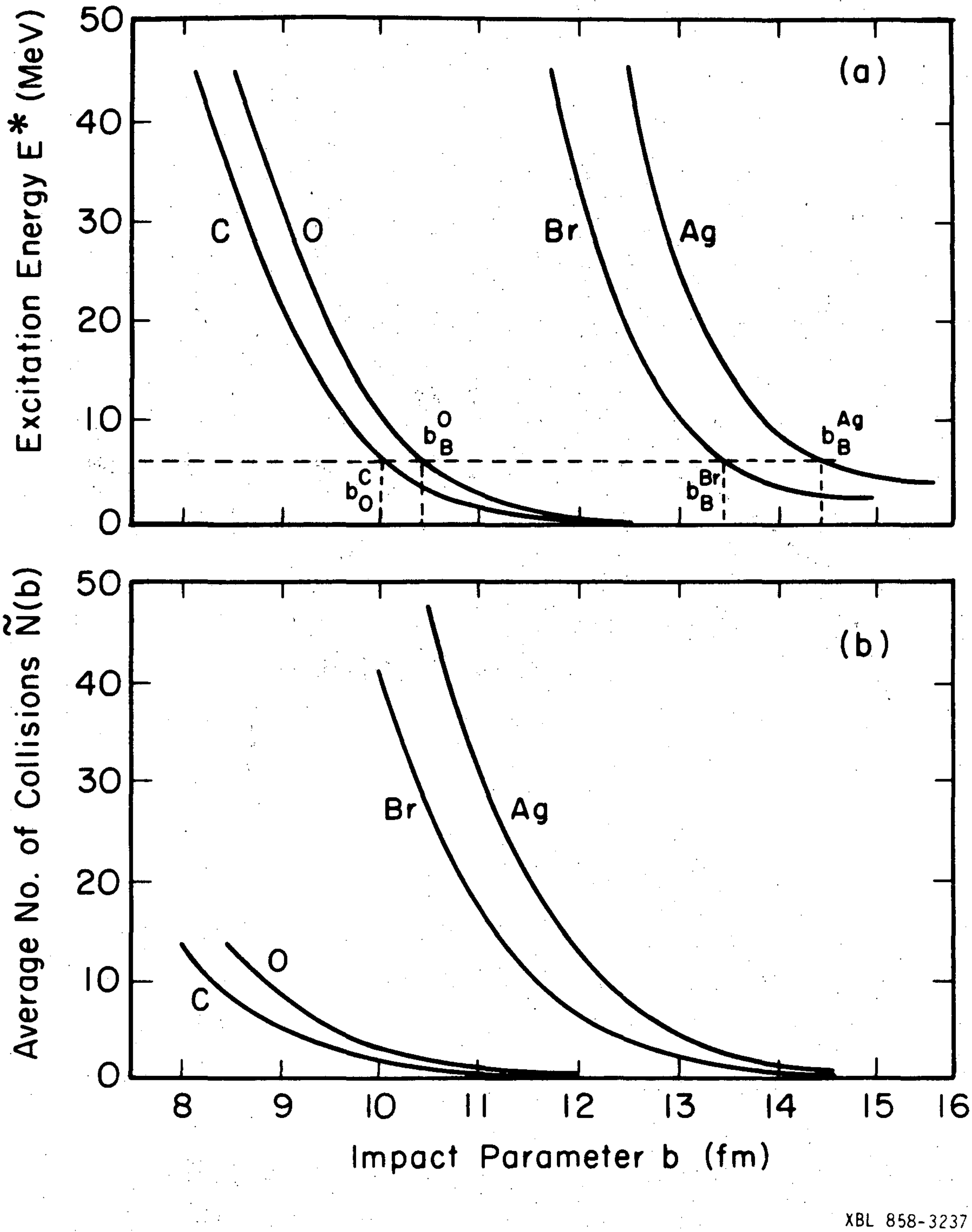
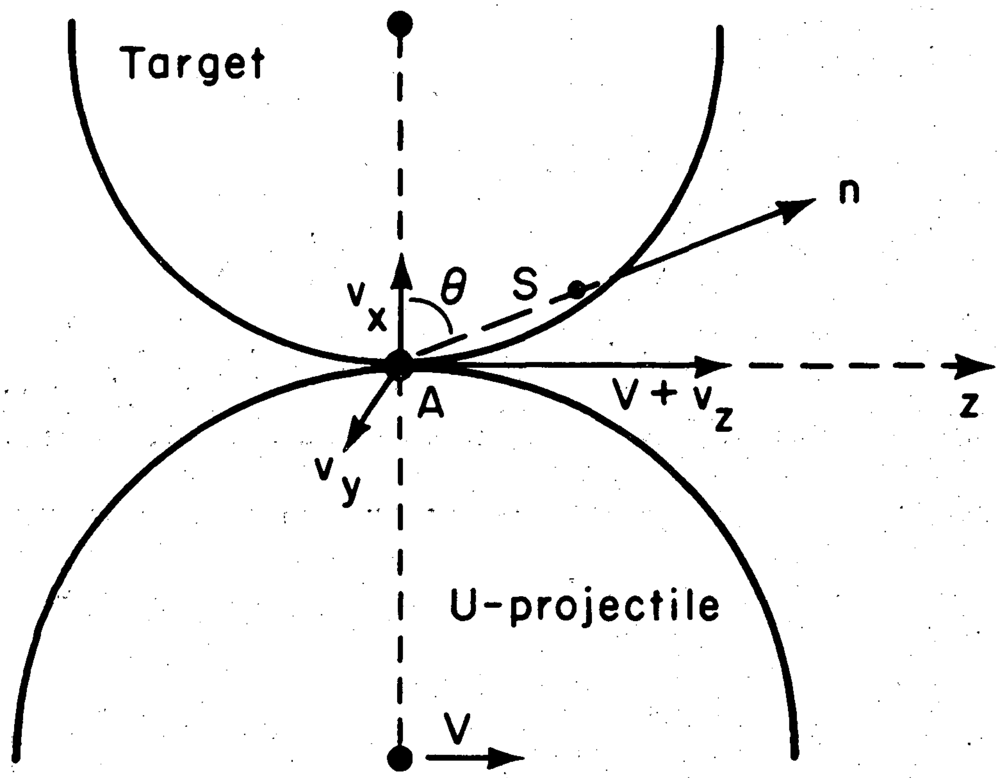
Fig. II.1



Excitation Energy E* (MeV)
50
40
30
20
10
0
(a)
C
O
Br
Ag
b_O^C
b_B^O
b_B^{Br}
b_B^{Ag}
Average No. of Collisions $\tilde{N}(b)$
50
40
30
20
10
0
(b)
Br
Ag
O
C
8
9
10
11
12
13
14
15
16
Impact Parameter b (fm)
XBL 858-3237

Fig. II.2



XBL 858-3235

Fig. III.1

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