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Collision of Deuteron at Ultra relativistic Energy With ^{197}Au Nuclei Utilizing Sharp Surface Density Profile

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Abstract

In the present work, the detailed calculations of a nuclear collision (deuteron + gold) (D+Au) using the sharp surface density profile as a function of collision impact parameter at center of mass energy ($\sqrt{s_{NN}} = 200$ GeV) are presented. The number of nucleons that participate in the collisions, in addition to the differential elastic cross-section, at different energies was calculated. The study of the effect of various energies on the outcome of intranuclear nucleon collisions can be carried out by varying the energy of each collision. Thus, properties of the particles resulting from the collision are observed by the different high energies, $\sqrt{s} = 200, 56, 200, 2760, \text{ and } 5440$ GeV. The nuclear overlapping function of the D+Au collision, as the probability of depth penetrating the potential, was different from that of the thickness function calculations. The main results of the $^{197}\text{Au}N_{part}$ at these energies are different as energy affects the outcoming nucleons. It was found that the elastic differential cross-section is larger for smaller impact parameters, and it decreases with increasing collision energy.

Keywords: Optical Glauber model; Heavy-ions collisions; Thickness function; Overlap function; Elastic cross-section.

تصادم الديوتيريون عند طاقة فائقة النسبية مع نواة الذهب 197 باستخدام شكل كثافة السطح الحاد

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قسم الفيزياء، كلية العلوم، جامعة الأنبار، الأنبار، العراق

الخلاصة

في هذا العمل نتائج الحسابات التفصيلية لتصادم نويي (الديوتيريون-الذهب) باستخدام شكل كثافة السطح الحادة كدالة لمعلمة تأثير الاصطدام عند طاقة مركز الثقل $\sqrt{s_{NN}} = 200\text{GeV}$. تم حساب عدد النيوكليونات التي تشارك في التصادمات بالإضافة إلى المقطع العرضي المرن التفاضلي عند طاقات مختلفة. يمكن إجراء دراسة تأثير الطاقة المختلفة على نتائج تصادم النيوكليونات داخل النواة عن طريق تغيير طاقة كل تصادم وبالتالي سيتم ملاحظة خصائص الجسيمات الناتجة عن الاصطدام من خلال الطاقات العالية المختلفة $\sqrt{s_{NN}} = 200, 56, 200, 2760, \text{ and } 5440$ GeV. دالة التداخل النووي لتصادم (D+Au) حيث ان احتمال اختراق العمق للجهد مختلف عن حسابات دالة السمك. النتائج الرئيسية لعدد النيوكليونات المشاركة من الذهب في هذه الطاقات وجد انها مختلفة حيث تؤثر الطاقة على النيوكليونات القادمة. لقد وجد

ان المقطع العرضي التفاضلي المرن يكون أكبر بالنسبة لمعاملات التأثير الاصغر ويتناقص مع زيادة طاقة الاصطدام.

1. Introduction

The process of absorbed stripping was initially hypothesized by Serber [1] and was recognized as the cause of the highly synchronized forward beam of neutrons observed in experiments when deuteron beams accelerated to 190 MeV and impacted internal targets in the Berkeley cyclotron. Then, Glauber [2] demonstrated that the process called "free dissociation," which lacks a classical

analog, might also lead to deuteron breakage. Even when neither nucleon makes contact with the target nucleus (which is regarded as a black disk), part of the deuteron is still absorbed.

Using the optical theorem, the imaginary part of the phase shifts is connected to the nucleon-nucleon scattering cross-section. The total phase shift of the incoming wave is calculated as the sum of all conceivable two-nucleon (complex) phase shifts [3, 4]. These nucleons will have enough momentum at high enough energies to be almost undeflected as the nuclei travel through one another. The nucleons are assumed to travel independently within the nucleus, and the nucleus's size is considerable concerning the strength of the nucleon-nucleon force [5]. The interaction of two colliding nuclei is treated as a wave phenomenon in the limit of the Optical Glauber Model. In the calculations pertaining to this model, it is assumed that the nucleus is made up of a smooth matter density that follows the Fermi distribution in the radial direction, and this distribution is uniform in azimuthal and polar angles [6]. In this context, the D-¹⁹⁷Au collision is an experiment made at the Relativistic Heavy Ion Collider (RHIC). The system size of the two colliding nuclei is combined. So, the different sizes of collision nuclei give insights into how the initial conditions of the collision impact the final state of the system [7]. It is very important to understand how the trajectories of collision-induced particles during a collision are affected by momentum. By analyzing the momentum distributions of collision-induced particles, information about the initial momentum of the colliding nuclei, momentum transfer during the collision, and collective states in the final state can be deduced [8]. Studies have shown that during collisions, as particles pass through and interact, a hard collision occurs, which significantly affects energy distributions and losses [9]. In general, the study of nuclear collisions at ultra-relativistic energy extends valuable insights about the dynamics in such interactions, particularly at the level of deuteron collisions with sharp surfaces.

A deuteron has the simplest nuclear system (having one proton and one neutron) and is commonly used in nuclear physics experiments due to its stability and relatively simple structure. When deuterons are accelerated to speeds very close to the speed of light, when studying fundamental interactions and particle behavior, they are said to have ultra-relativistic energy. When a deuteron falls towards a sharp surface at high speeds, this interaction can lead to various outcomes such as scattering, fragmentation, or even the creation of new particles [10]. This collision of deuterons with surfaces can be studied to understand the dynamics of heavy-ion collisions and other phenomena like nuclear reactions and particle production, in addition to the properties of nuclear matter under extreme conditions. This type of nuclear reaction advances our understanding of the fundamental forces and nuclear structure [11].

In this work, a collision between two different-sized nuclei (D+Au) was studied to give insights into how the initial conditions of the collision impact the final state of the collision

system. By varying the collision energy, it can be investigated how different energy levels affect the outcomes of the collisions and the properties of the produced particles. Despite its limitations, the sharp-sphere model is useful for introductory discussions and quick estimations for any collisions between the two collision nuclei. It helps illustrate basic concepts related to nuclear size and nucleon distribution.

2. Theory

The study of high-energy nuclear and particle physics, in particular the comprehension of hadron (such as protons and neutrons) scattering processes in a nuclear medium, is the main application of the Optical Glauber Model. This model describes how particles interact with a target by fusing ideas from classical optics and quantum physics. Recently, the importance of the interference between nuclear structures and high-energy collisions has brought attention to the Quark-Gluon Plasma (QGP) initial conditions and fundamental nuclear physics[12, 13].

Consider the collision of two nuclei (A and B) at high energy at collision parameter b , as in Figure 1, where the nuclei coming from the projectile nucleus (B) collide with target nucleus A that have no particular coordinates for the positions of the nucleons. We concentrate on the two flux tubes at a distance of $s-b$ from the projectile center and a displacement of s relative to the target nucleus center. These tubes overlap one another when they collide [5].

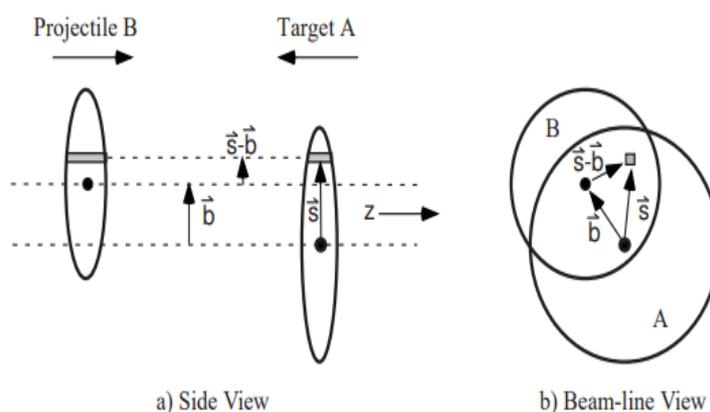


Figure 1: Schematic representation of the Optical Glauber Model geometry, with (a)transverse and (b) longitudinal views [5].

The density profile for this collision takes a sharp sphere, $\rho_A(r)$, which represents the nucleon density as a function of the radial distance (r) from the nucleus center:

$$\rho_A(r) = \begin{cases} \rho_0, & r \leq R \\ 0, & r > R \end{cases} \tag{1}$$

where ρ_0 is the constant nucleon density within a unit volume of the nucleus, $\rho_0 = \frac{3A}{4\pi R^3}$, R is the nuclear radius assuming $R=R_0A^{1/3}$ ($R_0 \sim 1.12$ fm). This can be compared with Woods-Saxon density distribution given as [14]:

$$\rho(r) = \frac{\rho_0}{1 + e^{(r-R/a)}} \tag{2}$$

Deuterons are usually described in terms of the Woods-Saxon and Hulton potentials, but describing the deuteron according to Hulton is better because it takes into account the proximity of the distance between the nucleons at short ranges. The overall density distribution of the nucleus $\rho(r)$, is the sum of the single-particle densities, and its normalization is [15]:

$$\int \rho(r) d^3r = A \quad (3)$$

Thickness function that describes the density of the nucleons have nuclear density integrated with longitudinal z-direction is given by the integral $\int d^2b T_A(b) = A$. For sharp-surface density, the this function is given by a product of path length with density as:[16]

$$T_A(b) = 2\rho_0 \sqrt{R^2 - b^2} \quad ; \quad b \rightarrow 0; \rightarrow 2\rho_0 R$$

$$T_A(b) = 3/2 \frac{A}{\pi R^3} \sqrt{R^2 - b^2} \quad \rightarrow \quad \frac{3A}{2\pi R^2}$$

$$T_A(b) = 2\rho_0 \sqrt{\left(\frac{3A}{4\pi\rho_0}\right)^{2/3} - b^2} \quad \rightarrow \quad \left(\frac{6A\rho_0^2}{\pi}\right)^{1/3} \cong 0.38A^{1/3} \quad (4)$$

As the product of the two nucleus collision thickness functions that are defined as the overlap function, the integral overlap function is [17]:

$$\int d^2b T_{AB}(b) = AB \quad (5)$$

Mazziotta et al. (2002) [18] explored short-range correlations in interaction effects and nuclear overlap functions and their effects on single-particle wave functions. However, the basic function introduced by Bialas et al. [19] is the overlap function, which includes the thickness function, which is very important in understanding collision strength, i.e. the relative effects that result from the collisions of nucleon-nucleon are considered as a measurement of the probability of the transitions from initial to final states. This overlap function for sharp-sphere distribution is given as:

$$T_{AB}(0) = 2\pi R^4 \rho_0^2 \quad \rightarrow \quad T_{AB}(0) = \frac{9A^2}{8\pi R^2}$$

$$T_{AB}(0) = \left(\frac{81A^4\rho_0^2}{32\pi}\right)^{1/3} \cong 0.29A^{4/3} \quad (6)$$

Finding out how many nucleons from the colliding nuclei interact during the collision is necessary to calculate the number of participant nucleons in a nuclear collision. This is especially important when discussing heavy-ion collisions since knowledge of nucleon dynamics can reveal information about the characteristics of nuclear matter. The number of participant nucleons can be approximated by integrating the thickness functions over the transverse area:

$$N_{part}(b) = \int d^2b T_A(b) T_B(b) \quad (7)$$

For such two colliding nuclei, the total geometric cross-section, which represents that at least one nucleon-nucleon collision occurs, is given as:

$$\sigma_G = \int d^2b [1 - \exp(-T_{AB}(b)\sigma_{NN})] \quad (8)$$

Where inelastic cross section is given as:

$$\sigma_{NN} = \int d^2b [1 - e^{-T(b)}] \quad (9)$$

The sharp sphere model provides a straightforward way to estimate the total number of nucleons in the nucleus that represent the number of participants. The total geometric cross-section for the sharp sphere distribution within the limit of an infinite nucleon-nucleon cross-section σ_{NN} , is given as:

$$\sigma_G = \pi(R_A + R_B)^2 = \left(\frac{9\pi}{16\rho_0^2}\right)^{1/3} \left(A^{1/3} + B^{1/3}\right)^2 \cong 3.94 \left[A^{1/3} + B^{1/3}\right]^2 \quad (10)$$

3. Results and discussion

3.1 Energy Consideration:

The square root \sqrt{s} denotes the center-of-mass energy, which is a frame-independent quantity in collider experiments. At $\sqrt{s} = 200 \text{ GeV}$, we're looking at relatively high energy where relativistic effects are significant, and such energies are typical for heavy ion collision experiments at facilities like the Relativistic Heavy Ion Collider (RHIC) or the Large Hadron Collider (LHC). To estimate the overlapping variables, the different center of mass energies, $\sqrt{s_{NN}} = 56, 200, 200, 2760, \text{ and } 5440 \text{ GeV}$ were used, which have a corresponding inelastic nucleon-nucleon cross-section according to Eq. (8) of $\sigma_{NN}^{inel} = 37, 30, 42, 60, 68 \text{ mb}$ obtained by algorithmic interpolation of cross-section measurements concerning collision energies.

3.2 Two nuclei sharp density

The nuclear density distribution describes how the density of nucleons is distributed within the nucleus as a function of the distance from the nuclear radius. From Figure (2), at energy 200 GeV, the steep density can be compared with the Woods-Saxon density, which is characterized by a gradual transition from high density in the center of the nucleus to low density outside the nucleus and provides a smooth representation of the density. Gold as a complex structure due to its large number of nucleons shows a broader distribution of nuclear density with multiple peaks and valleys, reflecting the complex arrangement of nucleons within the nucleus as in "Woods-Saxon" with the main three-parameters, Eq. (2), with $\rho_0 = 0.17 \text{ fm}^{-3}$. For the ^{197}Au nucleus, the actual empirical value of the radius in terms of A is $R = (1.12A^{1/3} - 0.86A^{-1/3}) = 6.368 \text{ fm}$, and the surface thickness parameter $a = 0.54 \text{ fm}$ [20]. Utilizing the "sharp shape" specific parameterizations ($0.16 \text{ nucleon. fm}^{-3}$) [21] of the nuclear density distribution, which determines the exact shape of the curves for both deuteron and ^{197}Au , gives the different shapes for two collisions nuclei, as in Figure (2). This figure represents the densities as a function of impact parameter (b) for both deuteron and ^{197}Au at 200 GeV (the dotted black line represents deuteron, and ^{197}Au is represented by a solid red line).

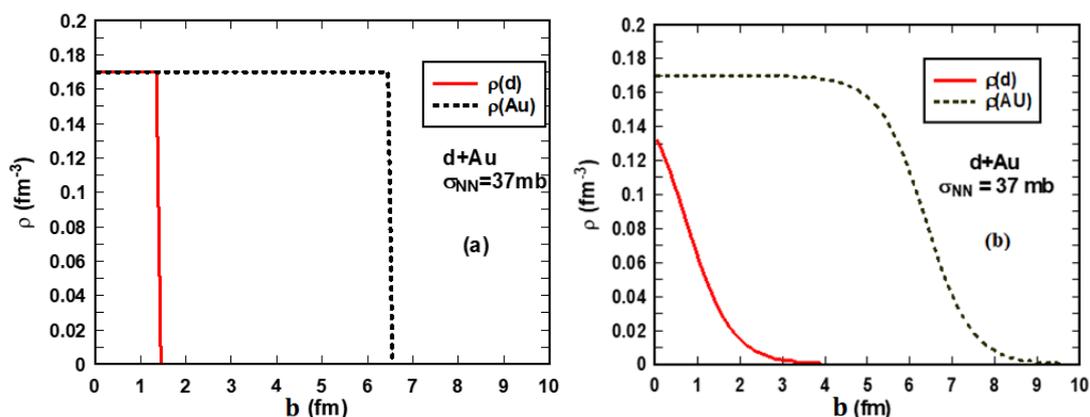


Figure 2: The nuclear density as a function of nuclear radius according to the default sharp shape parameter sets for deuteron (black dotted line) and ^{197}Au (red line) at 200 GeV by (a) sharp-surface (b) Woods-Saxon profiles.

It can be shown that the actual density distribution within the nucleus deviates significantly from the sharp surface due to nucleon-nucleon interactions and shell effects. While the sharp sphere model simplifies calculations, it does not capture the intricate details of the nuclear structure. The realistic density profiles, such as the Woods-Saxon distribution, take into account variations in nucleon density as a function of the radial distance and the shape of density overall.

In sharp density profile, the nuclear density is constant up to a certain radius (the sharp edge of the nucleus) and then drops to zero. This contrasts the Woods-Saxon model that includes a gradual decrease in density at the edge of the nucleus. Both models are good in representing the diffuse nature of the nuclear boundary. The density of each type of nucleon (proton and neutron) appears to be highest at the center of the nucleus and then tapers off to zero density at the outer edge. This suggests that the nucleus has a high density in the center and a low density at the periphery.

3.3 Thickness function

Calculating the thickness function utilizing the sharp density assumes a sharp transition from the maximum nuclear density to zero, as opposed to a more gradual decrease that might be more physically realistic utilizing the Woods-Saxon model. Figure (3) indicates that at 200 GeV, the thickness function for ^{197}Au is significantly higher than that of the deuteron, reflecting a larger number of interacting nucleons within a ^{197}Au nucleus than within a deuteron. The shape of the thickness function curves also suggests that the collision dynamics and the number of nucleon-nucleon interactions at various impact parameters are considerably different for the two types of nuclei. In collision experiments, such as those conducted at particle accelerators, these differences substantially affect the particle production rates and the distribution of the final state particles.

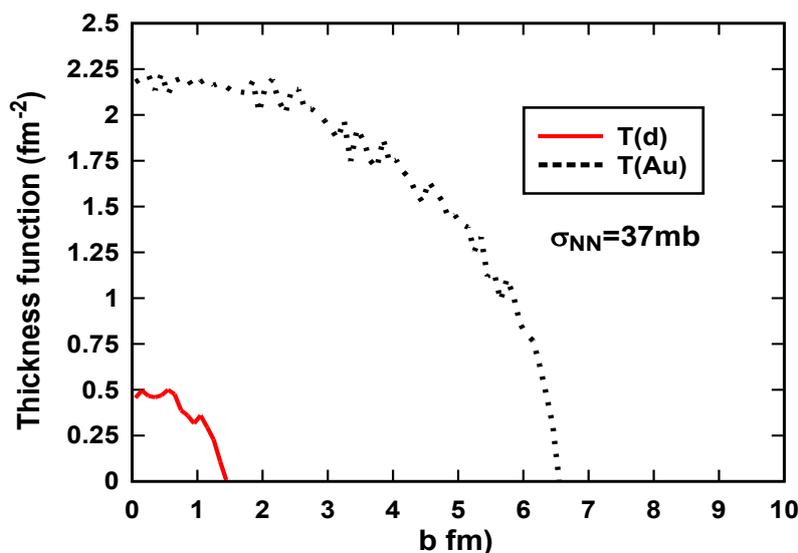


Figure 3: Thickness density function of the collide nuclei (D, Au) at 200 GeV.

3.4 Overlapping function

The parton flux for nucleus-nucleus collisions is enhanced by the number of nucleons in each nucleus. The nuclear overlapping function of the D-Au collision is shown in (Figure 4) as a function of the impact parameter. The probability of the deuteron penetrating to different depths is represented as the thickness function, (Figure 3), with a probability of encountering a ^{197}Au nucleus at different depths. But in Figure 4, the combined probabilities of a deuteron and a ^{197}Au overlapping at a specific depth indicate a potential collision, where the actual measured or calculated collision probability as a function of depth is represented as in the figure. It can be seen that $T(\text{D}+\text{Au})$ (dotted red) is a checked of thickness function that represented the density of nucleons integrated along the z -direction and shows the consistency of the theoretical model against the overlap function. It compares between a model's predictions and the actual measured or calculated values.

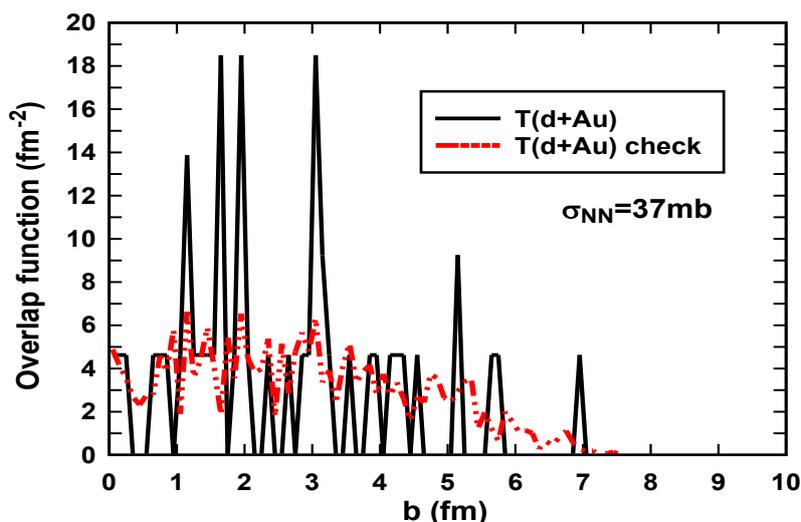


Figure 4: Overlap function of collision of (D+Au) (black curve) and the calculations of thickness function checked for (D+Au) collision (red curve) at 200 GeV.

3.5 Number of participants (N_{part}):

The number of nucleons participating in a collision depends on the type of collision and the energy of the particles involved. In Figure 5, the number of participants' nucleons in the collisions was calculated for different energies. For deuteron, the figure represents a deuteron composed of one proton and one neutron. It can be seen from the figure that the number of nucleons contributing to the collision relative to the deuteron is constant for all different collision energies. This is due to several reasons: i) The deuteron is a stable nucleus, so the proton and neutron are likely to participate in collisions regardless of the energy, meaning that as long as the collision is inelastic, the number of participants remains the same, ii) there is a threshold energy for forming new particles or excited states when colliding deuterons. If the energy of the collision exceeds this threshold energy, the number of deuteron nucleons remains the same, iii) Also, the small size of the deuteron plays an important role in the geometry of the collision, meaning that the colliding nucleons will be close to each other and interactions will occur regardless of the value of the energy used.

For ^{197}Au , which consists of $Z=79$ and $N=118$, the total number of nucleons participating in a collision involving ^{197}Au depends on the number of ^{197}Au nuclei involved. At different energies, the number of ^{197}Au nuclei participating in a collision could vary, but typically, it would involve the entire nucleus. The energy of the collision doesn't directly affect the number of nucleons involved, but it can affect the outcome and the behavior of the collision products. It appears that the number increases as energy increases for ^{197}Au .

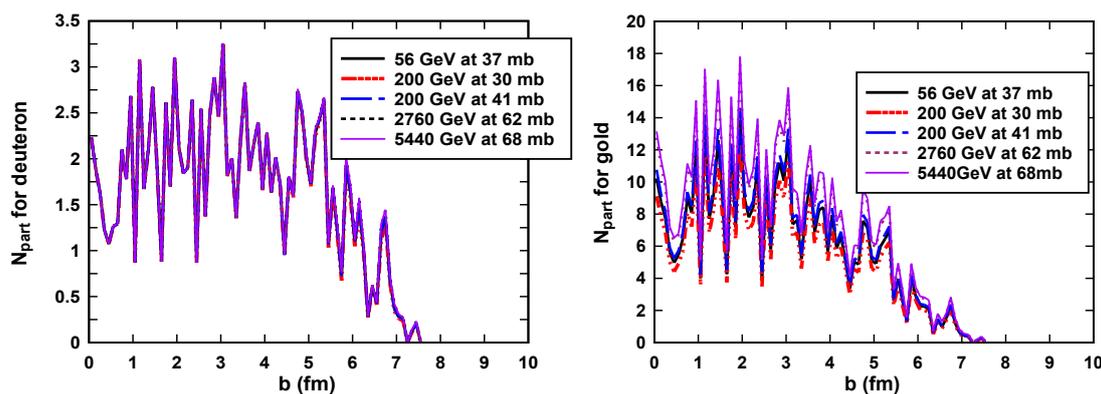


Figure 5: The number of nucleons that participate in the collision of deuteron and ^{197}Au at different energies.

3.6 Nucleon-Nucleon cross-section

In high-energy nuclear collisions, the nucleon-nucleon collision profile describes the probability density of inelastic nucleon-nucleon collisions at a given impact parameter (b). The elastic differential cross-section is a measure of how likely it is for two particles to be scattered in a particular direction. It represents the probability of scattering at a particular angle for a given impact parameter as a function of the impact parameter for D+Au collisions at different energies. This cross-section depends on the impact parameter and the energy of the collision. The data in Figure 6 is based on the Glauber model, which is a theoretical model for nucleus-nucleus collisions. The different curves of the figure correspond to different collision energies, as labelled in the figure. For example, the curve labelled "5440 GeV at 68 mb" shows the elastic differential cross section for d+Au collisions at a collision energy of 5440 GeV and an impact parameter of $\sigma_{\text{NN}}=68$ mb.

In general, the elastic differential cross-section is larger for smaller impact parameters. This overlap between the incoming particle and the nucleons are made possible by smaller impact parameters and this probability increasing is seen in Fig. (6). is because small impact parameters correspond to more head-on collisions, i.e. the incident particles passing closer to the center of the nucleus, where the density of nucleons is very high, are more likely to be scattered.

The elastic differential cross-section also tends to decrease with increasing collision energy. The specific values of the cross-section can be read from Figure 6 by following the curve for the desired collision energy to the desired impact parameter value. For example, the elastic differential cross section for a D+Au collision at 5440 GeV with an impact parameter of 2 fm is approximately 0.2 fm^2 . At different energies, the form of the scattering amplitude and, thus, the differential cross section may vary. However, without specific data or a model for the D+Au collisions at different energies, the exact values for the differential cross-section cannot be determined. This information is usually obtained through experimental measurements or theoretical calculations based on models like the Glauber model. Since the calculations of the cross-section within the optical limit of the Glauber model do not contain multiple integration limits, because during collisions the nucleons will hide behind each other, the cross-section obtained from the calculations at different energies will be slightly large.

Differential distributions normalized to the total number of collision events that are referred to as normalized cross sections are calculated as a function of impact parameter for each selected energy.

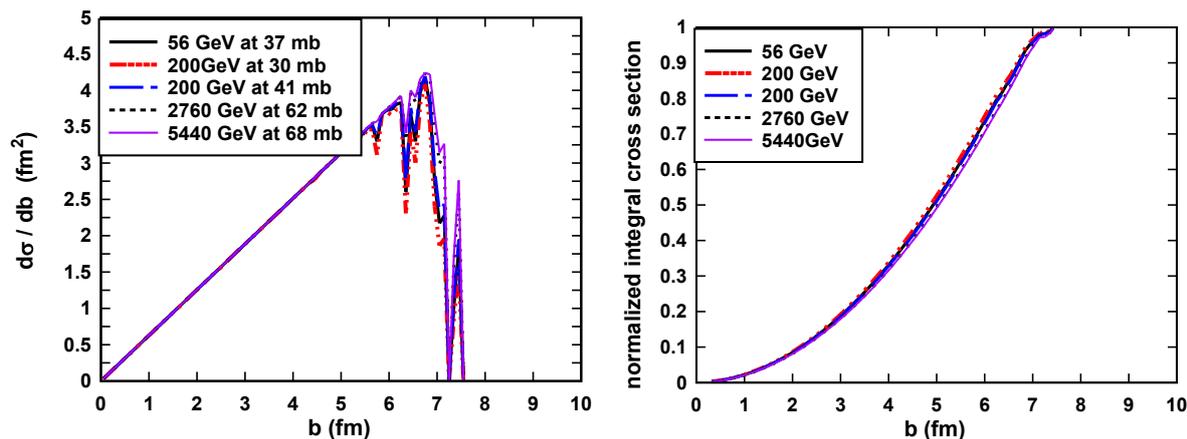


Figure 6: The elastic differential cross-section concerning impact parameters and normalized Integral cross-section for collisions in the different energy ranges.

4. Conclusions:

Nuclear physics and the characteristics of dense nuclear matter can be better understood by D-Au collisions. The main findings from this research on D-Au collisions include the following: this collision type aids in comprehending nuclear shadowing effects, in which a dense nucleus ^{197}Au can decrease the effective cross-section for scattering because the ^{197}Au nucleus absorbs incoming partons (gluons and quarks) in the deuteron. So, more profound knowledge of nuclear matter and the fundamental physics of high-energy collisions is made possible by the application of the Optical Glauber Model to D-Au collisions, which offers a solid framework for comprehending nuclear interactions, parton dynamics, and geometric consequences.

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