Estimation of Impact Parameter on event-by-event basis in Nuclear Emulsion Detector

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Abstract
Photographic Nuclear Emulsion Detector (PNED) has been in use in nuclear and particle physics experiments from the beginning, often as the major detector system. However, direct measurement of impact parameter in this detector does not seem possible due to some limitations. This paper describes a simple yet strong method to estimate the impact parameter of events on event-by-event basis. Though this method is developed specifically for the photographic nuclear emulsion detector, we envision that it should also be applicable to other multi-target detector systems.

Keywords: NUCLEAR REACTION Impact parameter, photoemulsion method, relativistic nuclear collisions.

1 Introduction
A study of relativistic nucleus - nucleus collision is an important tool to produce and investigate highly dense nuclear matter in the laboratory [1-3]. Based on straightforward geometrical considerations, theoretical models predict that the size of the dense nuclear matter zone produced in collisions depends strongly on the impact parameter (b) i.e., the transverse distance between the center of mass of the projectile and the target nucleus [4]. It is thus very important to sort out the collisions according to their centrality. The impact parameter, which characterizes the initial state, is not a directly measurable quantity. Thus, it is necessary to find out an observable that strongly correlated with it. The simplest observable one can think of is the total charged particle multiplicity of an event in case of nuclear emulsion detector. We can also try to use the shower (mostly pions) particle or projectile’s proton multiplicity as an observable but it does not show a strong correlation with impact parameter due to different size of the targets. In emulsion detector, emulsion provides medium to the projectile as well as targets. Emulsion mainly composed of H, CNO and Ag(Br). The variation in target size could create big confusion in identification of events having b = 0 and events having impact parameter b > 0 of the bigger size projectile with H and Ag(Br). In this paper, we have developed a simple method for estimation of impact parameter on an event-by-event basis, which allows one to translate the qualitative estimate of impact parameter from total multiplicity into a qualitative one. A quantitative estimate is very convenient in order to present consistent results obtained in various experiments. We will also discuss some basic characteristics of the interactions with respect to the impact parameter. Some of the characteristics are studied in different energy intervals like high, Mid., and low energy.

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Table 1: Mean Free Path of different projectiles in nuclear emulsion.

| Projectile | Energy (A GeV) | Mean Free Path (cm.) | Ref. |
|------------|---------------|----------------------|------|
| \(^4\text{He}\) | 2.1 | 21.80±0.70 | [9] |
| \(^{12}\text{C}\) | 2.1 | 13.80±0.50 | [9] |
| \(^{14}\text{N}\) | 2.1 | 13.10±0.50 | [9] |
| \(^{16}\text{O}\) | 2.0 | 12.60±0.50 | [10] |
| \(^{56}\text{Fe}\) | 1.7 | 7.97±0.19 | [11] |
| \(^{84}\text{Kr}\) | 1.0 | 6.76±0.21 | [Present work] |
| \(^{139}\text{La}\) | 1.2 | 5.18±0.30 | [12] |
| \(^{197}\text{Au}\) | 1.0 | 5.60±0.26 | [13] |
| \(^{238}\text{U}\) | 1.0 | 3.67±0.12 | [14] |

Table 2: The chemical composition of NIKFI BR-2 emulsion [15].

| Element | \(^1\text{H}\) | \(^{12}\text{C}\) | \(^{14}\text{N}\) | \(^{16}\text{O}\) | \(^{80}\text{Br}\) | \(^{108}\text{Ag}\) |
|---------|----------------|----------------|----------------|----------------|----------------|----------------|
| No of atoms/cc × 10\(^{22}\) | 3.150 | 1.410 | 0.395 | 0.956 | 1.028 | 1.028 |

2 Experimental Details

Nuclear emulsion is a detector composed of silver halide crystals immersed in a gelatin matrix [5-7] consisting mostly of hydrogen, carbon, nitrogen, oxygen, silver and bromine while a small percentage of sulfur and iodine are also present as shown in table 2. In the present experiment, we have employed a stack of high sensitive NIKFI BR-2 nuclear emulsion pellicles of dimensions 9.8×9.8×0.06 cm\(^3\), exposed horizontally to \(^{84}\text{Kr}\) ion at a kinetic energy of around 1 GeV per nucleon. The exposure has been performed at Gesellschaft für Schwerionenforschung (GSI) Darmstadt, Germany. The events have been examined and analyzed with the help of a LEITZ (ERGOLUX) optical microscope having total magnification of 2250X and measuring accuracy of 1 \(\mu\)m. In order to obtain an unbiased sample of events, an along-the-track scanning technique has been employed [8].

The interaction mean free path (\(\lambda\)) of \(^{84}\text{Kr}\) in nuclear emulsion has been determined and found to be 6.76±0.21 cm. Our collaborators (DGKLMTV Collaboration) [16] found a value of mean free path (\(\lambda\)) 7.10±0.14 cm. consistent, within the experimental error, with our value. We have tabulated the mean free path of different emulsion experiments at similar beam energy in table 1. From this table, we may conclude that the mean free path decreases with increasing beam mass number at similar energy. The mean free path value obtained in our experiment is well fitted in this trend i.e., during event scanning, we picked up all genuine events according to our event selection criteria and our criteria of event selection is also right. For the present work, we used 1197 events scanned by line scanning method and additional 162 events were picked up by volume scanning method. The grain density of a singly charged particle passing in the same emulsion at extreme relativistic velocity is called the minimum grain density (\(g_{\text{min}}\)). In this experiment, its measured value is equal to 28±1 grains per 100 \(\mu\)m. The \(^{84}\text{Kr}\) beam stops within a pellicle. Since, the beam energy decreases as it goes from the entrance edge, we have divided each plate in three major energy intervals where the beam has
energy in the range 0.95 - 0.80 (High Energy), 0.80 - 0.50 (Middle Energy), and below 0.50 (Low Energy) A GeV, respectively.

The mean number of fully developed and well separated grains per unit length is called the grain density $g$. It is a measure of the rate of ionization loss. The grain density of a track corresponds to a particular specific ionization but its actual value depends on the degree of development of the emulsion and the type of the emulsion used. It is therefore, necessary to introduce another quantity called normalized grain density which is defined as $g^* = g/g_{min}$. Here $g$ is the observed grain density. All charged Secondaries emitted or produced in an interactions are classified in accordance with their ionization, range and velocity into the following categories:

(a) **Shower tracks** ($N_s$): These are freshly created newly produced charged particles with $g^* < 1.4$. These particles have relative velocity $\beta > 0.7$. For the case of a proton it means energy of $E_p > 400$ MeV. They are mostly fast pions with a small admixture of kaons and of released protons from the projectile which have undergone an interaction. These conditions ensure that showers are filtered from the fragments and knockout protons of the target.

(b) **Grey tracks** ($N_g$): Particles having ionization in the interval $1.4 < g^* < 6.0$ and range $> 3$ mm are defined as greys. These particles having relative velocity $0.3 < \beta < 0.7$. They are generally knocked out protons of targets having energy $30 < E_p < 400$ MeV but also admixture of deuterons, tritons and some slow mesons.

(c) **Black tracks** ($N_b$): Particles having range $< 3$ mm from interaction vertex from which they originated and $g^* > 6.0$. This corresponds to a relative velocity $\beta < 0.3$ and a proton with energy $E_p < 30$ MeV. Most of these are produced owing to evaporation of residual target nucleus.

The **heavily ionizing charged particles** ($N_h = N_g + N_b$) are parts of the target nucleus and are also called target fragments.

(d) **Projectile Fragments** ($N_f$): These are the spectator parts of the projectile nucleus with charge $Z \geq 1$ having velocity close to the beam velocity. The ionization of projectile fragments (PFs) is nearly constant over a few mm and emitted within a highly collimated forward narrow cone whose size depends upon the available beam energy.

The forward angle is the angle whose tangent is the ration between the average transverse momentum of the projectile fragments to the longitudinal momentum ($p_L$) of the beam. Taking $p_L$ as the beam momentum itself, i.e., $\theta_F = tan^{-1}(p_t/p_L) \approx 9^\circ$ in this experiment. The PFs are further classified into three categories as follows:

(i) **Heavy Projectile Fragments** ($N_f^Z \geq 3$).

(ii) **Alpha Projectile Fragments** ($N_\alpha$): PF's having charge $Z=2$.

(iii) **Singly charged relativistic Projectile Fragments** ($N_f^{Z=1}$).

Since these PF’s have velocities nearly equal to the initial beam velocity, their specific ionization may be used directly to estimate their charge.

The **total multiplicity of the secondary charged particle** ($N_{ch}$ or $M$) is taken as the sum of all charged particles emitted or produced in an interactions ($N_{ch} = N_s + N_h + N_f + N_\alpha + N_{f^{Z=1}}$).
Figure 1: (a) Normalized multiplicity distribution of $N_h$ at $\sim 1$ GeV per nucleon. Dotted line separate the events from the admixture of CNO target and peripheral collisions with Ag(Br) targets. (b) $N_h$ distribution of events having $N_h \geq 8$. Solid line is a double Gaussian fit to separate Ag and Br target events.

3 Method of Target Identification

The exact target identification in an emulsion experiment is not possible as the medium is composed of various elements as mentioned in table 2. However, we can divide the major constituent elements into three broad target groups such as H (light), CNO (medium) and AgBr (heavy) with high accuracy. There are a lot of other ways of statistical separation [17-20], which roughly give the probability of interactions with different targets. It is well known that the number of heavy particles, $N_h$ is a good tool for target identification. Since we are interested in the separation of targets on event by event basis, we have employed short-range track distribution to identify targets for events with low $N_h$ value. In view of the distribution of heavily ionizing charge particles for all set of events as shown in fig. 1(a), we have attempted the separation of targets using the following criteria:

- **H target events**: $N_h = 0$; $N_h = 1$ but not falling in any of the below categories.
- **CNO target events**: $2 \leq N_h \leq 8$ and no track with range $\geq 10 \mu m$.
- **Ag(Br) target events**: $N_h > 8$; $N_h \leq 8$ and at least one track with range $\geq 10 \mu m$ and no track with $10 \leq \text{range} \leq 50 \mu m$.

As a result, we have obtained the percentage for the occurrence of the three different target group events as H : 12%, CNO: 48% and Ag(Br): 40%. The relevant data is summarised in table 3. Table 3 gives the results using the above criteria along with the results of other similar efforts [21-28]. It may be seen from the table that the probability of events due to Ag(Br) nuclei increases slowly with increasing projectile mass at similar energy. It also shows that the method of target separation is almost correct.

We are, first-ever, separating the Ag and Br nuclei in emulsion detector. For this, we examine only Ag(Br) type interaction. Their frequency distribution is shown in fig. 1(b) and has been fitted by the double Gaussian functions. We have found that the contributions of
Table 3: Percentage of interactions with different target groups.

| Interactions | Energy (A GeV) | H | CNO | Ag(Br) | Ref. |
|--------------|---------------|---|-----|-------|------|
| $^1P$        | 2.5           | 18.00 | 49.50 | 32.50 | [21] |
| $^4He$       | 3.7           | 21.03 | 40.42 | 38.55 | [22] |
| $^{12}C$     | 3.7           | 21.29 | 30.87 | 47.84 | [23] |
| $^{22}Ne$    | 3.7           | 12.94 | 32.50 | 54.47 | [24] |
| $^{28}Si$    | 3.7           | 15.29 | 33.79 | 50.92 | [25] |
| $^{40}Ar$    | 1.8           | 17.80 | 34.60 | 47.50 | [26] |
| $^{56}Fe$    | 3.7           | 23.13 | 22.64 | 54.23 | [27] |
| $^{84}Kr$    | 1.0           | 12.10 | 47.60 | 40.40 | [Present work] |
| $^{197}Au$   | 8.7           | 19.00 | 36.00 | 45.00 | [28] |

Figure 2: Reference distribution of b and total charge particle multiplicity for different target groups and for different energy intervals. Solid line is just to guide the eye.

Ag nuclei and of Br nuclei are 44% and 56% , respectively. The same numbers for Ag and Br nuclei are reported by B. Jakobsson et al [29], who employed the distribution of the sum of charges in events where all targets have been measured directly from an exposure at GANIL. From now, we will proceed for development of new method for impact parameter estimation on event by event basis only for separate target group to avoid the mathematical complications and making the method simpler.

4 Method of Impact parameter(b) Estimation

Shower particle multiplicity have strong correlation with impact parameter in the fix target mass experiments. Due to the invariant target mass, shower particle multiplicity will not show strong correlation with impact parameter. Because H target, with fix mass beam, having nearly zero impact parameter may show the similar shower multiplicity as CNO or Ag(Br) target, with fix beam, having larger impact parameters. That’s the reason we are interested in using total charged particle multiplicity ($N_{ch}$) to estimate the impact parameter and will show strong correlation between them. In some collider experiments [30] they found that the total
particle multiplicity \( N_{ch} \) is strongly correlated with the impact parameter \( b \). More precisely, its mean value decreases monotonically as a function of \( b \).

In this method the basic assumptions are as following: We treated interactions of each target group with projectile separately to make the method simpler. The total cross section is purely geometrical and there is a strong correlation between \( b \) and \( N_{ch} \). The targets are randomly distributed in the nuclear emulsion detector and the probability of interactions is totally random and the collisions geometry is also random.

Therefore, we used random number generator [31] to generate random numbers in between 0 and 1 for \( N_{ch} \) and \( b \). For making the random number values upto the order of total multiplicity \( N_{ch} \), we choose the maximum and minimum limit according to our real experimental values of maximum and minimum multiplicities of total charged particles in each target group and each target group multiplied by a suitable factor of numbers. For making the random number values upto the order of impact parameter according to the \( A_P \) and \( A_T \), we used real radius values of projectile and target nuclei and took the maximum and minimum as a combination and difference of radii of both nuclei, for \( b = R_P + R_T = b_{max} \) and \( b = |R_P - R_T| = b_{min}(\approx 0) \), respectively and made the order of magnitude according to the order of real experimental values. We assume that minimum multiplicity value belong to the \( b_{max} \) and maximum multiplicity belongs to the \( b_{min} \) and therefore we set two extreme points on the \( b \) versus multiplicity distribution and distributed rest of the values according to the monotonic relation between \( b \) and \( N_{ch} \) such as \( b = N_{ch(max)} - N_{ch} \) for different target groups and for different energy intervals. In fig. 2, we are showing relation between generated impact parameter and generated multiplicity of charged particles. We know the real event total charge particle multiplicity \( N_{ch} \) and match this real multiplicity with \( b \) with the help of fig. 2 and can easily estimate the impact parameter corresponding to the real event.

5 Experimental Results

To check the authenticity of the developed method, we have checked few characterestic parameters with respect to impact parameter. Most of them are also checked in different energy intervals as well as different target groups. In this sequence, first we checked total charge particles multiplicity with respect to impact parameter for different target groups in different energy intervals as shown in fig. 3 (a), (b) and (c), respectively. The error bars shown on the data points are purely statistical and different type of lines are the best fit of data in different energy intervals. From fig. 3, we may infer that in each target group, the relation between multiplicity and impact parameter is monotonic and the slope is variable with change in beam energy as well as change in the target mass number. The nature of the distribution is similar to the participant - spectator Model prediction i.e., at maximum overlap \( (b_{min}) \) region of target and projectile, multiplicity must be maximum and vice - versa.

We checked the emission of alpha particles in interactions with H - target with respect to the impact parameter as shown in fig. 4(a). The distribution shows a polynomial nature. The maximum number of emitted alpha particle in an interaction with H - target is 5 to 6 at maximum overlap. Here the size of H - target is much smaller than the size of the \( ^{84}Kr \)-projectile. That’s why it is very difficult to select head-on collisions and this can easily mix into the central as well as quasi-central events. Emission of the average number of shower particle versus \( b \) is plotted in fig. 4(b). The condition of this distribution is similar to the
Figure 3: The average total charge multiplicity is plotted as a function of estimated impact parameter in different energy intervals for different target groups (a) H, (b) CNO, and (c) Ag(Br). Solid, short dash and long dash lines are the best fit of high energy, mid. energy and low energy data set, respectively.

**fig. 4(a).** It shows a strong monotonic correlation between $< N_s >$ and $b$. The solid line is the best fit of data points and the error bars represent the statistical error.

The $Q (= \Sigma f_{Z=1} + 2 \times \Sigma f_{Z=2} + \Sigma Z \times f_{Z\geq3})$ is the total projectile fragments charge flow in the forward emission cone. The $< Q >$ value versus $b$ for all energy events in different target groups is shown in **fig. 5**. For making a comparison and guiding the eye, we have fitted the distribution with a linear function. The light and heavy target groups show nearly similar slopes while medium target group has slightly different slope. We can also see the $< Q >$ value change with target mass, specially with light and heavy targets. At $b_{min}$ and $b_{max}$, the difference in $< Q >$ is around double. At $b_{min}$, less than half of the projectile mass are converted into some other things (like energy and neutral particle) but at $b_{max}$ nothing is going to disappear while few neutrons are converted into protons and make the total charge $Q$ value larger than 36.

In **fig. 6**, we have plotted $< b >$ versus $Q$ for all high energy events for one combined target (H + CNO + Ag and Br). It can be seen that $Q$ is minimum at minimum value of $< b >$ and approaches the beam charge ($Z = 36$) at maximum value of $< b >$. The presence of some events having $Q$ values more than the value of beam charge (36) when $< b >$ has a value less than the maximum $< b >$ may be attributed to the conversion of neutrons into protons while nuclei collide with each other. All above described behaviour of parameters are consistent to the several theoretical models [32] specially participant spectator model [33].

### 6 Conclusions

A new method to estimate an Impact parameter on the basis of event-by-event in Photographic Nuclear Emulsion detector, was developed and studied in detail of some characteristic parameter. Although this work originates from the goals of handling data from photographic nuclear emulsion detector, and can be applicable to the similar kind of detectors or other multi-target detector systems where all type of targets are mixed together and only very limited information is in hand. These studies will boost the data analysis for emulsion detector in the light of impact parameter. This is a new method that’s why we have no any other experimental data for comparison but the experimental values obtained in this experiments strongly support the theoretical concepts.
Figure 4: (a) Average number of Helium nuclei emitted in interaction with H - target are plotted with respect to impact parameter for all energy. Solid line is the polynomial function fit is just to guide the eye. (b) Average number of shower particles emitted in interaction with H - target are plotted as a function of impact parameter for all energy range (0.06 - 0.95 A GeV). Solid line is the best line fit of data points.

Figure 5: The average Q values versus impact parameter for high energy interval with different target groups. Different lines are best fit of the data points and are guiding to the eye.
Figure 6: The average impact parameter versus Q for high energy interval. Solid line is the best fit of data points and is just to guide the eye.

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