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NON-EQUILIBRIUM NUCLEON EMISSION AROUND THE FERMI ENERGY REGION

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Abstract - Emission of fast energetic nucleons in intermediate energy nuclear collisions is investigated in the framework of two specific non-equilibrium models. In the lower energy region considered, the Fermi Jet mechanism dominates whereas results in the higher energy region are suggestive of emission from a hot dense source formed inside cold nuclear matter.

I - INTRODUCTION

Experiments /1/ have revealed that energetic collisions between nuclei far above their Coulomb barrier give rise to emission of fast nucleons or other complex particles. These particles carry unique information about the non-equilibrium flow properties of physical observables associated with nuclear matter, like mass, energy, momentum or heat. These collisions are dissipative, convert a large amount of energy in relative motion into intrinsic excitations and therefore particles emitted from each stage of the reaction process give snapshots of the dynamical evolution of the non-equilibrium process itself. Experience from phenomenology has also taught us that whereas at energies in the beginning of the Fermi domain (at nuclear sound velocities \(\sim 20 \text{ MeV/n} \)) or lower, nuclear flow is mainly non-turbulent and nucleon emission can still be described from mean-field and kinematic considerations, at higher energies, the flow becomes turbulent causing rapid deposition of energy in part of the whole system thereby creating a hot zone in an otherwise colder nuclear environment. In this paper, we would be concerned mainly with these two types of non-equilibrium emissions.

II - FERMI-JET

Nuclear collisions at energies \(\sim 6-8 \text{ MeV/n} \) start to show up in the nucleon energy spectrum a hard component in addition to the usual evaporation part. With increasing beam energy, this component becomes more pronounced and it is seen that even at \(\sim 20 \text{ MeV/n} \)/2/, the total nucleon spectra (Fig. 1), when measured in coincidence with evaporation residues arising from fusion of the colliding nuclei can be parametrised in terms of temperatures of two moving equilibrium sources, one being \(\sim 2-3 \text{ MeV} \), the other being \(\sim 7-8 \text{ MeV} \). From the cross-section \(d^2\sigma/d\Omega dE \) measured different angles, however, one finds that there is no unique temperature for different angles. The physical meaning of this temperature parameter is therefore not transparent. Here, we show that a major part of this hard component of the spectrum can be accounted for within the non-equilibrium model of 'Promptly Emitted Particles' (PEPs)/3/. In another continent, this is also called 'Fermi Jets' /4/ since the Fermi motion of the nucleons and simple kinematics play a decisive role in the emission of the energetic particles, mostly in the forward direction.
The Pauli-allowed nucleons that diffuse through the dinuclear neck in the recipient nucleus appear with a velocity given by the vector coupling of the relative velocity $v_{rel}$ and the intrinsic Fermi velocity $v_F$, and therefore, in the recipient frame, the transported particles may become highly energetic. These particles may be partly absorbed in the nuclear medium due to nucleon-nucleon collisions, may suffer reflection at the nuclear surface and if have sufficient energy, may be promptly emitted in the continuum after refraction at the nuclear boundary. The time evolution of this emission is controlled by conservative and non-conservative forces and also by the time-dependent temperature of both the nuclei which are generally different for asymmetric nuclei.

In Fig. 1, the differential multiplicities for the system $^{20}$Ne + $^{167}$Ho at $\sim 20$ MeV/n are compared with the experimental data. Zero temperature Fermi distribution underestimates the high energy part of the spectrum, but the temperature-dependent soft Fermi surface reproduces it adequately, though a too-strong forward focussing remains. Since the temperatures deduced at different angles from the hard spectrum are different, emission from a hot zone created with a subsystem of nucleons may look unphysical, but the underestimation at sideward and backward angles probably calls for a co-existing non-equilibrium mechanism. The introduction of two-body or many-body PEPs due to the importance of two-nucleon collisions at higher energies would produce more particles at larger angles and may probably improve the fit. If one sees that two-body or many-particle collisions are too important, then a co-existing hot-spot or hot-zone may be a distinct possibility and may not be so easily ruled out. We also look for the average number of non-equilibrium neutrons emitted in a given collision at several bombarding energies and find that the PEP model underestimates it (Fig. 2). Could this be another signature for a co-existing...
non-equilibrium mechanism? Add to it the data for the missing linear momentum in these reactions. From our theory, the promptly emitted particles can reproduce only 10% of the missing linear momentum!

III - HOT SOURCES

It is possible that nucleons emitted from a hot zone created due to the energetic collisions at energies beyond $\sim 20$ MeV/n might explain part of this anomalous situation. We, however, still have no solid theoretical understanding of this phenomena. Intuitively, we believe that since at these energies, some of the velocities connected with the collective degrees of freedom (the relative velocity, the velocity with which the neck grows) may be larger than the intrinsic nucleonic velocities, the nucleonic motion may not follow the collective nuclear motion resulting in the loss of self-consistency inherent in the description of the mean-field dynamics thus starting turbulence in the interface region and accentuating two-body and many-body nucleon-nucleon collisions. Increased collisions near the neck gives rise to rapid deposition and localisation of energy in this region that creates a hot zone of large energy content and possibly larger density in an otherwise colder nuclear medium.

Let us now look back to experiments. In Fig. 3, we display the proton energy spectra for the reaction $^{160}_{\text{O}} + ^{197}_{\text{Au}}$ at energies $\sim 20$ MeV/n ($E_{\text{lab}} = 310$ MeV). The spectra can be explained with two moving hot sources, one slow, corresponding to the velocity of the compound system and the other fast, moving with a velocity $\sim$ half the beam velocity. It is then tempting to assume that this random thermalised velocity distribution moving with half the beam velocity is the result of intimate interactions between only a subset of nucleons with nearly equal participation from both the target and the projectile. Though it is envisaged that a thermal look-alike distribution arises from reflection of the nucleons obeying cold Fermi distribution from the surface of a soliton mode (this is collective compressional energy) created in energetic collisions and moving with sound velocity in the nuclear matter, asymmetric emission of neutrons, coincident with projectile-like fragments in $35$ MeV/n $^{14}_{\text{N}} + ^{165}_{\text{Ho}}$ reaction, or detailed light-particle correlation spectra is possibly suggestive of a spatially localised region of high thermal excitation.

Absence of rigorous theory gives rise to schematic models. In one of the first calculations on hot zone, Mooney et al found good agreement for the nucleon spectrum, particularly at backward angles, between theory and experiment for $^{160}_{\text{O}} + ^{197}_{\text{Au}}$ at 20 MeV/n with co-existing PEP and hot zone emission (Fig. 4). The absence of nuclear shadowing and a rather unrealistic shape of the hot zone however, cast doubt about the validity of this model.

A more physical picture of the hot zone is discussed by Kariven et al where the space-time evolution of the hot zone is followed to treat the emission of nucleons from it. In the energy region of $\sim 40$ MeV/n to 90 MeV/n, only central reactions corresponding to strong inter-penetration and complete fusion of the system ($^{12}_{\text{C}} + ^{108}_{\text{Ag}}$) are considered. The energy loss obtained from a proximity treated dynamical trajectory is assumed initially to be located in a zone slightly more extended than the overlap region of the nuclei. Nucleons diffuse from the evolving hot zone boundary to the colder matter outside (and vice versa) which is heated up due to energy dependent absorption. Nucleons not absorbed are emitted in the continuum as fast non-equilibrium particles.

The angular distribution for one of the cases is displayed in Fig. 5 in the C.M. system. The pre-equilibrium neutrons show a predominant backward peaking because of a stronger forward absorptive shadow in these central and asymmetric collisions. The energetic nucleons, however, do not show any such preference in the backward direction. This backward peaked angular distribution is not however borne out by experiments. This may be mainly due to the reason that only near central collisions (impact parameters $< 6-8$ fm) are considered for which the cross-section is low and the shadow geometry is unfavourable. For emission from more peripheral collisions, we have recently extended the geometric hot-spot model of Bondorf et al (Fig. 6).
Fig. 3 - Differential proton spectra for the system $^{160}_{\text{O}} + ^{197}_{\text{Au}}$ at 310 MeV. The solid line represents moving source parametrisation.

Fig. 4 - Differential proton spectra for $^{160}_{\text{O}} + ^{197}_{\text{Au}}$ at two laboratory angles indicated. The dashed-dot and the dashed lines correspond to PEP and hot-spot contributions and the full line is their sum.

Fig. 5 - The neutron angular distributions with energies above 50 MeV for the three reactions indicated. The dashed line corresponds to neutrons with energies above 70 MeV for 86 MeV/n bombarding energy.

Fig. 6 - The hot-zone geometry. The hot-zone releases its energy at the point X when the projectile moves on to the dashed position. The target-like spectator receives hot particles within the effective cone indicated.
This model has been very successful in correlating the mass and recoil momentum of the heavy target-like spectator in energetic collisions (see Fig. 7. For an orientation of the experimental data, see ref. 9). We primarily assume the hot-spot to be formed from equal participation of nucleons from target and projectile in the overlap region and further assume an average energy-independent absorption of nucleons (in the cold spectator) emitted from the hot-spot, that moves with half the relative velocity. The absorption factor is given by $e^{-d/\lambda}$ where $d$ is the path length traversed in the spectator and $\lambda$ is the mean free path, taken to be 4 fm. The absorbed nucleons give their energy and momenta to the cold spectators and thus give rise to spectator recoil. The spectator variables may have sizeable fluctuations, mainly due to the momentum distribution of participant nucleons and due to the number of nucleons absorbed by the spectator. Due to absorption, the spectators also become hot and evaporate particles. Fluctuations due to evaporation have been neglected in these calculations.

Fig. 7 - Correlation between spectator (target-like) and the recoil momentum for the reaction indicated. The shades represent differential cross-section beams decreasing outwards.

Fig. 8 - Differential proton energy spectra for the system C + Au at 85 MeV/n. The full lines refer to calculations with $\lambda = 4$ fm and the dashed lines refer to those with no absorption.
In Fig. 8, the differential cross-sections at different angles for the system $^{127}_{\text{C}} + ^{197}_{\text{Au}}$ at 86 MeV/n $^{10/1}$ are presented and the theoretical predictions from this model compared with experiment. We have not included evaporation from either the fast-moving projectile or slow-moving target. Since at forward angles, evaporation from projectile also contributes to the nucleon spectra, we have compared our theoretical calculations only at larger angles. The results at $\theta_{\text{lab}} = 50^\circ$ and $90^\circ$ are in fair agreement with the experimental data. At the backward angle of $\theta_{\text{lab}} = 120^\circ$, though the calculated slope of the energy distribution is nearly the same as the experimental one, the cross-section is approximately three to four times smaller. This may be a reflection of the fact that near central collisions which generally show a backward peaking have not been included in this calculation. We further find that because of the particular geometry taken, the distributions at sideward and backward angles are nearly independent of absorption, whereas at more forward angles ($\theta_{\text{lab}} = 50^\circ$), absorption suppresses the distribution.

In conclusion, we find that though a number of theoretical non-equilibrium models have been developed to explain the fast emission of nucleons from energetic collisions based either on kinematics or from the formation of a hot compressed nuclear matter, our understanding is only sketchy and not yet complete and for this theoretical work is very much in the wanting.

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