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# Temperature of projectile like fragments in heavy ion collisions

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ABSTRACT

A model in which a projectile like fragment can be simply regarded as a remnant after removal of some part of the projectile leads to an excited fragment. This excitation energy can be calculated with a Hamiltonian that gives correct nuclear matter binding, compressibility and density distribution in finite nuclei. In heavy ion collisions the model produces a dependence of excitation energy on impact parameter which appears to be correct but the magnitude of the excitation energy falls short. It is argued that dynamic effects left out in the model will increase this magnitude. The model can be directly extended to include dynamics but at the expense of increased computation. For many calculations for observables, a temperature is an easier tool to use rather than an excitation energy. Hence temperature dependences on impact parameter in heavy ion collisions are displayed.



## 1. Introduction

In recent times we proposed a model [1–3] for projectile fragmentation whose predictions were compared with many experimental data with good success. The model has three parts. To start with we need an abrasion cross-section. This was calculated using straight line trajectories for the projectile and the target leading to a definite mass and shape to the projectile like fragment (PLF). The PLF will have an excitation energy. It was conjectured that this will depend upon the relative size of the PLF with respect to the projectile, i.e., on $(A_s/A_0)$ where $A_s$ is the size of the PLF and $A_0$ is the size of the whole projectile. Since the size $A_s$ of the PLF depends upon the impact parameter of the collision, dependence on $(A_s/A_0)$ means the excitation energy depends upon the impact parameter [2,3]. In our original version this dependence was neglected [1] but became an important feature in the improved model [2]. Instead of excitation energy we use temperature $T$. The hot PLF will disintegrate into different composites which can be calculated using a canonical thermodynamic model (CTM) [4]. Evaporation from hot composites which result from CTM was implemented [5].

In our model the temperature of the PLF was not calculated, it was fitted from data. In this Letter we try to estimate $T$ from a more basic approach. We are not trying here to formulate a complete model for projectile fragmentation. The earlier papers [1–3] had that goal. There are models which calculate observables which can be directly compared with experiment. One example is the heavy ion phase space exploration (HIPSE) [6] model. Another model that has been used is the antisymmetrised molecular dynamics (AMD) model [7]. These are relevant to our earlier papers rather than to the present work.

The concept of temperature has proved to be useful to understand many features of projectile fragmentation. Temperature $T$ in the PLF has been studied a great deal in the past using a combination of theory and experimental data. A very popular method uses experimental populations of excited states (for example, the "Albergo" formula [8]) to deduce a temperature. Many data suggest that the temperature is of the order of 5 MeV. There is also unmistakable evidence that the temperature falls off with increasing impact parameter. It was shown in [2] that for beam energies between 140 MeV/n and 1 GeV/n (the only cases that were tried) a remarkably simple parametrisation $T(b) = 7.5\ \text{MeV} - [A_s(b)/A_0]4.5\ \text{MeV}$ worked well for all the pair of ions. In this Letter we are trying to see if such simple feature can be understood in a transparent physical picture. Simple models for PLF excitations have also been made in the past [9,10]. The relationship of that work to ours will be discussed in the last part of this Letter.

If straight line geometry is used then it is obvious that the PLF is created with a crooked shape. If the excitation energy in the PLF is mostly due to its crooked shape at the time of separation, one can estimate the excitation energy assuming a liquid drop model with a volume term, a surface tension term and Coulomb contribution. One is probably confined to assuming a constant density which is not realistic.

The objective of this Letter is to estimate the temperature in the PLF using a more microscopic approach. The lowest order

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approximation we make to estimate the temperature arises from the crooked shape that results from straight line geometry for cuts. The excitation energy originates from structure effects solely as in a liquid drop model. But we are not using a liquid drop model nor are we limited to constant density. Our method can be extended to consider dynamic effects using a transport model, specifically the BUU (Boltzmann–Uehling–Uhlenbeck) model. The techniques we use, even for the lowest order estimates, are well-known in BUU calculations.

We should hasten to add that the calculations reported in this Letter are not transport model calculations. These are static calculations. There is no time evolution. The beam energy does not enter but for the validity of the model the beam should be sufficiently energetic so that straight line trajectories are a valid approximation. There are transport model calculations which compute excitation energy per nucleon for quasi-projectile and quasi-target [11] at 52 MeV per nucleon and 72 MeV per nucleon. Our model would not apply at such low energy. Our model here was developed for cases like Sn on Sn at 600 MeV per nucleon, Xe on Pb at 1 GeV per nucleon. The lowest energy we had in mind was 140 MeV per nucleon with Ni as the projectile.

We do calculation for Sn on Sn, Xe on Pb, Ni on Be and Ta as we have used our model for these cases before [1–3] and experimental results are known [12–14]. In heavy ion collisions we consider one ground state nucleus hitting another ground state nucleus. We first turn to the model of the ground state.

## 2. Model of the ground state

We use Thomas–Fermi (TF) solutions for ground states. Complete details of our procedure for TF solutions plus the choice of the interactions are given in Ref. [15]. For completeness the prescription is outlined. The kinetic energy density is given by

$$T(\vec{r}) = \int d^3p\, f(\vec{r},\vec{p})\, p^2/2m \tag{1}$$

where $f(\vec{r},\vec{p})$ is the phase space density. Since we are looking for lowest energy we take, at each $\vec{r}$, $f(\vec{r},\vec{p})$ to be non-zero from 0 to some maximum $p_F(\vec{r})$. Thus we will have

$$f(r,p) = \frac{4}{h^3}\theta\big[p_F(r,p) - p\big] \tag{2}$$

The factor 4 is due to spin–isospin degeneracy and using the spherical symmetry of the TF solution we have dropped the vector sign on $r$ and $p$. This leads to

$$T = \frac{3h^2}{10m}\left[\frac{3}{16\pi}\right]^{2/3}\int \rho(r)^{5/3}\, d^3r \tag{3}$$

For potential energy we take

$$V = A\int d^3r\frac{\rho^2(r)}{2} + \frac{1}{\sigma+1}B\int \rho^{\sigma+1}(r)\, d^3r + \frac{1}{2}\int d^3r\, d^3r'\, v\big(\vec{r},\vec{r}'\big)\rho(\vec{r})\rho\big(\vec{r}'\big) \tag{4}$$

The first two terms on the right hand side of the above equation are zero range Skyrme interactions. The third which is a finite range term is often suppressed and the constants $A, B, \sigma$ are chosen to fit nuclear matter equilibrium density, binding energy per nucleon and compressibility. In heavy ion collisions, for most purposes, this will be adequate but for what we seek here, possibly a small excitation energy, this is wholly inadequate. Thomas–Fermi solution is obtained by minimising $T + V$. With only zero range force, $\rho(r)$ can be taken to be a constant which goes abruptly to zero at some $r_0$ fixed by the total number of nucleons. Now if $\rho$ is chosen to minimise the energy then, a nucleus, at this density with a cubic shape is as good as a spherical nucleus. Besides the minimum energy nucleus will have a sharp edge, not a realistic density distribution. This problem does not arise in quantum mechanical treatment with Skyrme interaction. Including a finite range potential in TF one recovers a more realistic density distribution for the ground state and one regains the nuclear structure effects which will contribute to excitation the PLF. This is discussed in more detail in Ref. [15].

We note in passing that Lenk and Pandharipande introduced a diffuse surface by modifying the kinetic energy term [19].

Thomas–Fermi solutions for relevant nuclei were constructed with following force parameters. The constants $A$, $B$, and $\sigma$ (Eq. (4)) were taken to be $A = -1533.6$ MeV fm$^3$, $B = 2805.3$ MeV fm$^{7/2}$, $\sigma = 7/6$. For the finite range potential we chose a Yukawa: $V_y$.

$$V_y = V_0\frac{e^{-|\vec{r}-\vec{r}'|/a}}{|\vec{r}-\vec{r}'|/a} \tag{5}$$

with $V_0 = -668.65$ MeV and $a = 0.45979$ fm. Binding energies and density profiles for many finite nuclei with these parameters (and several others) are given in Ref. [15]. These have been used in the past to construct TF solutions which collide in heavy ion collisions [16].

## 3. Methodology

We use the method of test particles to evaluate excitation energies of a PLF with any given shape. The method of test particles is well-known from use of BUU models for heavy ion collisions [17]. Earlier applications were made by Wong [18].

We first construct a TF solution using iterative techniques [15]. The TF phase space distribution will then be modeled by choosing test particles with appropriate positions and momenta using Monte Carlo. Throughout this work we consider 100 test particles ($N_{test} = 100$) for each nucleon. For example, the phase space distribution of $^{58}$Ni is described by 5800 test particles. A PLF can be constructed by removing a set of test particles. Which test particles will be removed depends upon collision geometry envisaged. For example, consider central collision of $^{58}$Ni on $^{9}$Be. Let $z$ to be the beam direction. For impact parameter $b = 0$ we remove all test particles in $^{58}$Ni whose distance from the center of mass of $^{58}$Ni has $x^2 + y^2 < r_9^2$ where $r_9 = 2.38$ fm is the radius at half density of $^{9}$Be. The cases of non-zero impact parameter can be similarly considered.

The "sudden approximation" we consider is the following. We assume that the PLF is formed suddenly. At the time the PLF separates from the participants the shape and momentum distribution of the PLF can be described by removing some test particles as described above. Of course this PLF will undergo many more changes later but all we are concerned with is the energy of the system at the time of "separation". Since the PLF now is an isolated system, the energy will be conserved. Of course the Coulomb force from the participants will continue to be felt by the PLF. But the major effect of this will be on overall translation of the PLF and all we are interested in is intrinsic energy.

We now describe how we calculate the energy of this "crooked" shape object. The mass number of the PLF is the sum of the number of test particles remaining divided by $N_{test}$. Similarly the total kinetic energy of the PLF is the sum of kinetic energies of the teat particles divided by $N_{test}$. Evaluating potential energy requires much more work. We need a smooth density to be generated by positions of test particles. We use the method of Lenk and Pandharipande to obtain this smooth density. Other methods are