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REVIEW ARTICLE

A STUDY ON INELASTIC NUCLEAR REACTIONS

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A Study on Inelastic Nuclear Reactions

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INTRODUCTION

?reviewed. The most prominent collective degrees of freedom excited in these reactions are discussed within the framework provided by the natural hierarchy of their characteristic relaxation times. Both the quantal and classical aspects of these modes are described. The limitations of the Lagrangian treatment of heavy-ion reactions are pointed out, and a more general approach using transport theory is outlined. This latter approach is illustrated by the Langevin, Master and Fokker-Planck equations. The four most widely studied collective modes are then described in detail: the damping of the relative motion; the mass asymmetry degree of freedom; the isobaric charge distribution with iso-spin fluctuations and giant iso-vector modes; rotational degrees of freedom.

The K-shell ionization probability of the uranium like products has been measured in the deep-inelastic reaction U + U at a beam energy of 7.5 MeV/u as a function of the total kinetic energy loss −Q. PK was determined for Q values down to - 190 MeV. After the subtraction of the ionization induced by internal conversion of γ rays, a strongly Q- dependent PK is found in qualitative agreement with theoretical predictions. From the data we infer a nuclear reaction time of approximately 10−21s at Q=−100 MeV.

Inelastic ion-induced nuclear reactions are calculated in the isobar model, which assumes that an interacting resonant ion and nucleon form an unstable particle, the Δ, which can propagate through the nucleus and either decay or be absorbed by interacting with other nucleons in the nucleus. The propagation of the particles is treated classically and the interactions are assumed to be incoherent. The lifetime of the Δ is taken to be energy dependent as prescribed by measured ion-nucleon scattering and the cross section of the Δ absorption is determined by measured ion production in two nucleon collisions. The formation of the Δ by a ion and nucleon and the subsequent absorption of the Δ provide a two-step mechanism for ion absorption. These calculations indicate that the ion is absorbed mostly on the inside forward edge of the nuclear surface where the nuclear density has almost reached central density. The calculations are compared with measured ion absorption cross sections, proton spectra, and spallation products in ion-induced reactions. All of these data indicate that p ion absorption is underestimated in this model by perhaps as much as 35%, particularly for low energy (~ 100 MeV) ions.

RESEARCH STUDY

A considerable amount of data on 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 di-nuclear 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 .

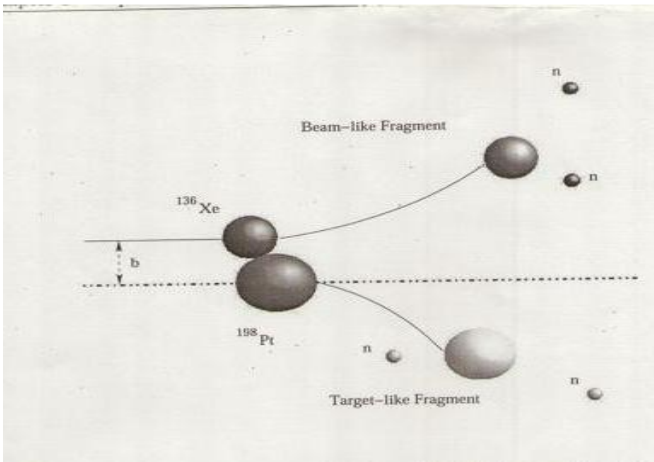

Figure 1: Semi classical description of an Inelastic Nuclear Reaction between heavy ions.

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.

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 immediately that the motion of the second outgoing particle must lie in the same plane.

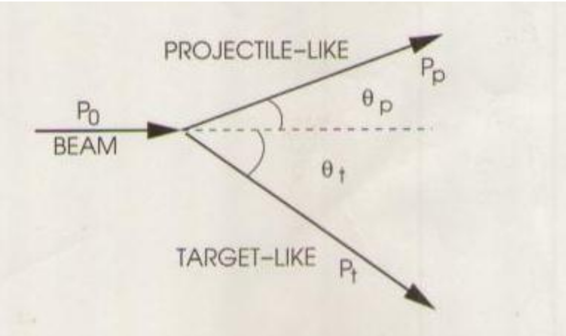

Figure 2: Reaction geometry. Projectile and target recoils define the reaction plane of the binary reaction.

Conservation of linear angular momentum gives,

$$P_0 = Pp \cos \theta p + Pt \cos \theta t$$

$$0 = Pp \sin \theta p - Pt \sin \theta t$$

where P_0 is the initial momentum of beam, P_p, P_t are the recoil momenta for the projectile and the target recoils respectively and θ_p, θ_t 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

$$Pp,t = P0 \ \sin(\theta t, \theta p) / \sin(\theta p + \theta t)$$

In a non-relativistic approximation the momentum is given by P = $^{m}\beta c$, whereas the relativistic momentum is given by P = mβcγ where m is the mass and γ = 1 √1−β2

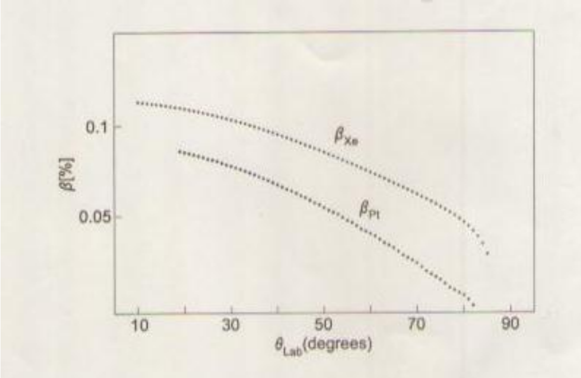

Figure 3: Calculated velocities of the projectile and the target recoils for the particular case of a ^{136}Xe beam at 850 MeV in the laboratory frame impinging on a ^{198}Pt target. An elastic collision and simple two-body kinematics have been assumed.

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

$$P^2_0 / 2m_{beam} = P^2_p / 2m_p + P^2_t / 2m_t$$

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

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 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 an 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:

$$L = \mu R^2\omega + \phi p\omega_p + \phi t\omega_t$$

where R = rp + rt, 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

$$\mu = A_pA_t / A_p + A_t$$

and Jp = ɸpωp and J_t = ɸt . ωt 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,

$$L_{max} = 0.219\, R \sqrt{\mu(E_{cm} - V_{cm})}$$

The Sliding model is the simplest case and the one in which no angular momentum is put into the fragments 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:

$$\omega = L / \mu R^2 + \kappa p + \kappa t$$

then

$$Jp = (\kappa p/ \mu R^2 + \kappa p + \kappa t)\, L$$

and

$$Jt = (\kappa t/ \mu R^2 + \kappa t + \kappa t)\, L$$

If the nucleus is considered to be a rigid sphere then **κ** = 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 ^{198}Pt + ^{136}Xe at ^{850} MeV, the following values are obtained. An incident ^{136}Xe beam at a laboratory energy of ^{850} MeV gives an L = Lmax = 297, then

$$3Xe = 2/5\, A\, Xe\, r^2\, Xe = 2072\, fm^2\, a.m.u.,$$

$$3P_t = 2/5\, A\, P_t\, r^2\, P_t = 3874\, fm^2\, a.m.u.,$$

and

$$\mu R^2 = A\, Xe.\, A\, P_t /A\, Xe + A\, P_t\, (r\, Xe + r\, P_t)^2 = 13973\, fm^2$$
a.m.u.

Therefore, the intrinsic spin put into the fragments for the sticking mode can be estimated to be

$$J_{Xe} = 3Xe.\, L / \mu R^2 + 3Xe + 3\, Pt = 31\, h$$

$$Jpt = 3pt.\, L / \mu R^2 + 3Xe + 3\, Pt = 58\, h$$

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

$$rp(\omega p - \omega) + rt(\omega t - \omega) = 0$$

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,

$$Jp / Jt = rp / rt = \chi_p w_p / \chi_t w_t \rightarrow w_p / w_t = \chi\, t\, rp / \chi_p\, rt$$

Combining Equations one obtains,

$$Wt = \chi_p r_t Rw / \chi_t r^2{}_p + \chi_t r^2{}_p$$

and

$$Wt = \chi t\, rp\, Rw / \chi_t r^2{}_p + \chi p\, r^{2t}$$

Recalling that **κ**p = 2/ 5Apr^2 p and **κ**t = 2/ 5Atr^2, the sum of the angular momenta of the projectile and target is given by,

$$Jp + Jt = \chi_{p\, Wp} + \chi_{t\, Wt} = 2/5\, uR^2 w$$

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 obtains,

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

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

JXe ≈ 17~

and

JPt ≈ 45~

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

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 maximized. 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

$d= (Z_t Z_p e^2 /4\pi\varrho_0 E_k) (1 + \cos \theta/2)$

where Zt and Zp are the atomic numbers of the two nuclei involved and E_k 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,

$d = 1.2 (A^{1/3}{}_t + A^{1/3}{}_p)$ fm

where A_t and A_p are the nuclear mass numbers for the target and beam respectively. A quick estimate for the grazing angle can be obtained equalizing Equations. The grazing angle is roughly the same for beam and target-like fragments in the laboratory frame, i.e. 50◦.

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 $m_{initial}$ and m_{final} 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 $Q > 0$ ($T_{final} > T_{initial}$), 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, $\Delta E = \Delta mc^2$.

REFERENCES

- A. Messiah, Quantum Mechanics, North-Holland, Amsterdam (2005).
- M.G. Mayer et al., Phys. Rev. 75, 2009.
- A. Poves and F. Nowacki, Lecture Notes in Physics, Springer, (2011).
- K. Higashiyama, N. Yoshinaga and K. Tanabe, Phys. Rev. C 65, 054317 (2012).
- K. Higashiyama, N. Yoshinaga and K. Tanabe, Phys. Rev. C 67, 044305 (2013).
- F. Iachello and A. Arima, Phys. Lett. B 53, 309 (2004).
- R.F. Casten, Nuclear Structure from a Simple Perspective, Oxford Science Publications 2010.
- J. J. Ressler et al., Phys. Rev. Lett., submitted (2003).
- M. Eisenberg and W. Greiner, Microscopic Theory of the Nucleus, North-Holland Publishing Company (2012).
- W. Greiner, Nuclear Models, Springer-Verlag Berlin Heidelberg New York(2006).
- S.G. Nilsson, Dan. Mat.-Fys. Medd. 29, 16 (2005).
- J. Bardeen, L.N. Cooper and J.R. Schrieffer, Physics Rev. 108, 1175 (2007).
- B.R. Mottelsson and J.G. Valatin, Phys. Rev. Lett. 5, 511 (2010).