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Dynamical analysis of isospin and angular momentum effects in peripheral heavy-ion reactions

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Abstract

The semi-classical Landau Vlasov model has been used to investigate the decay modes of peripheral Pb+Au reactions at 29 MeV/n. Statics and dynamics of these very massive nuclei are analyzed especially through the isospin dependence of the effective nuclear force. The degree of dissipation of the collisions is studied for different bins of impact parameter pointing out the influence of the nucleon-nucleon cross section. The appearance of intermediate mass fragments from neck-like structures is evidenced, the effects of angular momentum transfers are shown to play a fundamental role in this phenomenon. The theoretical results are compared with experimental data, showing the importance of the dynamical and out of equilibrium effects on the observables.

1 Introduction

The analysis of reaction mechanisms and highly excited nuclei in heavy-ion reactions at intermediate energies constitutes nowadays one of the principal tools for the study of fundamental properties of finite nuclear matter. A considerable effort has been devoted in the last years to the understanding of the wide variety of decay modes evidenced with heavy systems [1]-[6]. Indeed, at incident energies around the Fermi energy, a competition between binary fission and multi-fragment decay has been observed [1, 2] in massive target nuclei, like gold, with different projectiles. A strong correlation between the excitation energy of the system and the corresponding decay channel has been established, showing the evolution from sequential fragment emission to the so-called multifragmentation [7]. This last decay process presents many puzzling aspects, their underlying physical interpretation remaining at present controversial [8, 9, 10].

Much attention has been recently paid in central collisions to the study of the time scales involved in nuclear fragmentation. In Ref. [11] the analysis of fragment space-time correlations, in Pb+Au collisions at 29 MeV/n, is shown to characterize the evolution from “sequential” to “simultaneous” processes. In this massive system, it has also been shown [4] that the binary character of these processes remains, nevertheless, dominant for all degrees of dissipation and that their de-excitation modes result from the competition between evaporation, binary fission and complete disassembly of the partners into several fragments. In particular, in Ref. [12] the analysis of intermediate mass fragment production in peripheral and mid-peripheral reactions evidenced the preponderant role played by the collision dynamics. In the above mentioned reference, the production of three-body events in mid-peripheral Pb+Au reactions at 29 MeV/n is shown to arise from the intermediate overlapping zone, the so-called “neck” region. These kind of structures, also observed in other systems [13]-[16] have been predicted in peripheral nuclear reactions by a microscopic dynamical model [17]. The analysis of the onset and decay of these neck-like structures in peripheral collisions, in the

same way as bubbles in central collisions [18] can shed light on the understanding of the fragmentation processes [16].

In this work we perform a study of peripheral collisions in Pb+Au at 29 MeV/n within the semi-classical Landau Vlasov model. This microscopic approach, which describes the nuclear dynamics through a one-body kinetic equation, is in principle not suitable to describe dynamical phenomena where multi-particle correlations play a preponderant role. Nevertheless, nuclear Boltzmann-type equations have been shown [19, 20] to be well suited to correctly analyze the onset and grow of the instabilities giving rise to the break-up of the system. In the particular case of peripheral and mid-peripheral reactions we are interested in the global dependence of different mean quantities, on the nucleon-nucleon cross-section and on the effective force. Concerning this last aspect, a special attention is paid to the role played by the isospin-dependent part of the one-body Hamiltonian in the overall dynamics. Aiming at probing the reliability of our calculations, they are confronted with experimental data.

This paper is organized as follows: in Sect. 2 our model is briefly described. In Sect. 3 nuclear static characteristics of a lead nucleus are discussed in terms of the isospin dependence of the effective force. We also address the dissipative behaviour of the Pb+Au collision dynamics through mass-energy and charge-velocity correlations, as well as excitation energy and energy transfers. In Sect. 4 we analyze the formation of so-called neck-like structures and their dependence on the impact parameter and the nucleon-nucleon cross section. The importance of angular momentum transfers is also studied. In Sect. 5 we analyze isospin effects in the calculated neutron multiplicity and compare with the available data. Our conclusions are presented in Sect.6.

2 The Model

The Landau-Vlasov model describes the dynamics of nuclear collisions through a phase-space transport equation complemented by a Pauli-blocked Uehling- Uhlen-

beck collision term $I_{coll}(f)$ [21, 22]. The success of this model on the description of the nuclear dynamics in heavy-ion collisions at intermediate energies has been widely proved [23, 24, 25]. In the same way, it has been shown to reproduce accurately the equation of state of nuclear matter at zero and finite temperatures for many different interactions with zero or finite range [24]. Estimations of surface energy of semi-infinite nuclear matter are also correct [26]. The same model was used to study dynamical instabilities arising from fluctuations in the spinodal zone for nuclear matter [19] and characteristic times were extracted for the spinodal decomposition.

A detailed description of the Landau Vlasov model can be found in Refs. [21, 22, 26] and references quoted therein. Let us simply recall here that, in this model, the time evolution of the one-body phase-space distribution function $f(\vec{r}, \vec{p})$ is driven by the kinetic equation,

$$\frac{\partial f}{\partial t} + \{f, H\} = I_{coll}(f) \quad (1)$$

where $\{ , \}$ stands for the Poisson bracket and H is the one-body Hamiltonian. This equation is solved by projecting $f(\vec{r}, \vec{p})$ onto a moving basis of coherent states, which are frozen-width gaussians in coordinate and momentum spaces:

$$f(\vec{r}, \vec{p}) = \frac{A}{N} \sum_i w_i g_\chi(\vec{r} - \vec{r}_i) g_\phi(\vec{p} - \vec{p}_i) . \quad (2)$$

The w_i are here the projection coefficients determined by the initial conditions, χ and ϕ the variances in coordinate and momentum space. Concerning the Boltzmann-like collision term, we used in this work the free isospin and energy dependent nucleon-nucleon cross -section. We did not include any in-medium corrections, since in spite of intensive theoretical efforts [27, 28], they are not yet well known and they do not exceed 0.8 to 1 times the free value [27].

With respect to the one-body Hamiltonian in equation (1), we consider a simplified version of the zero-range Skyrme effective force, the so-called Zamick interaction [29], including an additional isospin dependent term as in Ref [30].

With this force the one-body potential reads:

$$\begin{aligned}
V_q(\rho, \xi) &= t_0 \rho + t_3 \rho^{\sigma+1} + \frac{c\xi^2}{\rho_\infty^2} + 4c \frac{q\rho\xi}{\rho_\infty^2} \\
\rho &= \rho_n + \rho_p \\
\xi &= \rho_n - \rho_p
\end{aligned} \tag{3}$$

where ρ_n (ρ_p) is the neutron (proton) local density, $q = \frac{1}{2}$ ($-\frac{1}{2}$) for neutrons (protons) and c is a parameter which, in the limit of infinite nuclear matter, can be related to the volume-symmetry coefficient J of the mass formula [30]. Also in equation (3), ρ_∞ is the saturation density of infinite nuclear matter, σ , t_0 and t_3 are parameters, adjusted to give saturation properties of infinite symmetric nuclear matter. In particular, the saturation density value is $\rho_\infty = 0.145 \text{ fm}^{-3}$. In this case:

$$\begin{aligned}
t_0 &= -356 \text{ MeV} / \rho_\infty \\
t_3 &= 303 \text{ MeV} / \rho_\infty^{\frac{7}{6}} \\
\sigma &= \frac{1}{6} \\
c &= 20 \text{ MeV} .
\end{aligned} \tag{4}$$

Within this transport model we met trusty conditions to examine the static and dynamical properties of very massive nuclear systems like Pb + Au, and compare with the available data.

3 Isospin effects on statics and dissipative dynamics

The sensitivity of the collision dynamics to the isospin dependence of the effective interaction, has been previously established with the Landau-Vlasov model [30], in peripheral collisions of light nuclei at low energies. In massive nuclei,

due to their strong neutron-proton asymmetry, important isospin effects can be expected in their initial configurations, when an isospin-dependent force is implemented. In Figs.1 the neutron (N), proton (P) and total (N+P) local densities,

$$\rho(\vec{r}) = \int d^3r \ f(\vec{r}, \vec{p}) \quad (5)$$

calculated for a Pb nucleus, are displayed as a function of r , the distance from the nucleus center, for two values of the isospin factor c of Eq. (3): $c = 20$ (Fig.1-a) and $c = 0$ (Fig.1-b). A clear characteristic of these curves is the central depletion appearing in the neutron (and total) density in Fig. 1.a, due to the more repulsive character of the neutron mean field [30]. In this case the difference between neutron and proton densities diminishes with respect to Fig.1-b, without changing the global aspect of the curves. In particular, the smooth behaviour of the densities at the surface is conserved.

Despite the actual numerical treatment of the ground state requires the resort to a rather undercomplete paving of the phase space, it is interesting to note that our semi-classical and self-consistent treatment of the nuclear dynamics is able to provide the expected sensitivity of the global properties. It will be further shown that the inclusion of an isospin dependent interaction in our formalism, not only plays a leading role for the initial configuration, but also for the dynamics of the reaction between two massive nuclei. Let us recall that in this work we are essentially interested in peripheral Pb over Au collisions, at impact parameters ranging from 6 to 12 fm. For the more central collisions the system undergoes a fragmentation process [18], the origin and dynamical mechanisms of which are not yet fully understood. As the impact parameter increases, the overlap zone and the involved reaction times are smaller, the outgoing system conserving a more marked memory of the entrance channel. In experimental works [12, 32], the total kinetic energy loss (TKEL) has been measured in order to characterize the centrality of the reaction. A typical plot of the fragment masses versus the TKEL observable is presented in Fig. 2. The experimental data (full dots) were extracted by summing the masses of the fragments detected in complete events,

with the XYZT+DELF+MUR+TONNEAU set up installed at GANIL [31]. Our theoretical results (stars) were obtained for different impact parameters. They show a progressive decrease of the fragment masses for increasing TKEL values (i.e. increasing centrality), in fairly well agreement with the experimental data.

In our description, the TKEL was estimated by the difference between the asymptotic and initial values of the collective energy, defined as follows:

$$E_{coll} = \frac{1}{2} \int d^3r \frac{J^2(\vec{r})}{\rho(\vec{r})} \quad (6)$$

with

$$\vec{J}(\vec{r}) = \rho(\vec{r}) \vec{v} = \int d^3p \frac{\vec{p}}{m} f(\vec{r}, \vec{p}) \quad (7)$$

The time evolution of the total kinetic energy is shown in dotted line in Fig.3 for the Pb+Au reaction at $b=10$ fm. The solid line represents the excitation energy of the heavier residues while the dashed one is the sum of the previous quantity and the energy carried away by the emitted particles. In this way, the collective energy is the difference between dotted and dashed lines. Starting from its high initial value $E_{coll}(0)$, it decreases as the collision proceeds, until the system passes through its maximum compression stage where E_{coll} is minimum. From this time on, above 150 fm/c, it smoothly increases, evidencing the increase of the relative fragment velocities in the exit channel.

According to Ref.[33] the local equilibration time t_{le} is defined as the time at which the initially out-of-equilibrium momentum distribution becomes locally an equilibrated Fermi sphere. For the particular collision we are concerned with, this time is $t_{le} \sim 110$ fm/c. The values of TKEL and the number of emitted particles (after and before t_{le}) are very sensitive to the impact parameter. In order to illustrate this assertion, in Table 1 we reported the number of particles and their corresponding kinetic energies at different times, for several impact parameters. The sensitivity of the preceding quantities with b is less evident for the two more central reactions than for the two more peripheral ones. This is essentially due to the long times involved in central reactions, compared with the time at which the simulation was stopped, and the systems were not yet completely relaxed.

In order to get more precise informations about the emission process, the rate of particle production dN/dt as a function of time is plotted in Fig.4 for the same reaction at $b=10$ fm. We observe here that most of the particles are emitted between 100 and 200 fm/c, i.e. during the breaking up of the system. Afterwards, it decays performing damped oscillations.

According to Ref. [4], the kinematic characteristics of the reaction can be extracted from the analysis of the fragment mean longitudinal velocity in the center of mass frame, $V_{CM}^{//}$. In Fig.5 the Z versus $V_{CM}^{//}$ contour plots corresponding to the same experimental data as in Fig.2 are reproduced. These fragments were detected in triple coincidences at different bins of the Total Kinetic Energy Loss (TKEL): 0 - 400 MeV (a), 400 - 800 MeV (b) and 800 - 1200 MeV (c). From Figs. 5.a) to 5.c) the TKEL values increase, manifesting a transition between two different scenarios: the fission of one partner to the onset of intermediate mass fragments formation. In these Figures our theoretical results are represented with full dots. In Fig.5.a) they describe either the quasi-projectile or quasi-target fragments, with velocities $V_{CM}^{//}$ of +4 and -4 cm/ns, respectively, and charges between 70 and 80. The appearance of fission products at around $Z=40$ cannot be observed since this long time scale process exceeds our typical computing times. Nevertheless, the global evolution with TKEL is according with the experimental trends. In particular, for the most central collision considered here (greatest TKEL) there appear intermediate fragments ($Z \leq 20$) with very low $V_{CM}^{//}$ which correspond to impact parameters between 8 to 9 fm. In Ref. [4] it has been suggested that these intermediate fragments are emitted by either the target-like or projectile-like fragment, the emission being then not originated in an equilibrated source. In the next section these results will be analyzed in more detail, from the point of view of angular momentum transfers.

4 IMF emission related to neck structures

We concentrate now our attention on the Pb+Au reaction at 29 MeV/n and $b=9$ fm. The corresponding local density $\rho(\vec{r})$, in the center-of-mass frame, projected on the reaction plane is shown in Fig.6 as a function of time. The system passes through a compressed stage at about 100 fm/c, after which it develops a long-shaped form, or “neck”, in the overlap region. This takes place at around 200 fm/c. From there on, the system breaks into essentially two heavy residues together with some other smaller fragments in the central zone, their number and mass depending on the impact parameter. Indeed, the appearance of these central fragments takes place roughly for an impact parameter range between 8 and 9 fm, and disappears for more peripheral or more central collisions.

In this section, the dynamical aspects of this scenario will be analyzed in terms of angular momentum transfers. The validity of our approach will be checked through the confrontation of our results with the available experimental data. To this end, let us perform the following preliminary analysis. In Fig. 7 the number of counts, in arbitrary units, is plotted as a function of the relative velocity between fragments for the same reaction. The triangles, open circles and full circles correspond to the experimental relative velocity between fragments (1,2), (2,3) and (1,3) from Ref.[12], with the convention that 1, 2 and 3 are the quasi- target, intermediate fragment and quasi-projectile, respectively. Let us note that even if several small fragments can be formed in the neck, only one of them was detected in this case, due to the experimental detection thresholds $Z \geq 8$ [12]. The relative velocities of the fragments were calculated with our model at $8 \leq b \leq 9$ fm. They were represented in the same figure with arrows. Their agreement with the experimental maxima provides with a good proof of working to our description.

The mean angular momentum with respect to the center of mass of the system (L) was calculated for the two heavy residues as a function of the time at several impact parameters. They are represented in Fig. 8 in full symbols for the quasi-

target, and in open symbols for the quasi-projectile. For the most peripheral collision ($b=12$ fm, in stars) they have the same behaviour: starting from almost $60\hbar$ at around 250 fm/c, they progressively decay with the emission of particles. The same remarks also hold for $b=10$ fm (squares), with the exception that in this case the magnitude of the angular momentum per fragment is higher, exceeding $100\hbar$. The situation is different at $b=8$ fm, where the symmetrical behaviour of the angular momenta corresponding to the two heavy fragments is lost. This aspect is also observed for impact parameters for which the neck is formed. Here the fragment with higher L value (in this case, the quasi-projectile) needs to release some amount of matter to equilibrate its highly excited collective motion. In order to go thoroughly into this problem we analyze in Figs. 9 the impact parameter dependence of the angular momentum L (with respect to the center of mass) of the fragments, at two different times. On the upper part of this figure, we represent the values of L calculated at $t=300$ fm/c, when the intermediate fragments are not yet fully separated. In this picture, triangles (crosses) represent mean quasi-target (quasi-projectile) angular momentum. The asymmetry between these values attains clearly its maximum at about $b=9$ fm, and it vanishes either for higher or for lower b values. On the lower part of Fig. 9 the mean angular momentum per fragment L_{frag} is represented as a function of b , at two different times: $t=300$ fm/c (crosses) and $t=400$ fm/c (triangles). At the earlier time, when the quasi-projectile has not yet broken up, L_{frag} smoothly increases with the centrality of the reaction and it saturates at around $120\hbar$. At the later time, a depression of L_{frag} appears around 9 fm, where the central IMF emission takes place (see Fig. 6), indicating a net momentum transfer from the heavy residues to the emitted light fragments.

Let us now analyze the influence of the nucleon-nucleon cross-section σ_{nn} on the fragment characteristics, for the impact parameter bin leading to a neck formation in the concerned reaction. In Table 2 we report our calculated charge of the centrally emitted fragments Z_f for three different scalings of the free nucleon-nucleon cross-section, σ^{free} , at $b = 8$ and 9 fm. We observe that for a given

σ_{nn} there is not essential difference in charge for the different values of b , except when σ_{nn} is scaled by a factor of 0.7. In this case, the impact parameter bin for which a “neck” emission appears is shifted from 8-9 fm to 7-8 fm. On the other hand, for a given b the higher is σ_{nn} the smaller are the corresponding fragments. In a hydrodynamical picture, increasing σ_{nn} means enlarging the range of the residual interactions, this makes the mean-free path to decrease together with the viscosity. As nuclear matter is less viscous, the central region becomes more diluted and the neck tends to disappear. On the other side, the experimentally estimated Z_f [32] is about 15. This finding can be utilized as an argument to gain more informations on σ_{nn} . Indeed, σ_{nn} should not exceed the free value without producing a drastic reduction of the intermediate fragment size.

5 Neutron multiplicity

In this section we analyze only those peripheral reactions leading to binary events. In recent experiments [3], informations about these kind of reactions have been extracted with the “hodoscope” and ORION detectors at GANIL. In our calculations, this scenario takes place for impact parameters greater than 10 fm. We have estimated the excitation energy of the colliding system, E^* , in analogy with the experimental techniques [3]. This means that we have calculated the energy carried away by the emitted particles at 400 fm/c, with respect to the energy at a given reference time, $t_{le} = 110$ fm/c. As stated previously, the choice of this time was dictated by local equilibrium considerations, according to Ref.[33].

In Fig. 10 we have drawn the total excitation energy E^* as a function of the neutron multiplicity. The bare experimental results from Ref. [3] are represented with stars. These values were corrected by taking the detector efficiency into account and they are symbolized by open circles. The calculated values of E^* versus the neutron multiplicity involve impact parameters between 10 to 14 fm and are represented by full circles. In the same figure we also show the values of

E^* versus the nucleon multiplicity in full squares. The global behaviour of our results is coherent with the experimental data, and they reveal the appearance of a strong energy loss when the violence of the collision increase.

The theoretical values exhibit a linear behaviour (as the experimental ones) and are located between the corrected and the bare data. Note that, if we consider the nucleon multiplicity instead of the neutron one, the slope of the corresponding straight line is smaller (squares in Fig. 10). This is essentially an isospin effect since, as suggested in Ref.[30], an enhancement of the neutron-neutron collisions, and consequently of their excitation energy, is favoured when an isospin-dependent term is included in the effective force.

In Fig. 11 we reproduce in full lines a profile of the charge-neutron multiplicity correlation of Ref. [3]. Starting from a first peak at about $Z=80$ for the most peripheral events and with low neutron multiplicity, multiplicities of the order of 40 are rapidly attained, even for massive fragments ($Z\sim 60$). These last events constitute an evidence of strong dissipative processes taking place in peripheral reactions. In these events, a considerable part of the initial projectile charge is conserved. From there on, with a given neutron multiplicity, the charge Z evolves towards small values with increasing probability. These events correspond to more central collisions.

In Fig. 11 we have plotted our theoretical results in full circles with the isospin-dependent force as defined in section 2. In the same figure we report in open symbols the results obtained by switching-off the isospin-dependent term, which leads to the usual Zamick local interaction. From this figure, the effect of the isospin-dependent part of the potential is to enhance neutron multiplicity for a given atomic number, allowing the appearance of strongly dissipative processes even at rather peripheral reactions. This trend, which is consistent with the experimental data [3], demonstrate the fundamental role played by isospin effects in this energy range.

6 Conclusion

In this work we have investigated the formation and decay of excited massive nuclear systems in peripheral Pb+Au collisions at 29 MeV per nucleon from a fully dynamical point of view. This experiment has been performed at GANIL and presents a special interest because, on one hand, a considerable amount of data is currently available and, on the other hand, the same colliding system has been analyzed through different and complementary experimental set ups. Special attention was paid to the initial preparation of the nuclei, which is the starting point of the dynamics. Indeed, the static properties of heavy nuclei are correctly described by our model, using an isospin dependent effective force in the one-body Hamiltonian. In the same spirit, we have checked the correct description of the dynamics. For this purpose we have displayed the dissipative behaviour of the reaction through the analysis of some observables like the Total Kinetic Energy Loss (TKEL), the particle production, the velocity vs charge plots, the excitation energy and the neutron multiplicities. The agreement with the experimental results confirms the reliability of this type of dynamical approach. The inclusion of an effective interaction taking into account the isospin degree of freedom is essential for a correct description of the dynamics. This is true in particular for the formation of neck-like structures, which are shown here to appear within a thin bin of impact parameters. We have also pointed out that, in this case, angular momentum transfers play a leading role in the formation of fragments around the neck region. These results were also shown to be sensitive to the nucleon-nucleon cross-section and its value should not exceed the free one, in order to be consistent with the experimentally measured charges.

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Table 1: Number of emitted particles and energies at different impact parameters (in fm) and times (in fm/c)

b	6	8	10	12
n(t=110)	12	11	7	6
n(t=400)	67	67	49	36
n(t=110-400)	55	56	42	30
$E_{emitt}(t=110)$	200	150	125	75
$E_{emitt}(t=400)$	1076	990	793	574
$E_{emitt}(t=110-400)$	876	840	668	499

Table 2: Charge of IMF for different nucleon-nucleon cross-sections and impact parameters

b(fm)	$0.7\sigma^{free}$	$1\sigma^{free}$	$1.3\sigma^{free}$
8	16	16	6
9	10	15	7

Figure Captions

Fig.1-a) Mean density as a function of the distance to the center of a lead nucleus for nucleons (P+N), neutrons (N) and protons (P), calculated with an isospin dependent mean field.

Fig.1-b) Same as Fig.1-a) but with an isospin independent mean-field.

Fig.2 Fragment mass as a function of the total kinetic energy loss in Pb+Au reaction at 29 MeV/n. Theoretical results (stars) are given for impact parameters between 6 and 12 fm. Experimental data are represented by full dots.

Fig.3 Excitation energy of heavy clusters (solid line), total excitation energy (dashed line) and total kinetic energy (dotted line) as a function of time in Pb+Au at 29 MeV/n, $b=10$ fm.

Fig.4 Particle production rate as a function of time in Pb+Au at 29 MeV/n, $b=10$ fm.

Fig.5 Experimental contour plots of fragment charge versus the longitudinal fragment velocity in the center of mass frame in Pb+Au at 29 MeV/n. They correspond to different bins of the Total Kinetic Energy Loss (in MeV): 0-400 (a), 400-800 (b) and 800-1200 (c). Theoretical values (full dots) correspond to $6 \leq b \leq 12$ fm.

Fig.6 Time evolution of the mean particle density projected on the reaction plane in Pb+Au at 29 MeV/n and $b=9$ fm.

Fig.7 Number of counts (arbitrary units) as a function of the relative fragment velocities from Ref.[12] in Pb+Au at 29 MeV/n. Arrows correspond to the theoretical mean values.

Fig.8 Time evolution of the calculated mean angular momentum (in $\hbar$ units) in Pb+Au at 29 MeV/n and different impact parameters. The values corresponding to the quasi-projectile (quasi-target) are in open (full) symbols.

Fig.9 (Top) Mean angular momentum (in $\hbar$ units) in Pb+Au at 29 MeV/n as a function of the impact parameter before the breaking up of the quasi-projectile. (Bottom) Mean angular momentum per fragment as a function of the impact parameter at two different times: before (crosses) and after (triangles) the quasi-projectile breaking up.

Fig.10 Excitation energy as a function of the multiplicity for the Pb+Au reaction at 29 MeV incident energy. Experimental data were extracted from Ref.[3].

Fig.11 Experimental neutron multiplicity versus charge (solid lines) from Ref.[3]. In the right column is the probability in logarithmic scale. Calculated values with isospin dependent (independent) force are in full (empty) symbols, for $6 \leq b \leq 12$ fm.

Figure 1a

Figure 1b

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11