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Light charged particle emission in heavy-ion reactions – What have we learnt?

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Abstract. Light charged particles emitted in heavy-ion induced reactions, their spectra and angular distributions measured over a range of energies, carry the signature of the underlying reaction mechanisms. Analysis of data of light charged particles, both inclusive and exclusive measured in coincidence with gamma rays, fission products, evaporation residues have yielded interesting results which bring out the influence of nuclear structure, nuclear mean field and dynamics on the emission of these particles.

Keywords. Light charged particles; heavy-ion induced reactions; particle spectra and angular distributions; reaction mechanisms.

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1. Introduction

The study of light charged particles (protons to alphas) emitted in heavy-ion induced reactions is interesting due to several reasons. The cross section for light particle production (including neutrons) is very large and compares well with the reaction cross section at a given energy. But even this prolific process is not fully understood. The emission process of these light particles is rather complex. The light particles are emitted due to broadly three different processes – compound, direct and pre-equilibrium which take place over different time scales as well. There are indications that they are also emitted during the formation stage of the compound nucleus. The light particles are influenced by the nuclear structure, nuclear mean field and dynamics of the collision. Recently, Zagrebaev and Penionzhkevich [1] have reviewed this field, covering some aspects of formation of light particles in nucleus–nucleus collisions over a range of energies.

In the present paper, a summary of the various features of the light charged particles produced in heavy-ion collisions is given broadly along three directions: as a function of spin, bombarding energy and excitation energy.

2. General features

The collision between two ions as a function of energy can be depicted in the following way [2]: At low energies, the collision is dominated by the mean field acting between the two

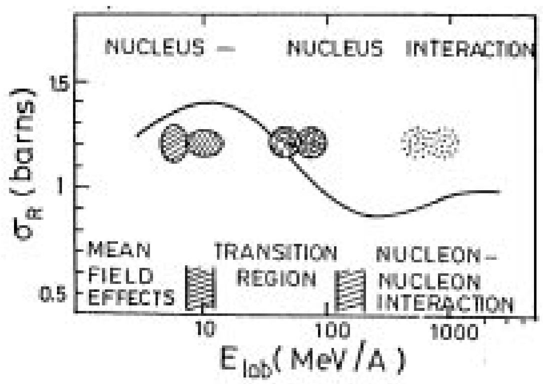

Figure 1. Heavy-ion induced nuclear reactions as a function of bombarding energy (in units of energy per nucleon).

ions. At very high energies, the nucleon–nucleon aspects dominate. In the intermediate energies, both the mean field and the nucleon–nucleon aspects play their roles (figure 1). These features in turn influence the light particles emitted from ion–ion interaction. When two ions collide over a range of bombarding energies, both complete fusion and incomplete fusion events take place with different amounts [2]. The light particles are emitted in both these processes. The incomplete fusion mechanism is more important at energies above 6–8 MeV/A. A typical light charged particle spectrum clearly reveals several aspects: the evaporation peak at low energies, the direct (fast) processes at the high energies and the pre-equilibrium emissions at intermediate energies. These components vary differently with angle of observation. The main feature of the particle energy spectra measured at low and medium bombarding energies and at forward and intermediate angles is their hardness: the yield of fast light particles decreases much slower with increasing energy than the evaporation part of the spectra from the corresponding compound nucleus. The higher the energy of the light particles, the more forward peaked is the angular distribution. It is observed that in the velocity spectra of light particles considerable part of them have velocities higher than the beam velocity. Further at forward angles the maximum yield lies at light particle velocity which is less than the beam velocity. With the increase of the beam energy, the maximum of the differential cross section moves to the light particle energy corresponding to the beam velocity. These features point to the role of dissipation or relaxation process in the case of light particle emission. It is generally assumed that the evaporation process from an equilibrated compound dominates the spectra at low energies and in the backward angles. It should be kept in mind that even in the one step direct massive transfer process the light particles are emitted predominantly in the backward hemisphere at the near barrier energies becoming isotropic at little higher energies. Only at very high energies the particles from the one step direct process are emitted predominatly at forward angles. But both the dissipative forces (hindering the incident ion) and the mean field (deflecting the projectile in the entrance channel and the light fragments in the exit channel) can certainly lead to a noticeable yield of non-equilibrium light particles at back angles [3]. One of the mechanisms responsible for the copious amount of light particles is the break-up of the projectile in the field of the target nucleus. The evaporative part of the light particle spectra is strongly influenced by the nuclear structure and the nuclear shape. While the shape of the emitter has a stronger influence on the lower energy part of the spectra, the nuclear structure (level density) has a stronger role to play in deciding the higher energy part of the spectra. To sum up, the mechanisms for light particle formation may be given as follows:

1. Evaporation from the equilibrated compound (also from the compound formed through incomplete fusion).
2. The two body primary process of incomplete fusion with the ejection of only one pre-equilibrium light particle.
3. The two body primary process of the dissipative few nucleon transfer with subsequent decay of the excited projectile like nucleus.
4. Quasi-elastic breakup of the projectile. The relative contributions of the various processes depend strongly on the mass and the energy of the projectile and on the outgoing angle of the light particle.
5. For compound nuclei formed at excitation energies above 50 MeV, and which decay by fission, the dynamical emission of light particles [4] from the equilibrium to the scission stages of the decaying compound beomes significant and this is related to dissipation. These light particles compete essentially in the energy region close to evaporation region and a bit higher. The various components are shown schematically in figure 2.

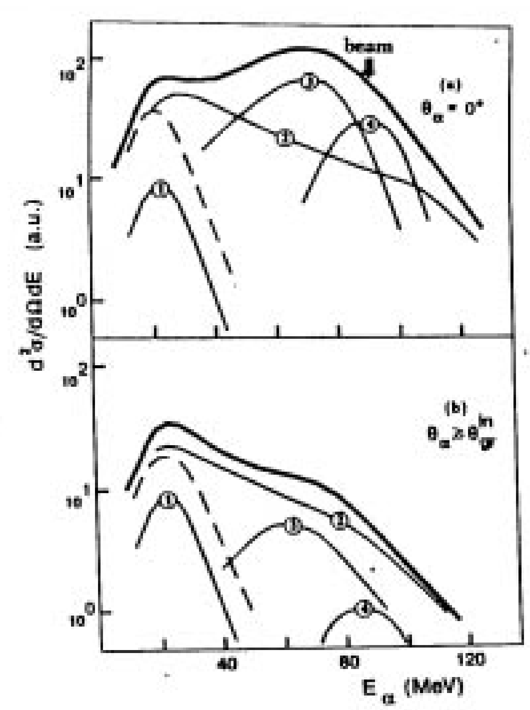

Figure 2. Light charged particle (α) spectra arising from various mechanisms discussed above.

3. Nuclear structure effects from particle spectra

It is conjectured that particle spectra might be influenced by the nuclear shapes and the nuclear structure of the emitting nucleus. According to Grover and Gilat [5] the particles emitted from cool nuclei would be affected by nuclear structure and this should alter the measured particle spectra. Blumenthal *et al* [6] tried to look for possible influence of nuclear structure in the reaction ^{58}Ni (^{29}Si, $xp, yn, z\gamma$) from measurement of proton spectra through the reaction channels leading to ^{80,81,83}Sr, ^{84,85}Zr and ^{83,84}Y. They observed differnces in the shapes of particle spectra. However, these differences could be understood in terms of the number of particles emitted and the reaction Q value differences. The authors could not confirm the possible influence of low-lying nuclear states (nuclear structure) on the shape of the proton spectra. However, recently Pal *et al* [7] have reported observation of very interesting but rather unusual bump like structure in the proton spectra from first chance emission. Pal *et al* in their study related ^{93}Nb (^{12}C, p)^{104}Pd reaction showed that the proton spectra when gated by a multiplicity filter of higher folds (spin selected) brought out a bump like structure in the otherwise smooth exponential falling proton spectra. Typical spectra measured are shown in figure 3. For a given fold, the bump energy moved to a

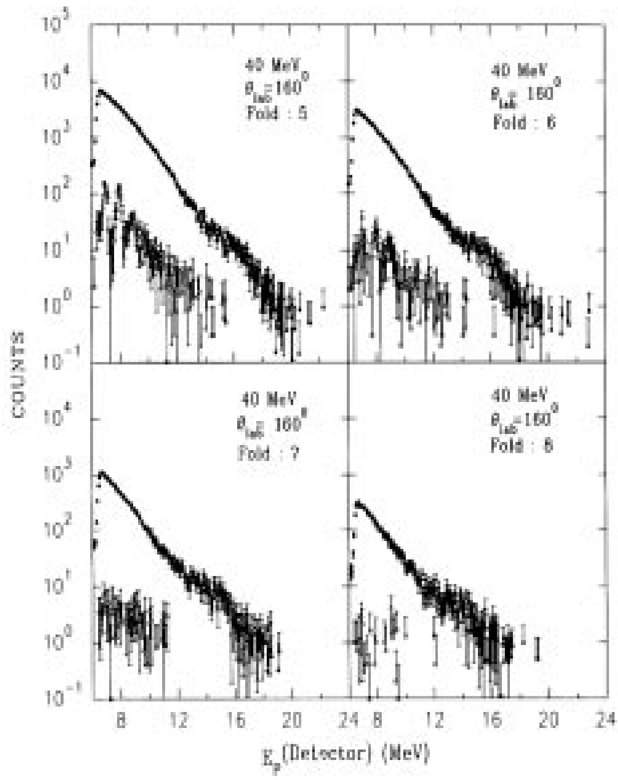

Figure 3. First chance proton spectra gated by spin. The protons from the target (Nb) and light impurities are shown respectively at the top and the bottom parts in each box.

higher value for a higher bombarding energy such that the excitation energy region in the residual nucleus remains roughly the same. At a given bombarding energy, the bump moves to lower energy values for higher folds. The centroid of this bump remains at the same excitation energy of the residual nucleus if the excitation energy is corrected for rotational energy and the average excitation energy is around 7 MeV above the yrast at each fold. It may be possible to understand this as arising due to presence of some kind of doorway states expected in the residual nucleus at these excitation energies.

In addition to nuclear structure, it is also expected that the shape of the emitter must influence the resultant particle spectra. In a recent work, Charity [8] has shown that due to thermal fluctuations, there should be shape distributions (spherical, oblate, prolate) of the compound nucleus emitting particles. This in turn will alter the shapes of the particle spectra and the effect being more for the alphas. Sometime back, Galindo–Uribari *et al* [9] in their study related to high spin states in ^{133}Nd, measured the proton spectra feeding the super deformed bands (with 1.4:1 axis ratio) and the normal bands using a 4π charged particle detector and a 8π gamma detector set up. However, the data did not reveal significant differences in the proton spectra which could be attributed to differences in the deformation of the two bands. Recently, Viesti *et al* [10] tried to look for characteristic differences in the proton spectra associated with the hyperdeformed and the normal bands in ^{152} Dy. In the reaction ^{37}Cl + ^{120} Sn, they measured proton spectra in coincidence with the prominent gamma rays of $^{150-153}$Dy and with prolate, oblate and super deformed bands of ^{152}Dy. Proton spectra showed effects due to the exit channel and to the angular momentum, but did not reveal significant changes associated with the lowering of Coulomb barrier for a deformed system. Unless one can tag on to one step proton emission, multistep processes can smear the proton spectra to make them rather independent of the deformed shapes of the emitter or the residue. As of now this research is inconclusive. More recently, Viesti *et al* [11] have extended this measurement to alphas. They have observed a shift in the position of maxima of alpha particle spectra feeding the normal and the superdeformed bands in the residual nucleus. Aiche *et al* [12] have carried out a similar measurement for the alphas from the reaction ^{37}Cl + ^{123}Sb associated with ^{151,152}Dy nuclei, same as that populated earlier from proton decay. While energy shift was observed in the case of ^{151}Dy, it was not seen for ^{152}Dy. They have carried out statistical model to understand these features. After accounting for other effects, they have concluded that the energy shift observed in the lower energy part of the alpha spectra could be an indication of the influence of the shape of the emitter/residual nucleus. It is clear from the above discussion that the shapes of both the emitter and the residue formed after particle emission should influence the measured particle spectra and this has to be taken into account in making statistical model calculations.

4. Pre-equilibrium particle spectra – Mean field and nucleon–nucleon aspects

Heavy-ion collisions below roughly 10 MeV/nucleon are dominated by nuclear mean field. With increasing energy there is a reduction of the Pauli blocking and the two body collisions become important. At about 100 MeV/nucleon, the dynamics is strongly governed by two body collisions. The intermediate energy region provides experimental evidence of a competition beween one body and two body dynamics. As the bombarding energy is increased beyond 8–10 MeV/nucleon, the complete fusion of the two interacting nuclei slowly gives way to incomplete fusion. The emission of fast nucleons is an important feature and this is in fact responsible for keeping the temperature of the compound nucleus to 5 to 6 MeV for medium mass nuclei and somewhat less for the heavier nuclei [2]. One of the succcessful models proposed for understanding the emission of the pre-equilibrium particles is the Fermi jet model [13–15]. According to this, as the projectile and the target make contact, a neck is formed between the two. The nucleons that are transferred may under favourable kinematical conditions, be sufficiently energetic in the receptor nucleus to escape promptly, their energy boost arising from the coupling of the original internal (Fermi) velocity of the nucleon in the donor nucleus with the relative velocity of the reacting nuclei. Obviously, the resulting yield of such promptly emitted particles (PEP) depends sensitively on the underlying dynamics of the collision, specifically its early stage when the relative velocity is largest. Starting with the nucleon exchange transport ideas, detailed calculations have been performed by incorporating the two body collisions in addition to the one body PEPs, the dyanamically changing momentum distribution due to deposition of energy in the colliding partners (heating due to collisions, cooling due to evaporation of particles), the influence of the driving force on the nucleon transfer probability and the effect of penetration through the barrier, including the Coulomb barrier for protons. Other theoretical developments include the Boltzman master equation approach and the VUU (Vlasov, Uehling–Uhlenbeck) approach. In general the heavy ion reaction mechanisms are dependent on the impact parameter of the collision. The largest impact parameters led to quasielastic reactions, with somewhat smaller impact parameters leading to more deeply inelastic collisions. A wide range of impact parameters led to complete and incomplete fusion. In the study of reaction mechanisms it is essential to have a tag which measured the impact parameter of the collision as light charged particles are emitted from a range of impact parameters. Prindle *et al* [16] have proposed a new tagging method for defining different impact parameter regions within the fusion like regime and it is based on the angular momentum dependence of evaporation residue – fission competition in the $A = 160-210$ region. While low impact parameter events lead to evaporation residues, the higher ones result in fissions. Detection of fission fragments or evaporation residue allows tagging of an impact parameter space. The mean impact parameter for a particular type can be adjusted by changing the mass/charge of the target and thereby changing the fissionability of the composite system. The total fusion cross section values for these systems are comparable and this ensures that the total angular momentum space is similar for all the systems and the angular momentum or impact parameter variation is achieved by change of ER (evaporation residue) to fission ratios which occurs as a function of A in the above mass region. Prindle *et al* [16,17] have carried out charged particle multiplicity measurements using 14 MeV/A and 25 MeV/A ^{16}O and 35 MeV/A, ^{14}N beams on targets ranging from ^{159}Tb to ^{197}Au, both with ER and fission tags. On the average the prompt proton multiplicity (M_p) decreases with increase of impact parameter consistent with the Fermi jet model prediction. It was also reported that more protons are emitted from evaporation residues than from fissions. Further, it was observed that both M_d/M_p and M_t/M_p increase with increase of E and saturate at high energies. However, the M_α/M_p ratio is observed to decrease at the higher energies. This might imply a different emission mechanism for alphas amongst the light complex particles. However, as a function of impact parameter all the ratios increase with increase of impact parameter (in contrast to the behaviour of protons) implying the peripheral dominance of the production of light complex particles. Some of these findings are depicted in figure 4. It will be important to study the

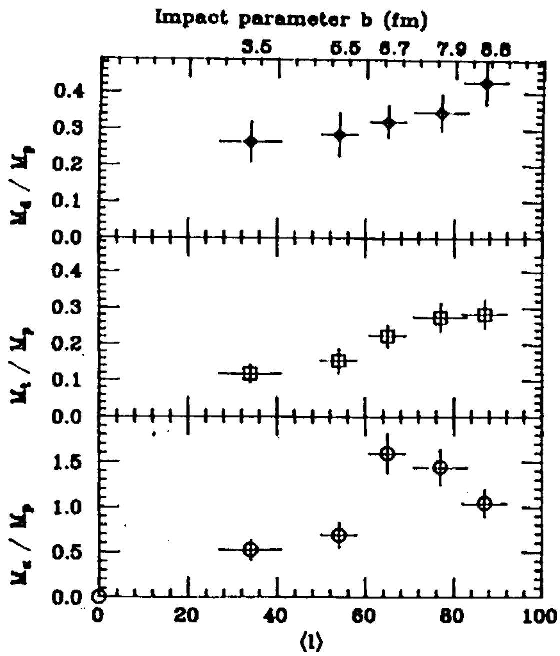

Figure 4. Light particle multiplicity as a function of impact parameter of collision.

M_n/M_p to investigate the role of isospin in PEQ (pre-equilibrium) as very little work in this direction has been done. Use of radioactive ion beams or neutron skin projectile/target will be interesting in this investigation.

5. Light charged particles and fission dynamics

In the case of compound nucleus decay, if the excitation energy of the compound system with $A = 160{-}250$ is increased beyond 50 MeV or so, it is found that light particle emission competes with fission decay and the decay times of fission and particle emission become comparable around this excitation. In essence the light particle emission time can be used as a clock to follow the fission dynamics from equilibrium to the saddle and finally to the scission point. The time scales of 10^{-20} to 10^{-21} sec can be followed using the particle tagging of fission decay. The presence of frictional forces affect not only the transient time from equilibrium to saddle point but also probability of passing over the saddle. As a result the fission width gets reduced. At this stage particle emission competes with fission and as a result of additional time for fission (fission hindrance) enhanced particle emission takes place both before and after the fission saddle. The nuclear viscosity coefficient has been deduced from pre-scission particle and gamma spectra. As pointed out before that the deformation degree of freedom should be taken into account in deducing time scales using statistical model. Further the other statistical model

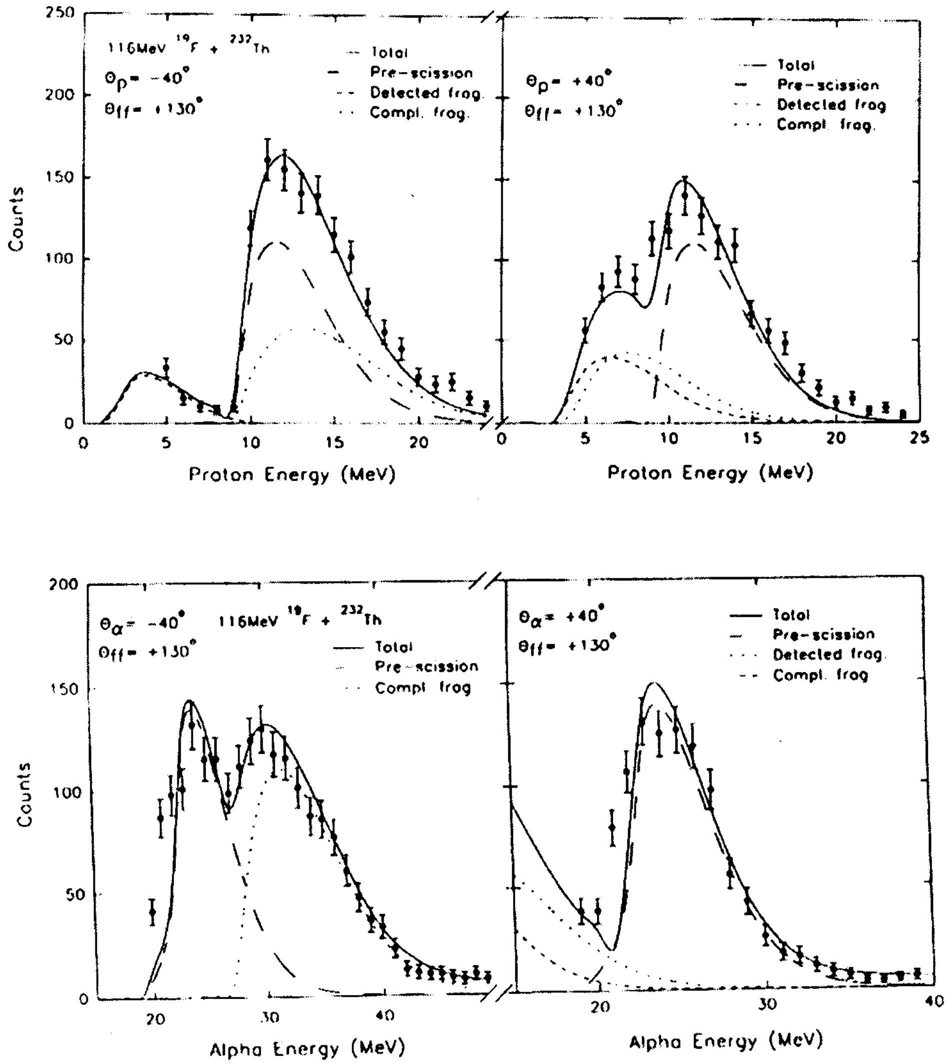

Figure 5. Proton and alpha spectra in the reaction $^{19}F + {}^{232}Th$. The charged particles arising from compound nucleus and fission fragments are shown in the figure.

parameters have also to be constrained before reliable information on the nuclear viscosity can be obtained. In addition, at higher bombarding energies the separation of complete and incomplete fusion components has to be done. The charged particle tagging of fission decay offers the following advantage: the emission spectra of light charged partciles arising from the compound nucleus and the fission fragments are very different energetically as the Coulomb barriers of the respective emitters are also different. Chatterjee *et al* [18] have made measurements of light charged particles in coincidence with fission for $^{19}F + {}^{232}Th$ system (figure 5).

By a careful choice of charged particle and fission detector angles, the separation of light particles from fission fragments and the compound nucleus has been achieved. In this work, the fission delay from dynamics/dissipation has been deduced. From a series of measurements where exclusive fission decay data have been carried out with gammas, neutrons and other charged particles, the fission delay times due to dyanamical effects have been determined to be in the range of 5 to 30 (10^{-21} sec) [4,18–20]. Hence light charged particle emission can be used as a probe to obtain the fission delay times over a range of deformation space from equilibrium to scission stages of the fissioning compound nucleus.

6. Conclusion

In the above discussion, it has been brought out that light charged particles in particular are efficient time keepers (fission delay studies), temperature regulators (pre-equilibrium studies), nuclear structure markers (shape sensors). Through their studies it has been possible to determine one and two body dissipation/friction/viscosity effects. The emission mechanism of light charged particles is also strongly influenced by mean field and nucleon–nucleon effects. At high bombarding energies and excitation of compound nucleus involving moderately large spins, all the above mentioned effects will be present simultaneously and hence they have to be adequately accounted for before deducing reliable information on the emission mechanism. It is desirable to have compelete data set as a function of energy for one system to understand better different features discussed above. In future when higher intensity radioactive ion beams will become available, it will be feasible and very interesting to pursue these studies in view of the exotic structures and shapes of the radioactive ions.

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