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Nucleon transport processes in fission and heavy ion reactions

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Abstract. The nucleon exchange process between two nuclei in close proximity and its application to an explanation of fragment mass and charge distributions in fission and in heavy ion deep inelastic collisions are reviewed. An analysis of the measured correlations between the energy loss from relative motion and the fragment mass and charge variances in the heavy ion deep inelastic collisions is presented. The recent data on fragment mass and charge variances as a function of the fragment kinetic energy in thermal neutron induced fission of ^{235}U, lends added support to the hypothesis that the nucleon transport process plays a similar role both in fission and in heavy ion deep inelastic collisions.

Keywords. Nucleon transport process; fission; heavy ion reaction; stochastic theory; nucleus-nucleus collision.

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1. Introduction

Nucleon exchange between the two nascent fragments formed during the fission process near the scission point as the mechanism leading to the observed mass distributions in fission was first proposed by Ramanna (1964) nearly two decades ago. More detailed models (Ramanna *et al* 1965; Ramanna and Ramamurthy 1969; Ramamurthy 1971; Prakash *et al* 1980) based on the above nucleon exchange mechanism were subsequently developed to satisfactorily explain the general features of the fragment mass and charge distributions in fission. In recent years, with the availability of a variety of accelerated heavy ion beams to study heavy ion-induced nuclear reactions, the nucleon exchange process taking place between two nuclei in close proximity has found additional experimental support from the study of deep inelastic heavy ion collisions. In fact, studies of nucleus-nucleus collisions at medium energies have now made possible investigations of the nucleon transport processes in a systematic and almost controlled manner. During the last decade, the large body of experimental data on the conversion of the relative kinetic energy into fragment excitation energies (commonly referred to as energy dissipation or energy loss), transfer of orbital angular momentum to the fragment spins and nucleon transfers between the target and the projectile in a nucleus-nucleus collision have been analysed in terms of the relevant transport coefficients which have found explanation in terms of statistical exchange of nucleons between the target and the projectile (see reviews by Schroder and Huizenga 1977; Lefort and Ngo 1978; Weiden Muller 1980; Gobbi and Norenberg 1980; Kapoor 1982 and references cited therein). These studies have also established that a significant number of nucleon exchanges take place in the very short interaction times of few times 10^{-21} sec involved in the deep inelastic collisions. In this work, we present a brief review of the nucleon exchange process operating between two nuclei in proximity, and its application to the fission process and heavy ion reactions.

2. Stochastic theory of fragment mass and charge distributions in fission

The application of the nucleon exchange mechanism for an explanation of the fragment mass and charge distributions in fission is based on the fact that during the last stages of the fission process, the fissioning nucleus can be well approximated by two weakly interacting nascent fragments. If one assumes that the relative motion of the nascent fragments is slow compared to the characteristic time for a nucleon transfer, the process can be treated as a stochastic process where not only the nascent fragments are in thermodynamic equilibrium within themselves but they also attain mutual equilibrium among themselves with respect to nucleon and energy transfers. The observed distributions of the fragment mass and charge then correspond to the equilibrium distribution near the scission point. Ramanna and coworkers (Ramanna *et al* 1965; Ramanna and Ramamurthy 1969) have given the theoretical formulation of the nucleon exchange process between the two nascent fragments for the calculation of the equilibrium mass and charge distributions. Considering for the sake of illustration a one-component system, the configuration of the fissioning nucleus at any instant near the scission point can be defined by specifying the number of nucleons on either side. Let ω_M be the probability that the fissioning nucleus has a configuration with M nucleons in the heavy side, the number of nucleons in the light side being determined from the total nucleon number conservation. If $P_{M',M}$ denotes the probability that a configuration with M' nucleons in the heavy side goes over to the configuration with M nucleons in the same side in a small interval of time Δt, one has

$$w_M(t+\Delta t) = \sum_{M'} w_{M'}(t) P_{M',M}$$

By definition

$$\sum_M P_{M',M} = 1 \quad \text{and} \quad \sum_M w_M = 1$$

Under the condition of complete equilibrium in the mass asymmetry degree of freedom, one has $w_M(t+\Delta t) = w_M(t)$. If the unit of time Δt is sufficiently small and one can neglect cluster transfers

$$P_{M',M} = 0,\ M \neq M' \text{ or } M' \pm 1$$

It has been shown that under these conditions the probabilities w_M follow the simple relation

$$w_{M+1}/w_M = P_{M,M+1}/P_{M+1,M} \tag{1}$$

Thus the ratio of the probabilities for adjacent configurations M and $M+1$ are simply equal to the ratio of the nucleon transfer probabilities in the directions $M \rightarrow M+1$ and $M+1 \rightarrow M$. A generalization of (1) in two dimensions to consider both proton and neutron transfers, gives

$$w_{N,Z}(t+\Delta t) = \sum_{N'} \sum_{Z'} w_{N',Z'}(t) P_{N'Z',NZ} \tag{2}$$

The steady state solution of w is given by

$$w_{N,Z} = \sum_{N'}\sum_{Z'} w_{N',Z'} P_{N'Z',NZ} \tag{3}$$

The probabilities w and P are also subject to the constraints

$$\sum_{N}\sum_{Z} w_{N,Z} = 1 \tag{4}$$

$$\sum_{N}\sum_{Z} P_{N'Z',NZ} = 1 \tag{5}$$

Assuming single-nucleon transfers, one gets

$$P_{N'Z',NZ} = 0 \quad N \neq N',\ N' \pm 1 \tag{6}$$

$$Z \neq Z',\ Z' \pm 1$$

Equation (3) can be solved numerically to obtain the probability distribution w, provided the transition probabilities are known. It is seen from the above equations that the central quantities which decide the mass and the charge distributions are the transition probabilities $P_{M',M}$ and $P_{N'Z',NZ}$ which are in turn given by the single-nucleon transfer probabilities from one of the fragments to the other.

Figure 1 illustrates the mechanism of nucleon transfers between the two nascent fragments. If the fragments are cold, the direction of spontaneous transfer of nucleons is from the fragment having the higher Fermi energy to the one having lower Fermi energy. Even if the nascent fragments have some excitation energy, a tendency for a preferential transfer of nucleons in the direction of decreasing chemical potential

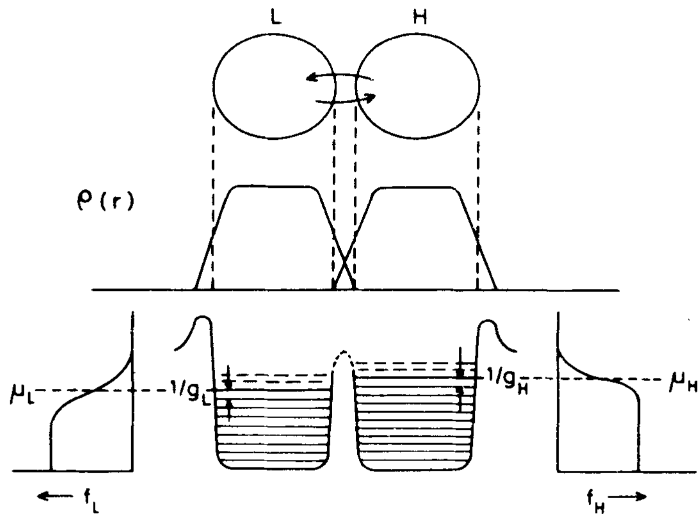

Figure 1. Schematic diagram illustrating the nucleon exchange mechanism between the fragments L and H. $\rho_{L/H}(r)$ represents the diffuse densities, $g_{L/H}$ are the single particle level densities, $f_{L/H}$ are the Fermi-Dirac occupation probabilities and $\mu_{L/H}$ are the chemical potentials of the fragments L and H respectively.

persists. A quantitative estimate of the relative probabilities of nucleon transfers in both directions can be made as (Prakash *et al* 1980; Ramanna and Ramamurthy 1969)

$$P_{M,M+1} = \frac{2\pi}{\hbar}\int g_L(E)f_L(E)g_H(E)[1-f_H(E)]\,|M_{LH}|^2\mathrm{d}E \tag{7}$$

$$P_{M,M-1} = \frac{2\pi}{\hbar}\int g_H(E)f_H(E)g_L(E)[1-f_L(E)]\,|M_{HL}|^2\mathrm{d}E \tag{8}$$

Here $g_L(E)$ and $g_H(E)$ are the single particle energy level densities and $f_L(E)$ and $f_H(E)$ are the Fermi-Dirac occupation probabilities in the light and the heavy nascent fragment respectively. The matrix elements of transfer M_{LH} and M_{HL} are equal because of microscopic reversibility. Since the main contribution to the integral comes from a small energy band around the chemical potentials of the two nascent fragments, the quantities g_L, g_H and the matrix element of transfer can be calculated at the mean chemical potential and taken out of the integral. One then has

$$P_{M,M+1} = \frac{2\pi}{\hbar}|\bar{M}|^2 g_L(\bar{\mu})g_H(\bar{\mu})I_{LH} \tag{9}$$

where

$$I_{LH} = \int f_L(E)[1-f_H(E)]\mathrm{d}E \tag{10}$$

and $\bar{\mu}$ is the mean chemical potential. A similar expression for $P_{M,M-1}$ can also be written. For a nearly degenerate system like a nucleus having a temperature much less than the mean chemical potential, one gets

$$I_{LH} = \frac{(\mu_H-\mu_L)}{e^{(\mu_H-\mu_L)/T}-1} \tag{11}$$

where μ_H and μ_L are the chemical potentials of the two nascent fragments. Thus the main driving force for the net transfer of nucleons from one of the fragments to the other is the difference in their chemical potentials though a finite temperature induces nucleon transfers in both directions.

In the limit of zero temperature, the difference in the chemical potentials is equal to the negative of the difference in the nucleon separation energies of the two nascent fragments, neglecting the small rearrangement energies. For finite temperatures, one can include a temperature dependence of the chemical potential in such a way that the shell effects on the chemical potential vanish at high temperatures. Figure 2 shows a typical plot of the difference in the chemical potentials versus the mass ratio for the case of ^{236}U fission (Prakash *et al* 1980). The fact that the difference $(\mu_H-\mu_L)$ is negative for all configurations upto neutron number $N = 86$ and is positive for all configurations above $N = 86$ is responsible for the increasing yields of the heavy fragments upto $N = 86$ and a decrease in the yield thereafter. Figure 3 shows typical mass distributions for the fission of ^{226}Ra, ^{252}Cf and ^{256}Fm as calculated from this model. It can be seen that the calculations reproduce the known qualitative features for all cases and even such details as the triple hump for ^{226}Ra fission are reproduced.

One of the early criticisms of the nucleon exchange model for explaining the fragment mass and charge distributions in fission was whether sufficient time is

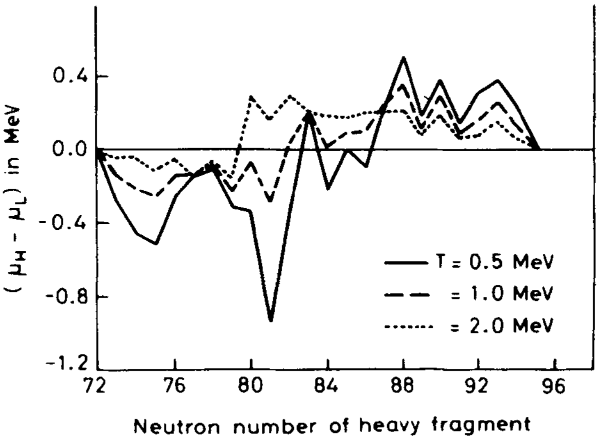

Figure 2. Difference in the chemical potentials of the light and heavy fragments as a function of the neutron number of the heavy fragment. The individual separation energies are calculated for the most probable deformations of the light and heavy fragments. Results are shown for mean fragment temperatures $T = 0{\cdot}5$, $1{\cdot}0$ and $2{\cdot}0$ MeV.

available for an appreciable number of nucleon transfers to take place during the descent from the saddle to the scission point. Direct experimental evidence for substantial nucleon exchange between two nuclei in close proximity in interaction times of the order of 10^{-21} sec has now come from the studies of heavy ion deep inelastic collisions.

3. Nucleon exchange processes in nucleus-nucleus collisions

It is now well known that in reactions induced by heavy ions, a sizable cross-section appears in a new process called deep inelastic collisions. These reactions are characterised by a rather short interaction time of few times 10^{-21} sec during which a large fraction of the kinetic energy of the colliding nuclei gets converted into intrinsic fragment excitation energies. In addition, a large number of nucleons are also exchanged between the target and the projectile as inferred from the observed width of the mass and charge distributions of the target-like and the projectile-like binary fragments emitted as the reaction products. An important observation is the presence of strong correlation between various quantities such as the kinetic energy loss from relative motion, fragment mass and charge widths and the angular momentum transfer (see for example, Wollersheim *et al* 1982; Dyer *et al* 1980; Dakowski *et al* 1982). A nucleon exchange mechanism similar to the one proposed earlier for an explanation of fragment mass and charge distributions in fission has been found to be useful in bringing out the main features of the deep inelastic collision process. One difference between the earlier model for fission and that for deep inelastic collisions comes from the effect of the relative motion of the two ions exchanging the nucleons. In addition, unlike the case of fission, in deep inelastic collisions the number of nucleon transfers are not sufficient to attain complete equilibration in the nucleon exchange degree of freedom. Under these conditions, it is advantageous to define the nucleon drift and the

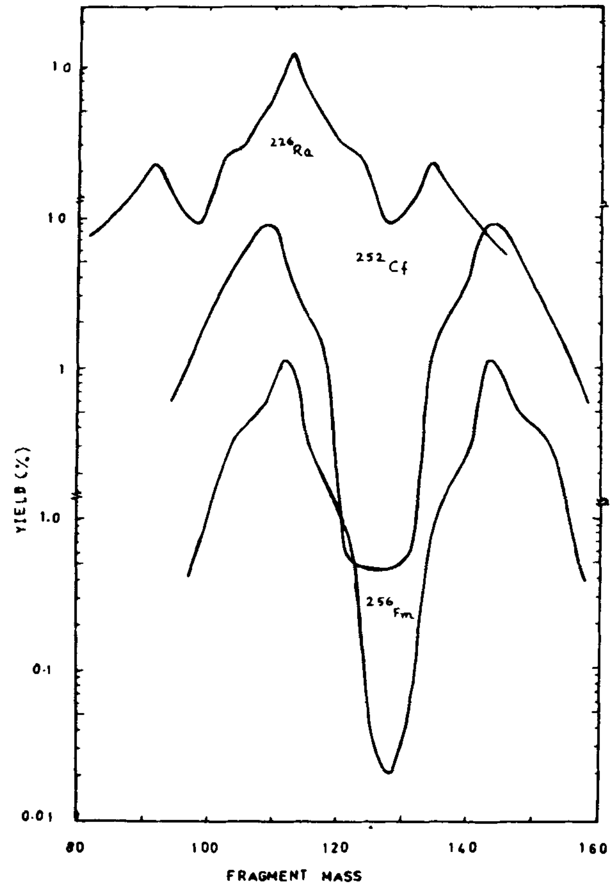

Figure 3. Calculated fragment mass yields for the fission of ^{226}Ra, ^{252}Cf and ^{256}Fm with a mean fragment temperature of $T = 0.5$ MeV.

diffusion coefficients within the Fokker-Planck approximation (Prakash *et al* 1981). Theoretical formulations of the nucleon exchange process between two ions in relative motion and the resulting transport coefficients can be found in the recent literature pertaining to the heavy-ion deep inelastic collisions.

Considering the relative motion between the colliding nuclei, the fermion nature of the exchanged particles and the associated Pauli blocking effect, it has been shown (Randrup 1977) that the diffusion of nucleons between the two nuclei results in a time variation of the width of the fragment mass distribution as

$$d\sigma_A^2/dt = N'_A \langle w \coth \frac{w}{2T} \rangle_F \tag{12}$$

where N'_A is the differential total particle current, w is the change in excitation energy associated with the transfer of a nucleon, T is the temperature of the system. The suffix F denotes that the average is taken around the mean value of the Fermi energies of the two nuclei. It is easy to see that the quantity w, denoting the change in excitation energy on account of transfer of a nucleon from one nucleus to the other having a relative velocity $\mathbf{v}$ is given by

$$w = F_A - \mathbf{p}.\mathbf{v}$$

where F_A is the difference in the Fermi energies and $\mathbf{p}$ is the momentum of the transferred nucleon.

The rate of the resulting energy dissipation is given by

$$-\frac{\mathrm{d}E}{\mathrm{d}t} = N'_A \langle w^2 \rangle_F \tag{13}$$

In most cases of the deep inelastic heavy ion collisions, it is a good approximation to take

$$\coth(\langle w^2 \rangle_F)^{\frac{1}{2}}/2T \approx 1$$

and (12) is then often approximated as

$$\mathrm{d}\sigma_A^2/\mathrm{d}t \approx N'_A(\langle w^2 \rangle_F)^{\frac{1}{2}} \tag{14}$$

From (13) and (14) it then follows that

$$-\mathrm{d}E/\mathrm{d}\sigma_A^2 = (\langle w^2 \rangle_F)^{\frac{1}{2}} \tag{15}$$

For peripheral collisions, where most of the nucleon transfers take place, (15) reduces to

$$-\mathrm{d}E/\mathrm{d}\sigma_A^2 \simeq \left[\frac{m}{\mu} E E_F\right]^{\frac{1}{2}} \approx \alpha \frac{m}{\mu} E \tag{16}$$

where m is the nucleon mass, μ is the reduced mass of the di-nuclear complex and E_F is the average of the Fermi kinetic energies of the two nuclei. E is the kinetic energy in relative motion above the Coulomb barrier V_c given by

$$E = E_{\mathrm{cm}} - V_c(R_{\mathrm{int}}) - E_{\mathrm{loss}}$$

R_{int} refers to the interaction distance between the colliding ions, and E_{loss} is the energy loss from the relative motion. In a slightly different approximation, one obtains

$$\mathrm{d}\sigma_A^2/\mathrm{d}t \approx N'_A \langle |w| \rangle_F$$

which when flux-averaged gives an additional factor of $3\pi/8$ over that of (16). Although we base the following discussion on the use of (16), the main conclusions would remain unaltered if the factor $3\pi/8$ is included. For the classical case of exchanged particles being motionless in the individual nuclear containers, α will be unity. Thus, the value of

$$\alpha = \left(\frac{\mu}{m}\frac{E_F}{E}\right)^{\frac{1}{2}}$$

in (16) results from the consideration of the Fermi nature of the exchanged particles and the Pauli blocking effect.

On integrating (16), one gets

$$E^{1/2} \approx E_0^{1/2} - \frac{1}{2}\left(\frac{m}{\mu}E_F\right)^{1/2} \sigma_A^2 \tag{17}$$

The Fermi energy E_F is a reasonably well-known quantity (~ 37 MeV), and thus the above predictions of the nucleon exchange model do not involve any free parameter.

Before we discuss the comparison of the experimental results with the predictions of (17) some additional facts must be pointed out. In most experiments the quantity which is measured is σ_Z^2, the variance of the fragment charge distribution and not σ_A^2. Conversion of σ_Z^2 into σ_A^2 requires a knowledge of the neutron-proton correlation in the exchange process. For uncorrelated transfers $\sigma_A^2 = (A/Z)\sigma_Z^2$ while for fully correlated transfers $\sigma_A^2 = (A/Z)^2\sigma_Z^2$. Thus, in some earlier studies the comparison of the correlation between the measured σ_Z^2 and the energy loss with the predictions of the above transport model involved some ambiguity as a result of uncertainty in the conversion of σ_Z^2 into σ_A^2 representing the total number of nucleon exchanges. Further studies of this problem carried out at Trombay (Kapoor and De 1982; De and Kapoor 1983) have clarified that it is possible to make comparisons of experimental results on σ_Z^2 with the theoretical predictions of the transport model without much ambiguity arising from the degree of neutron-proton correlation. It was pointed out in this work that if there is a neutron-proton correlation in the exchange process, not only should the experimental σ_Z^2 be suitably converted into σ_A^2 but one must also consider that the theoretical predictions of the transport model also get modified. It was shown (Kapoor and De 1982; De and Kapoor 1983) that while in the case of uncorrelated neutron-proton transfers, the variance of the fragment mass distribution σ_A^2 is equal to the total number of nucleon transfers, for fully correlated motion, the value of σ_A^2 is larger than the number of nucleon transfers by a factor $A^2/2ZN$. If one considers the correlated and uncorrelated motion for a given number of particle exchanges, the rate of energy dissipation remains unaltered. It then follows that the theoretical value of $\mathrm{d}E/\mathrm{d}\sigma_A^2$ for correlated transfer is related to the expression for uncorrelated transfers as

$$[\mathrm{d}E/\mathrm{d}\sigma_A^2]_{\mathrm{corr}} = \frac{2ZN}{A^2}[\mathrm{d}E/\mathrm{d}\sigma_A^2]_{\mathrm{uncorr}} \tag{18}$$

The experimental results on the variance of the fragment charge distributions versus energy loss for several heavy ion reactions were analysed earlier (Kapoor and De 1982; De and Kapoor 1983; Kapoor 1982a) by including the effect of correlations in the transport model in a manner which is consistent with the assumption made in the transformation of σ_Z^2 into experimental σ_A^2. Figures 4 and 5 show the comparisons with the experimental results for cases of heavy ion reactions of Xe + Bi, Pb + U, and Pb + Pb. The dashed curve in figure 4 represents the theoretical curve if one is not consistent in applying the effect of correlation in neutron-proton exchanges in both the transport model, and in the relationship between σ_Z^2 and experimental σ_A^2. The good fits of the experimental points to the solid lines in the figures show satisfactory agreement with model predictions, nearly independent of the assumptions made about neutron-proton correlations in the exchange process, bringing out unambiguously the dominant role of nucleon-exchange process in the energy loss.

The influence of the neutron-proton correlation in the evolution of the fragment mass and charge distributions in fission has been studied recently at Trombay (Rekha Govil *et al* 1983). Making use of a back-to-back $\Delta E - E$ detector arrangement, the correlation between the variances in the fragment mass and charge distributions versus the total fragment kinetic energy was studied in the case of thermal neutron induced fission of ^{235}U. Figure 6 shows the measured correlations and shows a rather close resemblance to the known systematics (Breuer *et al* 1979) in the case of heavy ion deep inelastic collisions, namely, the ratio σ_A^2/σ_Z^2 is close to $(A/Z)^2$ for low kinetic energies and approaches (A/Z) for higher kinetic energies. This similarity lends support to the

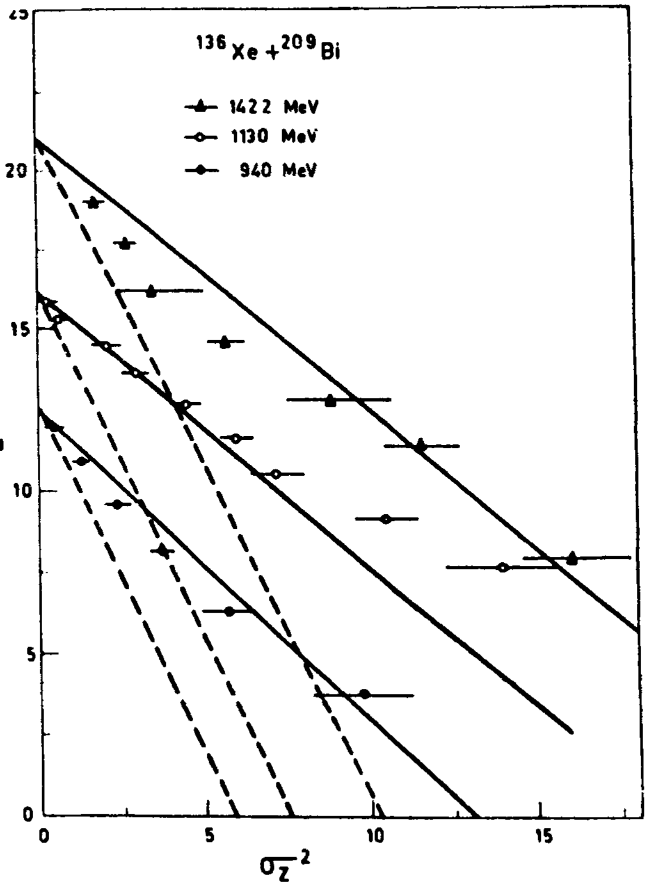

Figure 4. Plots of $E^{1/2}$ versus σ_Z^2 for three bombarding energies of ^{136}Xe on ^{209}Bi.

hypothesis that the final mass and charge distributions in fission as well as in DIC are governed by similar processes, namely, a nuclear exchange process.

There has also been some discussion in the earlier work on the question of the nuclear shell effects on the nucleon exchange process. In the analysis of the heavy ion deep inelastic collision data with (17), the single particle states of the nucleons are assumed to be given by a smooth distribution, and therefore nuclear shell effects are neglected. Good fits obtained above for the cases of Bi + Xe and Pb + U do indicate that the shell effects have little influence on the above description which may partly be due to the washing out of the shell effects at finite temperatures reached during the nucleon exchange processs. However, for the case of Pb + Pb, where both the colliding nuclei have doubly closed shells and where we are dealing with nuclei which have highest shell correction energy, noticeable deviations from the predictions of the Fermi gas model are apparent in figure 5. Although bulk of the energy loss in heavy ion collisions originates from the nucleon exchange process, it is also to be expected that some energy loss arises from other competing mechanisms. One effect of the energy gap at the Fermi-surface, that is, of shell effects, would be to slow down the nucleon exchange process, on account of a smaller density of states at the Fermi surface. This could then

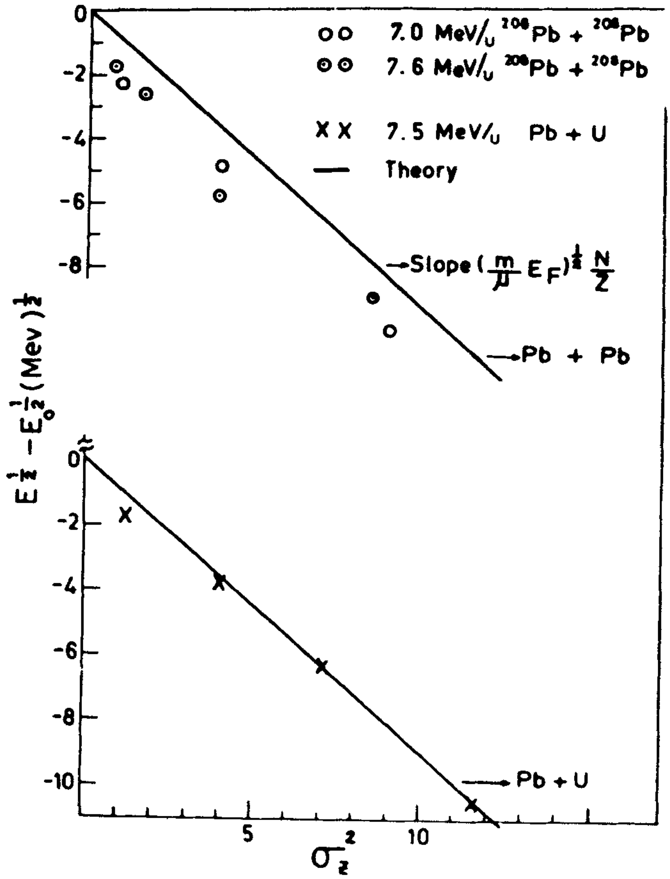

Figure 5. Plots of $E^{1/2}$ versus σ_Z^2 for 7·0 MeV/u Pb+Pb, 7·6 MeV/u Pb+Pb and 7·5 MeV/u Pb+U.

relatively enhance the importance of other mechanisms competing with the nucleon exchange process, resulting in deviations of the theoretical predictions from the experimental results. However, this question of nuclear shell effects in the nucleon exchange process needs to be further investigated.

Thus, the main conclusions resulting from the above discussions are as follows:

When the effect of isospin correlations in the exchange process is considered both in the conversion of measured σ_Z^2 into experimental σ_A^2, and also in the transport model, it turns out that comparison of σ_Z^2 versus energy loss with the model is almost independent of the degree of the isospin correlation in the exchange process. Thus such a comparison focusses on the magnitude of the energy loss arising from the exchange process without much ambiguity due to the presence of isospin correlation. The analysis of a number of heavy-ion systems, supports the above conclusion and also brings out in an unambiguous way that the observed energy loss can be accounted primarily by the nucleon exchange mechanism alone without having to invoke any arbitrary parameter. For most of the systems including Xe+Bi and Pb+U where the target or the projectile nuclei have significant negative shell correlation energies, there is

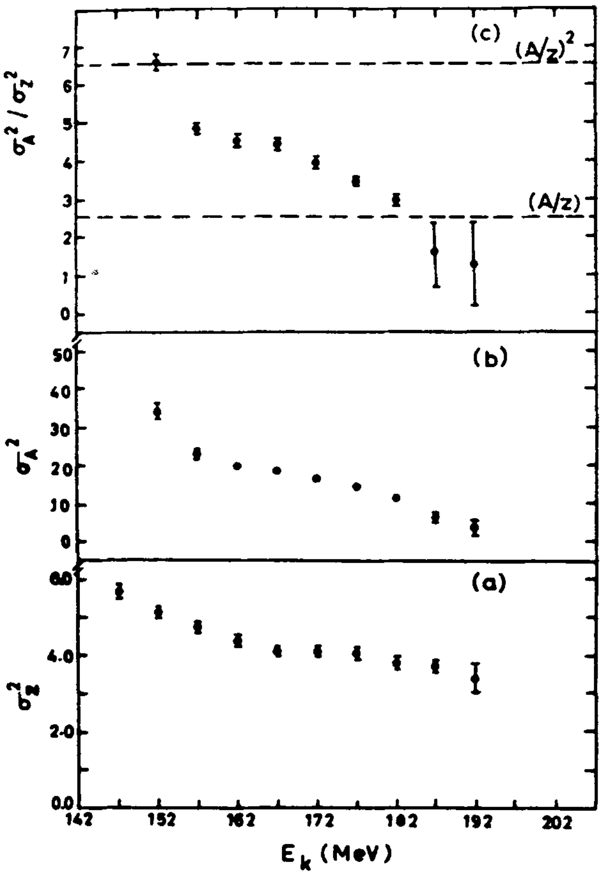

Figure 6. Kinetic energy dependence of the fragment charge variance σ_Z^2 (**a**), mass variance σ_A^2 (**b**) and the ratio σ_A^2/σ_Z^2 (**c**). The dotted horizontal lines are values of $(A/Z)^2$ and (A/Z) for the ^{236}U compound nucleus.

no evidence for significant shell effects in the observed correlations between the energy loss and σ_Z^2. However, for Pb + Pb system, some deviations from the predictions of the model are observed which need further investigations.

In the above discussion, we have focussed on the expected correlation between energy loss and the variance of the fragment mass and charge distributions in heavy ion deep inelastic collisions. But there are other features of the heavy ion collisions which are also governed by this basic mechanism. The transfer of the orbital angular momentum to the fragment spins, and the misalignment of the transferred spins with respect to the reaction plane have also been discussed in the literature (Randrup 1983) on the basis of the nucleon exchange mechanism. In a recent study (Ramamurthy and Kapoor 1984) aimed at understanding the observed anomalous fragment angular distributions in heavy ion induced fusion-fission, where the relaxation of the dinuclear complex in the mass-asymmetric degree of freedom is reached during fusion, the analysis of the data brings out that such a complex relaxes in the K-degree of freedom on a time scale of several times 10^{-21} sec, and the fused composite nuclei with fission barriers comparable to temperature can fission from the non-equilibrium state of unrelaxed K-distribution. Presence of this type of non-equilibrium fission is shown to be responsible for the apparently anomalous fragment angular distributions. The importance of the role of nucleon-exchange mechanism in the process of K-equilibration has been recognized, but a quantitative study is needed to arrive at more definite conclusions. There are several other aspects of nucleon exchange mechanism in fission and heavy-ion reactions such as the effects of cluster transfers which are also currently being explored.

In conclusion, the nucleon exchange mechanism operating between two nuclei in proximity first suggested for the fission process has now been extensively studied through the deep inelastic heavy ion collisions. The experimentally well-established correlation between the dissipated energy and the variance of the fragment charge or mass distribution in the deep inelastic heavy ion collisions, and the transport model description taking into account neutron-proton correlations in the exchange process, bring out in an unambiguous way the dominant role of the nucleon exchange process in the energy loss mechanism in heavy ion reactions. It is also recognized that several other observed features in heavy ion reactions are also governed by this underlying mechanism.

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