ELECTROMAGNETIC INTERACTIONS OF ULTRARELATIVISTIC NUCLEI: A CHALLENGE FOR PRESENT AND FUTURE HEAVY-ION COLLIDERS*

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One of the options within the project of the Future Circular Collider (FCC) at CERN is represented by a proton–proton collider (FCC-hh) with $\sqrt{s_{pp}} = 100$ TeV collision energy. As planned, the collisions of lead nuclei at $\sqrt{s_{NN}} = 39.4$ TeV will be also possible at the FCC-hh. In this work, the electromagnetic interactions of nuclei at the Large Hadron Collider (LHC) and at the FCC-hh are compared with respect to their impact on the operation of these accelerators and to the relation between the rates of hadronic and electromagnetic collision events. Ion species, like ^{115}In, may be advantageous at the FCC-hh due to a reduced frequency of electromagnetic processes in comparison to heavy ^{208}Pb presently used at the LHC. The cross sections of production of secondary nuclei in electromagnetic dissociation of ^{115}In and ^{208}Pb at the FCC-hh are calculated with RELDIS model. These cross sections can be used for estimating the impact of secondary nuclei on components of the FCC-hh to design its collimator system.

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1. Introduction

Heavy ions for the CERN experimental program are produced with the GTS-LHC 14.5 GHz Electron Cyclotron Resonance (ECR) ion source [1]. The substance to be filled in the ECR should have suitable physical and chemical properties to ensure a stable and safe operation of the source. After passing through a linear accelerator (LINAC 3), ions can be either used in the Super Proton Synchrotron (SPS) for fixed target experiments [2] or injected into the Low Energy Ion Ring (LEIR) [3], which prepares them for the fills in

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the Large Hadron Collider (LHC). Since the program of the NA61/SHINE experiment at the SPS includes a systematic scan over the sizes of colliding nuclei [4], the beams of p, Ar, Xe and Pb have been provided for this purpose. The beams of O, S and In have been also delivered for other experiments, see Ref. [5] for a review.

In contrast, the list of ion species accelerated so far at the LHC is rather short. The collisions of protons, lead nuclei and p–Pb collisions have been studied in 2010–2018, with the priority given to p–p. The choice of ion species for the LHC depends not only on the availability of the respective ion sources, but it is also motivated by the need to compare p–Pb and Pb–Pb data obtained in different runs, sometimes in different years. An injection of new ions also requires a thorough tuning of the LHC to switch to a new ion mode [6] as, for example, for a single one-day Xe–Xe run on October 12, 2017. The comparative studies of Xe–Xe and Pb–Pb collisions help to characterize the system size dependence of hot and dense hadronic matter created in nucleus–nucleus collisions.

One can expect that the Future Circular Collider (FCC) at CERN [7, 8] will promote the progress in high-energy physics in the following decades [9]. A proton–proton collider (FCC-hh) with $\sqrt{s_{pp}} = 100$ TeV collision energy is one of the options of the FCC project. A possibility to collide ^{208}Pb at $\sqrt{s_{NN}} = 39.4$ TeV, with the beam energy eight times larger than presently at the LHC, is also under discussion [10]. However, as known for the LHC [11], the electromagnetic dissociation (EMD) of $^{208}\mathrm{Pb}^{82+}$ leading to the production of specific secondary nuclei (*e.g.*,^{206,207}Pb) as well as the bound-free e^+e^- production (BFPP) creating $^{208}\mathrm{Pb}^{81+}$ ions with a single electron are the sources of specific LHC beam losses that may quench its superconducting magnets. It will be a challenge to alleviate the impact of secondary ions on the components of the FCC-hh because of its much higher beam power compared to the LHC. Lighter nuclei, like ^{115}In, may be advantageous at the FCC-hh due to a reduced frequency of electromagnetic processes in comparison to ^{208}Pb. In this work, we compare In–In and Pb–Pb collisions at the LHC and FCC-hh with respect to the ratio between electromagnetic and hadronic events in interaction points of the colliders. We also discuss the cross sections of production of specific secondary nuclei with their Z/A ratios similar to those of the beam nuclei.

2. Total hadronic and electromagnetic cross sections for In–In and Pb–Pb at the LHC and FCC-hh

As a rule, the main attention in heavy-ion collision experiments at colliders is paid to hadronic interactions of nuclei in events with overlapping nuclear densities of collision partners. However, relativistic heavy nuclei are lost from colliding beams not only due to hadronic collision events, but also after their electromagnetic interactions in ultraperipheral collisions (UPC). Electromagnetic interactions are represented by the EMD of nuclei [12] and the BFPP [13]. The relations between the rates of the processes of each kind in the colliders are defined by the respective cross sections: $\sigma_{\rm had}$, $\sigma_{\rm EMD}$ and $\sigma_{\rm BFPP}$. The total hadronic (reaction) cross sections $\sigma_{\rm had}$ were calculated for In–In and Pb–Pb, respectively, by the modified abrasion–ablation (Glauber-like) model [14] and Glauber Monte Carlo Model 3.0 [15]. The electromagnetic dissociation cross sections $\sigma_{\rm EMD}$ were calculated by RELDIS model [12]. Various atomic states for electrons captured by ^{208}Pb were taken into account in calculating $\sigma_{\rm BFPP}$ on the basis of the approximation $\sigma_{\rm BFPP} = A \ln \gamma_c + B$ from Ref. [13]. These cross sections were then downscaled via Z^7 from Pb–Pb to obtain $\sigma_{\rm BFPP}$ for In–In. All these cross sections are listed in Table I for ^{115}In–^{115}In and ^{208}Pb–^{208}Pb collisions at the LHC and FCC-hh together with their sums $\sigma_{\rm tot}$ in each case.

TABLE I

The cross sections of hadronic and electromagnetic interactions of ^{115}In and ^{208}Pb nuclei at the LHC and FCC-hh.

	LHC		FCC-hh	
Cross section [b]	^{115}In–^{115}In $\sqrt{s_{NN}}$ = 5.54 TeV	^{208}Pb–^{208}Pb $\sqrt{s_{NN}}$ = 5.02 TeV	^{115}In–^{115}In $\sqrt{s_{NN}}$ = 42.6 TeV	^{208}Pb–^{208}Pb $\sqrt{s_{NN}}$ = 39.4 TeV
$\sigma_{\rm had}$	5.34	7.66	5.47	7.9
$\sigma_{\rm EMD}$	40.4	211.4	53.8	284.2
$\sigma_{\rm BFPP}$	~ 7.4	271.8	~ 9.4	344.
$\sigma_{\rm tot}$	53.	491.	68.7	636.
$\sigma_{\rm had}/\sigma_{\rm tot}$ [%]	10	1.6	8	1.2

As seen from the table, $\sigma_{\rm EMD}$ and $\sigma_{\rm BFPP}$ are essentially larger for Pb–Pb than for In–In. As a result, $\sigma_{\rm had}/\sigma_{\rm tot}$ is about six times smaller for Pb–Pb. In other words, only one out of ~ 60 Pb nuclei lost from the beams of the LHC is used to produce hadronic events which are of primary interest for the LHC experiments. At the FCC-hh, this factor drops down to one per ~ 80 events. However, when the option of In beams is considered, one of ~ 10–12 collision events is attributed to hadronic interactions to be studied at the colliders.

3. Production of secondary nuclei in electromagnetic dissociation of ^{115}In and ^{208}Pb at the FCC-hh

The dominant products of BFPP are $^{115}\mathrm{In}^{48+}$ and $^{208}\mathrm{Pb}^{81+}$, because a simultaneous capture of two electrons is much less probable [13]. Thus, the range of ions from BFPP is well-defined in contrast to EMD, where several nucleons are emitted by beam nuclei leaving various residual nuclei. As known [12], a single neutron is emitted by ^{208}Pb leading to the production of ^{207}Pb in $\sim 50\%$ of EMD events because of the absorption of soft virtual photons. However, a multiple emission of neutrons and protons takes place in other events associated with the absorption of more energetic photons by ^{208}Pb leading to various secondary nuclei.

Regarding the collider operation, the production of nuclei with Z/A close to beam nuclei is of primary interest because such nuclei can pass through the collimators of the collider and impact its sensitive components like superconducting magnets. As discussed [10], due to the very high beam energy and current of the FCC-hh, secondary ions from UPC can deliver a well-localized high thermal impact on the collider components. Cross sections of production of secondary nuclei in EMD of ^{115}In at $\sqrt{s_{NN}} = 42.6$ TeV and in EMD of ^{208}Pb at $\sqrt{s_{NN}} = 39.4$ TeV calculated with RELDIS model for the FCC-hh are visualized in Figs. 1 and 2. In these figures, secondary nuclei are arranged according to their Z/A ratio to indicate their proximity

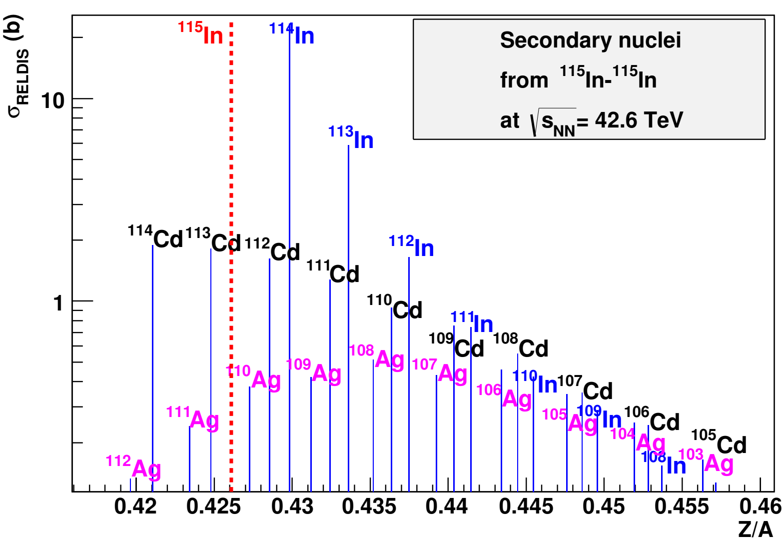

Fig. 1. Cross sections of production of secondary nuclei in EMD of ^{115}In at the FCC-hh at $\sqrt{s_{NN}} = 42.6$ TeV calculated with RELDIS model. The Z/A ratio of primary ^{115}In nuclei is marked by a dashed line.

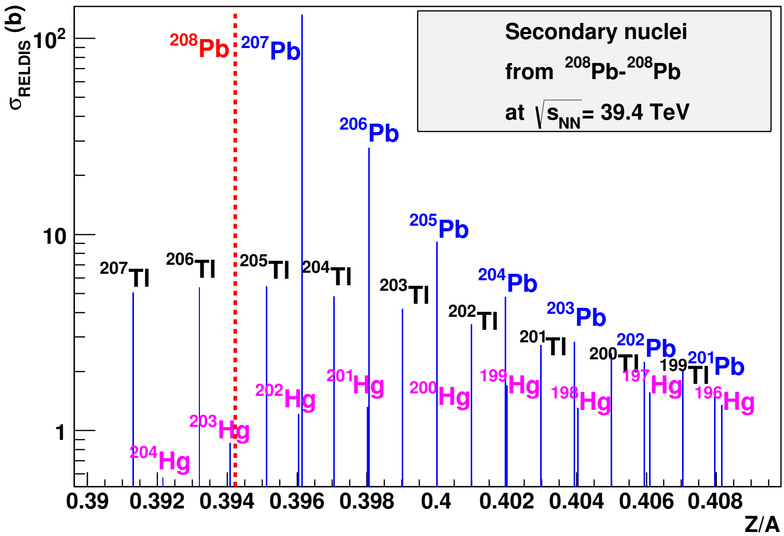

Fig. 2. Cross sections of production of secondary nuclei in EMD of ^{208}Pb at the FCC-hh at $\sqrt{s_{NN}} = 39.4$ TeV calculated with RELDIS model. The Z/A ratio of primary ^{208}Pb nuclei is marked by a dashed line.

to beam nuclei. RELDIS model has been validated previously with the data collected at the CERN SPS on charge distributions of secondary nuclei produced in fragmentation of ^{208}Pb and ^{115}In [14, 16], as well as with the data on neutron emission by these nuclei in EMD [17, 18]. Moreover, a good description of ALICE data on neutron emission from EMD of ^{208}Pb has been also demonstrated [19].

As seen from Figs. 1 and 2, the highest rates are predicted for nuclei produced after the emission of one, two and three neutrons (^{112,113,114}In and ^{205,206,207}Pb). The emission of a proton accompanied by several neutrons with the production of Cd and Tl is also frequent, but typically less frequent than $2n$ emission from ^{115}In and less than $3n$ emission from ^{208}Pb, respectively. One can note that nuclei which are quite distant from beam nuclei have comparable rates of production independently of the numbers of emitted protons. For example, the cross sections of production of ^{201}Pb, ^{199}Tl and ^{196}Hg are similar to each other. In summary, the following secondary nuclei can be potentially harmful for the FCC-hh in ^{115}In–^{115}In collision mode: ^{112,113,114}In and ^{110,111,112,113,114}Cd. In ^{208}Pb–^{208}Pb mode, ^{205,206,207}Pb and ^{203,204,205,206,207}Tl are of the main concern.

4. Conclusions

Beams of medium-weight nuclei, like ^{115}In, have several advantages in experiments on nucleus–nucleus collisions at the LHC and at the FCC-hh. In comparison to ^{208}Pb presently used at the LHC, a more favorable ratio between the rates of hadronic and electromagnetic events in In–In collisions has been predicted. This will lead to a higher effective nucleon–nucleon luminosity in In–In collisions because $\sim 10\%$ of collision events are hadronic. In Pb–Pb mode, less than 2% of collisions are hadronic, while the number of nucleon–nucleon collisions is only about twice as large as in In–In. The secondary nuclei which can be potentially harmful for the FCC-hh operation in In–In mode are identified on the basis of RELDIS model.

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