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REVIEW ARTICLE

DEEP – INELASTIC NUCLEAR REACTIONS

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Deep – Inelastic Nuclear Reactions

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A considerable amount of data on deep inelastic collisions has been accumulated over the last three decades albeit limited in character. From these accumulated experimental data, it is possible to list the following general features of DIC.

i) An essential feature is that these collisions preserve the binary character of the system, so that the final fragments maintain some resemblance to the initial nuclei,

ii) These reactions involve a fast redistribution of protons and neutrons among the colliding nuclei, which is governed by strong driving forces associated with the potential energy surface of the dinuclear complex. This fast rearrangement of neutrons and protons is called N/Z equilibration .The time involved in this equilibration is around 10−22 seconds.

iii) Momentum analyses of the nuclide distributions indicate that the exchange of nucleons starts out in an uncorrelated fashion. Then, due to the confinements imposed on the exchange process by the gradients of the potential energy surface, a correlation develops with increasing energy loss. Moreover, there are indications that the development of charge and mass flow is not only determined by macroscopic dynamics and liquid-drop potentials, but for small bombarding energies and small energy losses, single-particle degrees of freedom and tunneling probabilities add to the complexity of the observed phenomena .

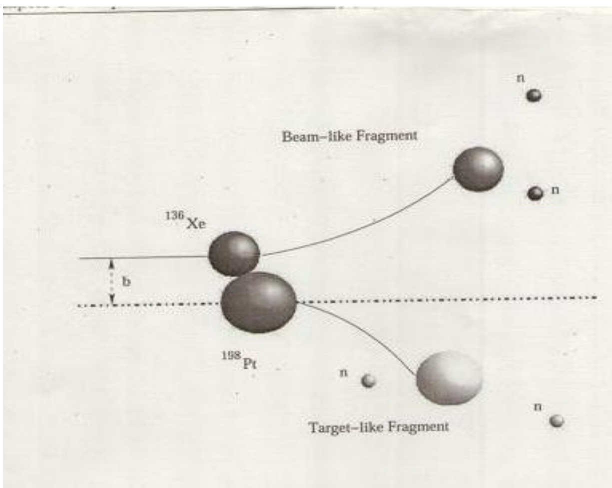


Figure 2.1: Semiclassical description of a Deep Inelastic Nuclear Reaction between heavy ions.

iv) Angular momentum is transferred from relative orbital motion to the intrinsic spin of the two primary fragments.

v) The primary fragments produced in these reactions de-excite mainly through the evaporation of light particles, namely neutrons, protons and α-particles, the emission of γ rays and in the case of heavier fragments via fission.

KINEMATICS IN BINARY REACTIONS

The following kinematic equations refer to the laboratory reference frame, where the nuclei in the target are considered at rest. If the reaction plane is defined by the direction of the incident beam and one of the outgoing particles, then conserving the component of momentum perpendicular to that plane shows inmediately that the motion of the second outgoing particle must lie in the same plane.

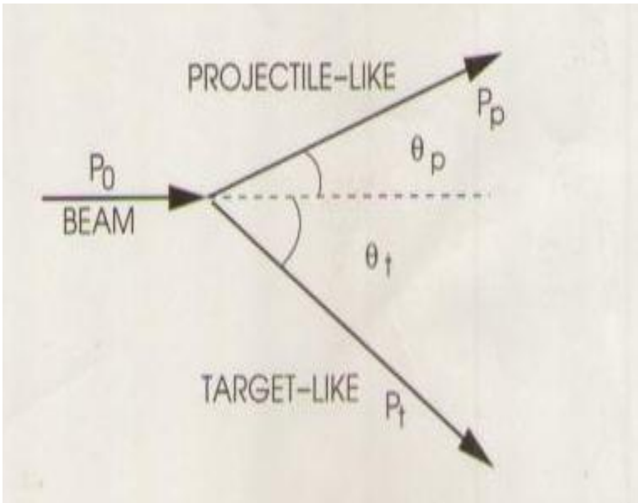


Figure 2.2: Reaction geometry. Projectile and target recoils define the reaction plane of the binary reaction.

Conservation of linear angular momentum gives,

$$P_0 = P_p \cos\theta_p + P_t \cos\theta_t$$

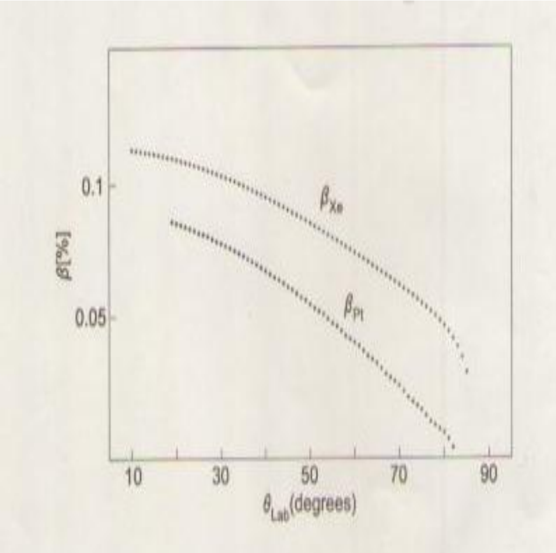
$$0 = P_p \sin \theta_p - P_t \sin \theta_t$$

where P0 is the initial momentum of beam, Pp, Pt are the recoil momenta for the projectile and the target recoils respectively and θp, θt are the scattering angles for the projectile and target nuclei respectively. After some algebra manipulation, the relation of the recoil momenta to the initial beam momentum is given by,

$$P_{p,t} = P_0 \sin(\theta_t, \theta_p) / \sin(\theta_p + \theta_t)$$

In a non-relativistic approximation the momentum is given by P = mβc, whereas the

relativistic momentum is given by P = mβcγ where m is the mass and γ = 1 √1−φ2



.**Figure 2.3: Calculated velocities of the projectile and the target recoils for the particular case of a 136Xe beam at 850 MeV in the laboratory frame impinging on a 198Pt target. An elastic collision and simple two-body kinematics have been assumed.**

If an elastic collision is assumed, where the energy conservation can be given by Equation then using Equations for a given recoil angle, the recoil angle of the other fragment and the velocity of the recoils can be calculated using,

$$P^2 / 2m_{beam} = P^{2} / 2mp + P^2 / 2mt$$

Figure shows the calculated velocities for the projectile and target recoils in the case of a 136Xe beam at laboratory energy of 850 MeV impinging on a 198Pt target.

ANGULAR MOMENTUM IN BINARY REACTIONS

Unlike the fusion evaporation reactions where most of the input angular momentum of the reaction goes into the intrinsic angular momentum of the final products in deep inelastic collisions the transfer of angular momentum into intrinsic spins is not as efficient. There are different semi classical models to explain the angular momentum distribution of the nuclei produced in a deep inelastic collision. The sharing of the angular momenta between relative and intrinsic rotation depends upon the details of the frictional forces between the nuclei. The particular limiting cases of interest are sliding, rolling and sticking modes which correspond to minimum, intermediate and maximum angular momentum dissipation from the relative motion.

Consider a nucleus of radius rp approaching the target nucleus of radius rt at an impact parameter such that the initial angular momentum is L. In any real case there would be a distribution of L values corresponding to the range of partial waves that contribute to the DIC. After contact, the spheres will move around the centre of mass with an angular speed ω. Each sphere may have its own intrinsic rotation ωt and ωp. Conservation of angular momentum requires:

L = μR2ω + ℑ pωp + ℑ tωt

where R = rp + rt, ℑ is the moment of inertia and μ is the reduced mass, which is given in terms of the mass numbers of the target At and projectile Ap as

μ = Ap At / Ap + At ,

and Jp = ℑ pωp and Jt = ℑ tωt are the intrinsic angular momenta of the projectile and target, whose calculated values can be compared with those obtained experimentally. The maximum angular momentum input in the reaction can be estimated to be,

$$L_{max} = 0.219 R_p \sqrt{(E_{cm} - V_{cm})}$$

The Sliding model is the simplest case and the one in which no angular momentum is put into the fragments (Jp = Jt = 0), since they slide with respect to one another. The sticking model corresponds to the case where the projectile and target stick together, each nucleus rotates around its own centre at the same speed, i.e. ωp = ωt. This model is the one that converts more translational energy into rotational energy. From Equation one can deduce the following relative angular speed:

ω = L / μR2 + ℑ p + ℑ t

then

Jp = ℑ p / μR2 + ℑ p + ℑ t L

and

Jt = ℑ t / μR2 + ℑ p + ℑ t L.

If the nucleus is considered to be a rigid sphere then $\Im = 2/5Ar^2$ and $r = 1.2A^{1/3}$, where A is the mass of the nucleus and r is its radius. For the reaction Pt + Xe at 850 MeV that will be discussed in this thesis, the following values are obtained. An incident Xe beam at a laboratory energy of 850 MeV gives an L = Lmax = 297 ~, then

$$\Im_{Xe} = 2/5\, A_{Xe} r^2_{Xe} = 2072 fm^2 \text{ a.m.u.},$$

$$\Im_{Pt} = 2/5\, A_{Xe} r^2_{Xe} = 2072 fm^2 \text{ a.m.u.},$$

and

$$\mu R^2 = A_{Xe} A_{Pt} / A_{Xe} + A_{pt} (r_{Xe} + r_{Pt})^2 = 13973 \text{ fm}^2 \text{ a.m.u.}$$

Therefore the intrinsic spin put into the fragments for the sticking mode can be estimated.The rolling model is a situation intermediate between the sliding and the sticking models, which arises in the presence of a strong frictional force. In the rolling case, the point of contact has a velocity equal to zero in the rest frame. The condition for not sliding is given by,

$$r_p(\omega_p - \omega) + r_t(\omega_t - \omega) = 0$$

If a frictional force, F, is considered to be acting at the contact point, this force gives a torque on the projectile and the target in opposite directions,

$$F \times r \rightarrow J$$

Therefore, the angular momentum sharing is given by,

$$J_p / J_t = r_p / r_t = \Im_p \omega_p / \Im_t \omega_t \rightarrow \omega_p / \omega_t = \Im_t r_p / \Im_p r_t$$

Combining Equations one obtains,

$$\omega_t = \Im_p r_t R\omega / \Im_t r^2$$

and

$$\omega_p = \Im_t r_p R\omega / \Im_t r^2$$

Moreover

$$L = \mu R^2\omega + J_p + J_t = \mu R^2\omega + 2/5\, \mu R^2\omega = 7/5\, \mu R^2\omega$$

therefore

$$J_p + J_t = 2/7\, L$$

A fraction of 2/7 of the initial angular momentum is converted into the intrinsic angular momentum of the target and projectile while 5/7 stays in relative motion. Combining Equations one obtains,

$$J_p = 2/7(1/ 1 + (A_t/ A_p)^{1/3})L$$

and

$$J_t = 2/7(1/ 1 + (A_p/ A_t)^{1/3})L.$$

So in the same case as before, for a 136Xe beam at a laboratory energy of 850 MeV incident on a 198Pt target, the angular momentum transferred to the fragments for the rolling mode can be estimated to be,

$$J_{Xe} \approx 17\sim$$

and

$$J_{Pt} \approx 45\sim$$

In this case the model predicts less angular momentum put into the fragments than in the case of the sticking model.

GRAZING ANGLE IN A DIC

For experimental purposes it is very important to know where the grazing angle of the reaction in the laboratory frame is expected to be due to the fact that at this angle the binary reaction cross section is expected to be maximised. The grazing angle, is the angle at which one can be sure that nuclear interactions happen, rather than only Coulomb or Rutherford interactions. It is defined as the angle at which the distance of closest approach, d, is given by

$$d = (Z_t Z_p e^2 / 4\pi\varepsilon_0 E_k) (1 + \csc \theta^{\,2})$$

where Zt and Zp are the atomic numbers of the two nuclei involved and Ek is the kinetic energy. The distance of the closest approach equals the sum of the nuclear radii, i.e. when the two nuclei are just touching, which can be estimated by the expression, where At and Ap are the nuclear mass numbers for the target and beam respectively. A quick estimate for the grazing angle can be obtained equalizing For the reaction of interest in this thesis the grazing angle is roughly the same for beam and target-like fragments in the laboratory frame, i.e. 50◦.

Q-VALUE OF A NUCLEAR REACTION

The Q-value of a nuclear reaction can be derived from the conservation of energy. In a nuclear reaction, the Q-value can be defined as ,

$$Q = (m_{initial} - m_{final})c^2 = T_{final} - T_{initial}$$

where minitial and mfinal are the total initial and final masses of the system respectively and Tinitial, Tfinal are the total kinetic energies of the system before and after the reaction respectively. The Q-value may be positive or negative. If Q > 0 (T_{final} > Tinitial), then nuclear mass or binding energy is released as kinetic energy, which is shared between the final products. On the contrary when Q < 0 ($T_{final} < T_{initial}$), then the kinetic energy has been converted into binding energy. The changes in mass and energy must be related by the Einstein's familiar equation from special relativity, $\Delta E = \Delta mc^2$.