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Spectator nucleons in ultracentral ^{208}Pb-^{208}Pb collisions as a probe of nuclear periphery

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We study the composition of spectator matter in ultracentral collisions of heavy relativistic nuclei with neutron-rich periphery known as a neutron skin (NS). The yields of spectator neutrons and protons in ultracentral ^{208}Pb–^{208}Pb collisions at the LHC were calculated within a new version of Abrasion-Ablation Monte Carlo for Colliders (AAMCC) model. Calculations demonstrate variations of the cross sections $\sigma(N_n, N_p)$ to produce given numbers of spectator neutrons N_n and protons N_p depending on the parameters of NS in ^{208}Pb, in particular, for events with low N_n. The relative difference between $\sigma(N_n, N_p)$ obtained with different NS thickness reaches 150%. Furthermore, the values of $\sigma(N_n, N_p)$ calculated with same difference between neutron and proton RMS-radii, but with different neutron half-density radius and diffuseness parameter, differ by 45%. The considered cross sections can be measured in the ALICE experiment at the LHC for ^{208}Pb–^{208}Pb to restrict the parameters of NS in colliding nuclei.

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1. Introduction

In nuclei with a predominance of neutrons over protons the ratio of their densities increases towards the nuclear periphery. This effect is known as neutron skin (NS). NS thickness is characterized by the difference between neutron and proton RMS-radii: $\Delta r_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$. However, even for such a well-studied nucleus like ^{208}Pb, the values of Δr_{np} reported by different authors diverge. For example, Δr_{np} in ^{208}Pb calculated with different versions and parameters of the mean-field models of nuclear structure ranges from 0.12 fm to 0.32 fm [1] depending on the stiffness of the nuclear symmetry energy. Measured Δr_{np} in ^{208}Pb also diverge by a factor of 2, as, for example, the latest result of the PREX experiment [2] and the result of the A2 collaboration [3]. Since the parameters of NS are connected with the symmetry energy term in the equation of state of nuclear matter, their precise determination helps to extrapolate this equation to nuclei at the border of stability [4], and also to neutron stars [5]. This motivates the search for alternative methods to constrain the parameters of the distributions of neutrons and protons in heavy nuclei.

In collisions of relativistic nuclei spectator matter is represented by nucleons beyond the overlap of the collision partners. In contrast to interacting participant nucleons, spectator neutrons and protons propagate forward and can be detected, in particular, by Zero Degree Calorimeters (ZDC) in the ALICE experiment at the LHC [6] to estimate collision centrality in ^{208}Pb–^{208}Pb collisions [7]. In this work we propose to use same instrumentation for measurements of cross sections $\sigma(N_n, N_p)$ of emission of given numbers of spectator neutrons N_n and protons N_p in ultracentral ($b < 3.49$ fm, 0–5 % centrality) ^{208}Pb–^{208}Pb collisions to evaluate the difference between the density distributions of neutrons and protons at the periphery of ^{208}Pb. It can be expected that in ultracentral collisions of equal heavy nuclei the nuclear periphery is peeled off, propagates forward and thus can be detected in ZDC. The relative yields of spectator neutrons and protons reflect their ratio in a thin nuclear periphery which remains intact beyond an extended overlap of colliding nuclei in ultracentral collisions. In this work the yields of spectator neutrons and protons in ultracentral ^{208}Pb–^{208}Pb collisions at the LHC were calculated with the latest version of the Abrasion-Ablation Monte Carlo for Colliders (AAMCC) model [8]. The sensitivity of these yields to the parameters of NS was demonstrated.

2. Abrasion-Ablation Monte Carlo for Colliders

AAMCC [8] is based on Glauber Monte Carlo model [9] to simulate the initial geometry of colliding nuclei. Neutrons and protons are considered as spheres and sampled randomly according to the individual density distributions of neutrons and protons [9] to account for neutron skin at nuclear periphery. It is assumed that non-interacting spectator nucleons form an excited prefragment. Its excitation energy is calculated with a hybrid approximation that combines Ericson's formula [10] applied to peripheral events with less than 10% nucleons abraded and ALADIN approximation [11] otherwise. Since this work is focused on ultracentral collisions with a characteristic narrow half-ring or a crescent shape of spectator prefragments, their pre-equilibrium decays are additionally simulated. It is expected that nucleons inside such prefragments with reduced nuclear density have less chances to interact and establish equilibrium in comparison to more dense and rounded prefragments produced in peripheral collisions. Hence, the AAMCC model was supplemented by a pre-equilibrium decay model based on the Minimum Spanning Tree [12] (MST) clusterisation algorithm with the break up distance parameter depending on prefragment excitation energy [13]. The MST-clustering algorithm is applied at the very beginning of the ablation stage to define secondary clusters formed from prefragments of narrow crescent shapes with the excitation energy distributed between clusters proportionally to their masses. After that, at the ablation stage, the decays of these clusters are modelled by means of the statistical evaporation model, Statistical Multifragmentation Model (SMM) and the Fermi Break-up model adopted from Geant4 toolkit [14].

3. Results

The cross sections $\sigma(N_n, N_p)$ of emission of given numbers of spectator neutrons N_n and protons N_p were calculated for ^{208}Pb–^{208}Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for 0-5% centrality ($b < 3.49$ fm). Calculations were carried out for four different neutron density distributions in ^{208}Pb taken as two-parametric Fermi distributions, see Table 1. Since the parameters of the proton density distribution also taken in this form are known well from measurements, they were same in all four sets of calculations, see Table 1. The set Pbpnrw was obtained with the distribution proposed in Ref. [3] to describe the data on coherent pion photoproduction on ^{208}Pb, while the other three parameterizations correspond to the results of PREX Collaboration [2]. However, only the value of Δr_{np} were reported by PREX, leaving the exact values of the half-density radius R_n and the diffuseness parameter a_n of neutron distribution unknown. Therefore, in the sets of calculations denoted as PREX1 and PREX2 we calculate a_n from R_n taken as the minimal and maximal half-radii, respectively, predicted by various mean-field models of nuclear structure [1]. The value of R_n used in PREX is the average between R_n used in PREX1 and PREX2 options.

Table 1: Half-density radii $R_{n,p}$, diffuseness parameters $a_{n,p}$ and the corresponding neutron skin thickness Δr_{np} for different parameterizations of proton and neutron density distributions used in AAMCC modelling of ^{208}Pb–^{208}Pb collisions.

option	R_n, fm	a_n, fm	R_p, fm	a_p, fm	Δr_{np}, fm
Pbpnrw	6.69	0.56	6.68	0.447	0.15
PREX	6.81	0.60	6.68	0.447	0.283
PREX1	6.68	0.66	6.68	0.447	0.283
PREX2	6.94	0.53	6.68	0.447	0.283

The sensitivity of $\sigma(N_n, N_p)$ to Δr_{np} can be evaluated from the comparison of calculations carried out with AAMCC with Pbpnrw and PREX options for the neutron and proton density distributions in ^{208}Pb. As found, the transition from Pnpnrw to PREX shifts the maximum of absolute values of $\sigma(N_n, N_p)$ towards higher N_n and lower N_p. Such a shift is especially significant for low numbers of spectator protons, $N_p \leq 3$. The relative difference between $\sigma(N_n)$ calculated with Pnpnrw and PREX is presented in Fig. 1 for two multiplicity classes of accompanied spectator protons, $N_p \leq 3$ and $N_p > 3$. Because of the PREX neutron density distribution extending to larger radii, ultracentral events with the dominance of neutrons over protons are more probable with this option at large N_n. In such events NS is peeled off almost completely and moves forward as spectator neutrons. As seen, the difference between Pnpnrw and PREX is high (up to 150%) for events with low N_n and high N_p. It is smaller (up to 50%) for events with high N_n and low N_p. Therefore, the measured cross section with such extreme N_n and N_p can be compared with results of AAMCC or other models to distinguish between $\Delta r_{np} = 0.15$ fm (Pnpnrw) and $\Delta r_{np} = 0.283$ fm (PREX) representing, respectively, thin and thick NS.

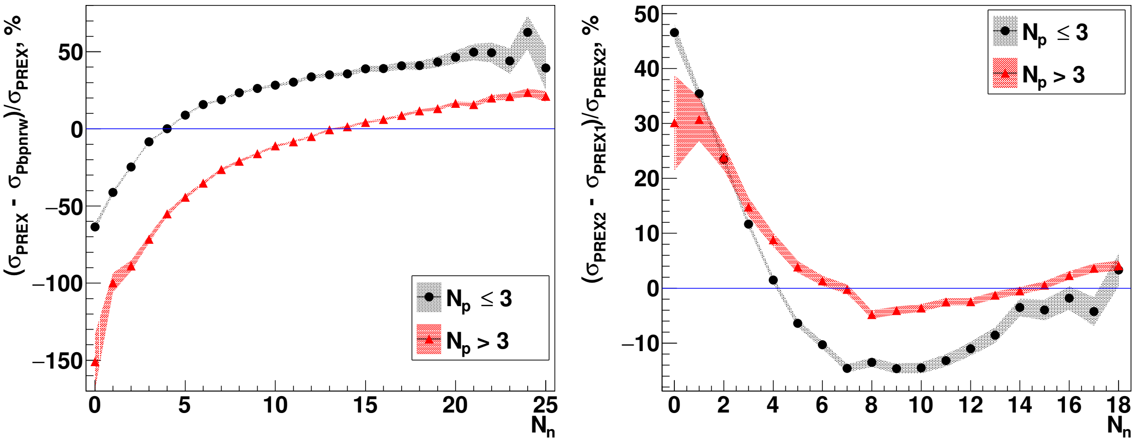

Figure 1: Relative difference between the cross sections $\sigma(N_n)$ of emission of spectator neutrons in events with low ($N_p \leq 3$) and high ($N_p > 3$) multiplicity of spectator protons in ultracentral ^{208}Pb–^{208}Pb collisions ($b \leq 3.49$ fm) at $\sqrt{s_{NN}} = 5.02$ TeV calculated with Pbpnrw and PREX (left panel) or with PREX1 and PREX2 (right panel) options for neutron and proton density distributions in ^{208}Pb.

It is interesting to find out whether $\sigma(N_n, N_p)$ are sensitive to more subtle details of neutron density distributions. The options PREX1 and PREX2 are characterized by same Δr_{np}, but different R_n and a_n, see Table 1. Usually, $\langle r_n^2 \rangle^{1/2}$ are measured in experiments [2, 3], and several combinations of R_n and a_n provide same $\langle r_n^2 \rangle^{1/2}$ as, for example, PREX1 and PREX2 options. As seen from Fig. 1, the relative difference between $\sigma(N_n)$ calculated with PREX1 and PREX2 is essential for low ($N_p \leq 3$) multiplicity of spectator protons. In this case, the largest difference ($\sim$ 45%) is found for low N_n. For large proton multiplicity ($N_p > 3$) the relative difference between $\sigma(N_n)$ calculated with PREX1 and PREX2 is large ($\sim$ 30%) only for low N_n. In summary, the measurements of $\sigma(N_n)$ for $N_p \leq 3$ and low N_n in ultracentral ^{208}Pb–^{208}Pb collisions at the LHC can help to find the most relevant parameterization of neutron density out of several parameterizations of same $\langle r_n^2 \rangle^{1/2}$ and, consequently, Δr_{np}.

On the basis of our calculations with AAMCC, we conclude that the measurements of the cross sections $\sigma(N_n, N_p)$ of emission of certain numbers of spectator neutrons N_n and protons N_p in ultracentral ^{208}Pb–^{208}Pb collisions at the LHC can be used to restrict the parameters of neutron density distributions obtained in calculations [1], or confirm measurements with other methods [2, 3]. The considered effects of NS in ^{208}Pb–^{208}Pb collisions can be studied in the ALICE experiment at the LHC by selecting most central events on the basis of procedures of centrality determination using various detectors [7]. The respective yields of spectator neutrons and protons have to be corrected for the acceptance and efficiency of ALICE neutron and proton Zero Degree Calorimeters [6].

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