

Nuclear fragmentation at the future electron-ion collider

C.A. Bertulani^{a,b,c,*}, Y. Kucuk^{d,e}, F.S. Navarra^f

^a Department of Physics and Astronomy, East Texas A&M University, Commerce, TX 75429, USA

^b Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany

^c Helmholtz Research Academy Hesse for FAIR, D-64289 Darmstadt, Germany

^d Turkish Accelerator and Radiation Laboratory (TARLA), 06830, Ankara, Turkey

^e Akdeniz University, Department of Physics, 07058, Antalya, Turkey

^f Instituto de Física, Universidade de São Paulo, Rua do Matão 1371, CEP 05508-090, Cidade Universitária, São Paulo, Brazil

ABSTRACT

We explore the potential of conducting low-energy nuclear physics studies, including nuclear structure and decay, at the future Electron-Ion Collider (EIC) at Brookhaven. By comparing the standard theory of electron-nucleus scattering with the equivalent photon method applied to Ultrapерipheral Collisions (UPC) at the Large Hadron Collider (LHC) at CERN. In the limit of extremely high beam energies and small energy transfers, very transparent equations emerge. We apply these equations to analyze nuclear fragmentation in UPCs at the LHC and eA scattering at the EIC, demonstrating that the EIC could facilitate unique photonuclear physics studies. However, we have also shown that the fragmentation cross-sections at the EIC are about 1,000 times smaller than those at the LHC. At the LHC, the fragmentation of uranium nuclei displays characteristic double-hump mass distributions from fission events, while at the EIC, fragmentation is dominated by neutron emission and fewer fission products, about 10,000 smaller number of events.

1. Introduction

The upcoming Electron-Ion Collider (EIC) at Brookhaven National Laboratory (BNL) will address fundamental questions in Quantum Chromodynamics (QCD), such as the role of sea quarks and gluons, their spin contributions, and their spatial and momentum distributions within the nucleon and the nucleus. The nuclear environment is expected to influence these distributions and gluon interactions within nuclei [1]. Additionally, there is significant anticipation that low-energy nuclear physics experiments can be conducted at the EIC, where the fragmentation of nuclei in electron-ion collisions could produce numerous isotopes, including exotic and potentially undiscovered rare isotopes [2,3]. Low-energy nuclear spectroscopic studies may also be feasible by detecting photons in the far-forward detection area, where Doppler-shifted photons can reach high energies. The resulting time dilation effect enables the detection of lifetimes as short as a few nanoseconds, because high-energy photons are easier to detect.

Fragments produced in Coulomb excitation of relativistic nuclei in ultra-peripheral collisions (UPC) have provided relevant information on fission dynamics, the discovery of new isotopes and isomeric states, and more than 1000 nuclear fission residues [4–6]. Therefore, relativistic Coulomb excitation provides an extremely useful tool for studying the pathway to fission, studies of neutron emission and their relation to the astrophysical rapid capture (r -)process and to many other nuclear decay studies [7]. The fragmentation process proceeds via the excitation of giant resonances and in particular the nuclear dipole response is probed reflecting the isospin imbalance in the nucleus. This can be used to constrain the slope of the symmetry energy L of the nuclear matter equation of state (EoS) [8,9]. As an alternative to UPCs in relativistic heavy ion collisions it is worthwhile investigating how the future EIC can be used to study the dynamics of excitation and decay and if new nuclear isotopes can be produced that are not accessible in heavy ion

* Corresponding author.

E-mail addresses: carlos.bertulani@tamuc.edu (C.A. Bertulani), ykucuk@akdeniz.edu.tr (Y. Kucuk), navarra@if.usp.br (F.S. Navarra).

collisions. This is the main motivation for this work focusing on the specific issue of nuclear fragmentation due to the electromagnetic (EM) interaction of electrons with nuclei at low energies ($\hbar\omega < 50$ MeV).

The most significant region for nuclear fragmentation induced by real photons is within the giant dipole resonance (GDR) region, with excitation energies around 10-20 MeV for heavy nuclei, and slightly higher for lighter nuclei. Electron-nuclear interactions have a large cross-section for exciting GDRs or high-energy nuclear states. These GDRs typically decay by emitting neutrons, protons, light elements, and, in the case of actinides, fission fragments. The neutrons emitted in this process have low energies in the ion frame, significantly lower than the energy scales of neutrons produced in central relativistic heavy-ion collisions. As a result, these emitted neutrons can serve as indicators of strong electromagnetic fields. In the laboratory frame, these neutrons will have an energy comparable to the ion energy per nucleon.

In this study, we demonstrate that neutron emission and fission, primarily driven by EM dissociation of nuclei through GDR decay, are highly significant and may be observed abundantly at the future EIC. We also compare the absolute yield of fragments at the EIC with those in UPCs of heavy ions at the Large Hadron Collider (LHC) at CERN [10]. Our results highlight the role of different multipolarities and the correspondence between virtual photons at the EIC and UPCs and pinpoint the key features that distinguish low-energy photonuclear physics in these two processes. Throughout this work, we use natural units with $\hbar = c = 1$.

2. Electron scattering at ultra-high energies

In electron-nucleus scattering, the momentum transfer Q^2 in terms of the electron energy E and scattering angle θ is given by

$$Q^2 = -(k - k')^2 \simeq 2EE'(1 - \cos\theta) \simeq 4E^2 \sin^2(\theta/2), \quad (1)$$

where the energy and momentum transfer are $\omega = E - E'$ and $\mathbf{q} = \mathbf{k} - \mathbf{k}'$, respectively, so that $Q^2 = q^2 + \omega^2$. It is easy to show that, for a given energy transfer ω , the minimum momentum transfer is $Q_{\min} = m_e \omega / E$, with m_e being the electron mass.

In 1924, Fermi demonstrated that a high energy electric charge passing near a atom at a distance b (impact parameter) can be analyzed by Fourier transforming the field it generates and relating it to a flux of equivalent real photons with energy ω [11,12]. This concept was later extended by Weizsäcker and Williams (WW) [13,14] and the following expression for the number of equivalent photons emerges, integrated over collisions at all impact parameters:

$$n(\omega) = \frac{2Z^2 e^2}{\pi\omega} \left[x K_0(x) K_1(x) - x^2 (K_1^2(x) - K_0^2(x)) \right] = \frac{2Z^2 e^2}{\pi\omega} \ln(x), \quad (2)$$

where Z is the particle charge, ω is the photon energy, and $x = \gamma/\omega b_{\min}$, with $\gamma = (1 - v^2)^{-1/2}$ being the Lorentz contraction factor for a projectile with velocity $v \sim c$, and $b_{\min}$ being the minimum impact parameter. This expression matches Fermi's result for non-relativistic energies by just using $\gamma = 1$. The rightmost formula is particularly accurate for low-energy photonuclear studies at the LHC.

Nordheim, Nordheim, Oppenheimer, and Serber [15] have shown that when applying this expression to electron scattering, the smallest impact parameter $b_{\min}$ should be taken as $1/k_{\max}$, where $k_{\max}$ is the maximum effective momentum transfer. While this momentum transfer can be as large as the electron energy, a more appropriate value for $k_{\max}$ is $1/R$, where R is the nuclear radius. Various studies, some using the extended WW formula and others based on the quantum electrodynamics (QED) treatment of electron-nucleus scattering, have yielded slightly different expressions for the number of equivalent photons [16–18]. Here, we will derive accurate expressions for the equivalent photon numbers directly from the conventional electron scattering formulas. Additionally, we will show that certain terms, which are crucial for electron-nucleus scattering at lower electron energies, become negligible when the electron energy significantly exceeds the energy-momentum transfer to the nucleus.

In the Plane Wave Born Approximation (PWBA), the electron-nucleus cross section is given by [19–21]

$$\frac{d\sigma}{d\Omega d\omega} = 4\pi\sigma_M f_{\text{rec}} \sum_{\lambda} \left[\frac{Q^4}{q^4} |F_{\lambda}^L(q)|^2 + \left(\frac{Q^2}{2q^2} + \tan^2 \frac{\theta}{2} \right) |F_{\lambda}^T(q)|^2 + |F_{\lambda}^M(q)|^2 \right] g(\omega), \quad (3)$$

where $\lambda \geq 1$ denotes the multipolarity, F_{λ}^L , F_{λ}^T , and F_{λ}^M are the Coulomb longitudinal, electric transverse, and magnetic form factors, respectively. $g(\omega)$ is the density of states in the continuum as we will apply this equation to the excitation of giant resonances. The Mott cross section is

$$\sigma_M = \alpha^2 \frac{\cos^2(\theta/2)}{4E^2 \sin^4(\theta/2)} = 4\alpha^2 \left(1 - \frac{Q^2}{4E^2} \right) \frac{E^2}{Q^2}, \quad (4)$$

where we used $Q^2 = 4E^2 \sin^2(\theta/2)$, $\alpha = e^2$ is the fine-structure constant, and e is the elementary charge. The nuclear recoil correction is $f_{\text{rec}} = (1 + 2E \sin^2(\theta/2)/M)^{-1}$ where M is the nuclear mass. For the energies at the future EIC, $f_{\text{rec}} \simeq 1$ because $E \gg M$, although for large angle scattering it may become significant.

The Coulomb longitudinal form factors for the nuclear transition from initial to final states are given by

$$eF_{\lambda}^L(q, \omega) = \frac{\hat{f}_f}{\hat{f}_i} \int_0^{\infty} \delta\rho_{\lambda}(r, \omega) j_{\lambda}(qr) r^2 dr, \quad (5)$$

where $\hat{J} = \sqrt{2J+1}$, with J_i and J_f being the initial and final angular momenta of the nucleus, respectively. Here, $j_\lambda(x)$ is the spherical Bessel function, and the transition density is $\delta\rho_\lambda = \langle \Psi_f | \hat{\rho}(r) Y_\lambda | \Psi_i \rangle$, with $\hat{\rho}$ being the electric charge operator and Y_λ the spherical harmonics. Similar expressions for the electric transverse and magnetic form factors involving transition currents can be found in the literature [19–21]. The photonuclear cross section encodes nuclear structure information, including details about nuclear wavefunctions. We will use known experimental photonuclear scattering data on giant resonances to make predictions, thereby avoiding explicit use of nuclear wavefunctions. At energies higher than the giant resonances, sub-nucleon degrees of freedom become relevant, and first-order perturbation theory, as implied by Eq. (3), may not suffice for modeling the reaction accurately.

When one applies Eq. (3) to study electron scattering, including angular distributions, a few more corrections are in order. The Coulomb attraction between the electron and the nucleus causes the electron to accelerate as it approaches the nucleus, leading to a focusing effect that concentrates the electron wavefunction more onto the nucleus. In their interaction with the nucleus, electrons “see” a higher momentum transfer. The PWBA form factors should be modified so that Q is shifted to an effective momentum transfer [19–21]: $Q_{eff} = Q(1 + 3Ze^2/2ER)$, where $R \simeq 1.12A^{1/3}$ fm is the nuclear radius. This focusing effect leads to an increase in the scattering cross section and a smearing that fills in the minima that would be observed in a PWBA calculation. For the energies available at the future EIC, $E \gg Z/R$, and this correction is again insignificant.

Collective excitations in nuclei are dominated by the excitation of giant electric dipole (E1) and quadrupole (E2) resonances, which decay via the emission of neutrons, protons, and α -particles, or by nuclear fission. For these processes, the small argument approximation for the spherical Bessel function in Eq. (5) yields [19–21],

$$eF_\lambda^L(q^2) = -\sqrt{\frac{\lambda}{\lambda+1}} \frac{q}{\omega} eF_\lambda^T(q^2) \simeq -\frac{q^\lambda}{(2\lambda+1)!!} \left[1 - \frac{q^2 R_{tr}^2}{2(2\lambda+3)} + \dots \right] \sqrt{B(E\lambda, \omega)}, \quad (6)$$

where R_{tr}^2 is the “transition radius” associated with the electric transition density $\delta\rho_\lambda(r)$ for the multipolarity λ . The transition density is surface-dominated, implying $R_{tr} \sim R$. In Eq. (6),

$$B(E\lambda, \omega) = \left[\frac{\hat{J}_f}{\hat{J}_i} \int_0^\infty \delta\rho_\lambda(r, \omega) r^{\lambda+2} dr \right]^2, \quad (7)$$

is the reduced transition probability of the nucleus for the electric multipolarity λ and excitation energy ω .

Using $d\Omega = \pi dQ^2/E^2$ in Eq. (3), the total electron-nucleus differential cross section in PWBA can be expressed as

$$\frac{d\sigma}{d\omega dQ^2} = 16\pi^2 \alpha \frac{1 - Q^2/4E^2}{Q^4} \sum_\lambda \left\{ \frac{Q^4}{q^4} + \frac{\lambda+1}{\lambda} \frac{\omega^2}{q^2} \left[\frac{Q^2}{2q^2} + \frac{Q^2/4E^2}{1 - Q^2/4E^2} \right] \right\} \frac{q^{2\lambda}}{[(2\lambda+1)!!]^2} B(E\lambda, \omega) g(\omega). \quad (8)$$

Low energy excitation $\omega \lesssim 50$ MeV at the EIC will lead to very forward scattering, such that we can use $Q \ll E$, and to leading order in Q the above expression reduces to

$$\frac{d\sigma}{d\omega dQ^2} = 8\pi^2 \alpha \frac{\omega^2}{q^4 Q^2} \sum_\lambda \frac{\lambda+1}{\lambda} \frac{q^{2\lambda}}{[(2\lambda+1)!!]^2} B(E\lambda, \omega) g(\omega). \quad (9)$$

The cross section induced by a real photon with energy ω and multipolarity λ is known to be related to $B(E\lambda, \omega)$ as [22]:

$$\sigma_\gamma^{(\lambda)}(\omega) = (2\pi)^3 \frac{(\lambda+1)}{\lambda[(2\lambda+1)!!]^2} \omega^{2\lambda-1} B(E\lambda, \omega) g(\omega), \quad (10)$$

where the total photonuclear cross section is a sum over all multiplicities, $\sigma_\gamma(\omega) = \sum_\lambda \sigma_\gamma^{(\lambda)}(\omega)$.

We can cast Eq. (9) in the form

$$\frac{d\sigma}{d\omega dQ^2} = \sum_\lambda \frac{dN_\lambda(\omega)}{d\omega dQ^2} \sigma_\gamma^{(\lambda)}(\omega), \quad (11)$$

where the equivalent photon spectrum for a given momentum and energy transfer and for a given multipolarity λ is

$$\frac{dN_\lambda}{d\omega dQ^2} = \frac{\alpha}{\pi} \frac{1}{\omega Q^2} \left(\frac{q}{\omega} \right)^{2(\lambda-2)}. \quad (12)$$

This is our main expression, derived in an extremely straightforward fashion from well known electron scattering theory. It shows that at the EIC the electron-nucleus scattering cross section is directly proportional to the corresponding photonuclear cross section. This is useful as many photonuclear cross sections are known from experiments performed with real photons. The dependence on Q is very simple and the cross sections reach their maximum at the minimum momentum transfer $Q_{min} = m_e \omega / E$ which is extremely small at the EIC even for $\omega \sim 50$ MeV. A dependence on the multipolarity also remains and it can be useful to disentangle nuclear structure features in future experiments at the EIC via the analysis of the angular dependence of the nuclear excitation cross sections. This is specially true for small momentum transfers, $q^2/\omega^2 \sim 1$ because $q^2 = Q^2 + \omega^2$.

Since $dQ^2 = 2QdQ$, the integration of the virtual photon numbers from Q_{min} to a maximum value Q_{max} , yields

$$\frac{dN_\lambda}{d\omega} = \frac{2\alpha}{\pi} \frac{1}{\omega} \ln \left(\frac{EQ_{max}}{m\omega} \right), \quad (13)$$

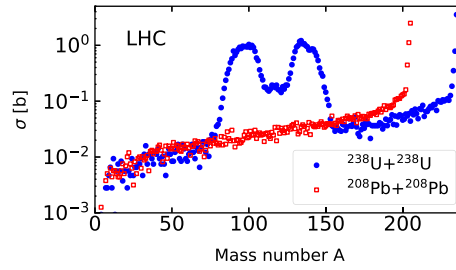


Fig. 1. Cross sections for the production of fragments as a function of their masses in ultraperipheral collisions of ^{208}Pb (open red squares) and ^{238}U (closed blue circles) nuclei at the LHC. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

which is independent of λ , so that

$$\frac{d\sigma}{d\omega} = \frac{dN_\lambda(\omega)}{d\omega} \sigma_\gamma(\omega). \quad (14)$$

The substitutions $E/m_e \rightarrow \gamma$ and $Q_{\max} \rightarrow 1/R$ result in the same Fermi's equivalent photon equation (2). Except that the nuclear radius R now takes the role of the minimum impact parameter $b_{\min}$ in heavy ion collisions. For a typical nuclear radius of $R = 5$ fm, the maximum momentum transfer is $Q_{\max} \sim 40$ MeV. This value is right at the high energy tail of the giant resonances. Therefore, taking $Q_{\max} = 1/R$ or $Q_{\max} = \omega_{\max}$, where $\omega_{\max}$ is the maximum excitation energy, does not make much difference as they enter in the argument of a logarithmic function. For excitation energies larger than $\omega_{\max}$, the photonuclear cross section for heavy nuclei is only a few millibarns, whereas in the giant resonance region it can reach values close to 1 barn. $Q_{\max} = \omega_{\max}$ is also a good choice if one wants to study particle production, such as Λ or J/Ψ particles. In this case, one can set $Q_{\max} = M_\Lambda$, $M_{J/\Psi}$, or another appropriate mass for the problem under scrutiny.

The Lorentz factor entering Eq. (2) needs to be calculated in the frame of reference of one of the ions and is related to the laboratory factor γ_{lab} for the ions by $\gamma = 2\gamma_{lab}^2 - 1$. At the LHC one finds $\gamma = 1.73 \times 10^7$. At the EIC, the effective electron-nucleon center-of-mass energy is $E = 2\sqrt{E_e E_{ion}}$, where E_e is the electron energy and E_{ion} is the energy per nucleon of the ion. This yields a center-of-mass energy range of 45-85 GeV for electrons with energy 5-18 GeV and ions with energy 100 GeV/nucleon. If we use $E = 80$ GeV, we find $\gamma = 1.6 \times 10^5$ at the EIC. Therefore, the logarithmic factor in the equivalent photon expressions are not very different for either laboratory. But there is a notable difference in the magnitude of the corresponding equivalent photon numbers because of the factor Z^2 missing in the expression for the EIC. The cross sections for the excitation of giant resonances are therefore at least a factor 10^3 smaller at the EIC compared to the LHC.

3. EM fragmentation at the LHC and at the EIC

To calculate the excitation of the isovector giant dipole resonance (IVGDR) and the isoscalar and isovector giant quadrupole resonances (ISGQR and IVGQR) [10,23–25] we assume a Lorentzian shape for each resonance:

$$\sigma_\gamma^{GR}(\omega) = \sigma_0 \frac{\omega^2 \Gamma^2}{(\omega^2 - \omega_0^2)^2 + \omega^2 \Gamma^2}. \quad (15)$$

For the IVGDR, we use the energy centroid given by $\omega_0 = 31.2A^{-1/3} + 20.6A^{-1/6}$ MeV and its strength σ_0 determined by the Thomas-Reiche-Kuhn (TRK) sum rule, which is a nearly model-independent result for the nuclear response by an electric dipole operator [21]. The energy centroids of the ISGQR and IVGQR states are taken as $\omega_0 = 62A^{-1/3}$ MeV and $130A^{-1/3}$ MeV, respectively. All resonances are assumed to exhaust their associated operator sum rules, as found, e.g., in Ref. [26].

We consider an 18 GeV electron beam colliding with a 110 GeV/nucleon ^{238}U or ^{208}Pb beam at the EIC corresponding to $E_{lab} = 89$ GeV, and $^{208}\text{Pb} + ^{208}\text{Pb}$ collision at the LHC with energy $\sqrt{s_{NN}} = 5.5$ TeV/nucleon, corresponding to a laboratory beam energy of $E_{lab} = 2.76$ TeV/nucleon and to a Lorentz factor $\gamma_{lab} = 2941$. We will also consider a hypothetical collision of $^{238}\text{U} + ^{238}\text{U}$ at the LHC as we want to assess the fragments arising from fission channels in both accelerators. The de-excitation of the giant resonances leads to nucleon emission, light-charged particles, photon emission, intermediate-mass fragments (IMFs), as well as fission products. The production of an isotope $x = (Z, A)$ is obtained from

$$\sigma_x(\omega) = b_x(\omega) \sum_{GR} \sigma_\gamma^{GR}(\omega), \quad (16)$$

where the sum is carried over all giant resonances (GRs) and $b_x(\omega) = \Gamma_x(\omega^*)/\Gamma_{tot}(\omega^*)$ is the branching ratio or probability of fragment x emission when the nucleus is excited to an energy ω , where Γ_x is the partial decay width for emitting particle x and ω^* is the excitation energy of the compound nucleus. For the excitation of a giant resonance, the pre-equilibrium emissions are small, and the excitation energy ω^* is approximately equal to the photon energy ω . To calculate $b_x(\omega)$, we adopt the Ewing-Weisskopf model and use the ABLA07 code [27]. We include the separation energies and emission barriers for charged particles using the 2017 atomic mass evaluation [28] and the Bass potential [29] for the calculation of transmission probabilities. Additionally, fission yields are obtained

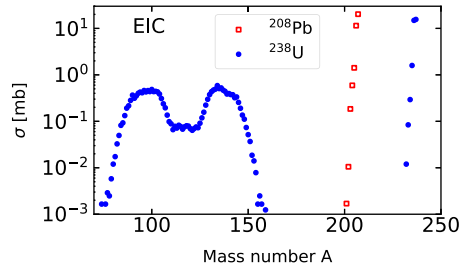


Fig. 2. Cross sections for the production of fragments as a function of their masses for electron- ^{208}Pb (open red squares) and electron- ^{238}U (filled blue circles) collisions at the LHC.

within the dynamical model of Refs. [5,6]. ABLA07 has been extensively utilized in numerous publications and shown to work very well to describe isotopic distributions of fission fragments measured in spallation and fragmentation reactions with relativistic nuclei.

In Fig. 1, we show the fragmentation cross sections for UPCs of ^{238}U (filled blue circles) and ^{208}Pb (open red squares) nuclei at the LHC. The mass distribution of Pb fragments displays a strong decrease of the distribution as the mass of the fragment decreases, mainly due to neutron emission. The same behavior is observed for uranium ions, but a noticeable number of fission fragments originating from the excitation of the ^{238}U projectile produces the observed double-hump structure, which is a characteristic signature of fission, with pronounced peaks with masses around $A \sim 100$ and $A \sim 140$.

Fig. 2 shows the fragmentation cross sections of ^{238}U (filled blue circles) and ^{208}Pb (open red squares) nuclei at the EIC. The magnitude of the cross sections is about 10^3 times smaller than at the LHC. The mass distributions of fragments for both nuclei also show a strong decrease of the cross sections with decreasing mass number of the fragment due to neutron emission. Again, the peaks of fission fragments around $A \sim 100$ and $A \sim 140$ for uranium nuclei are visible. It is evident that neutron removal from both nuclei decreases much faster than for UPCs at the LHC. Almost all events go to evaporation of a few neutrons and fission fragments.

The behavior displayed in Figs. 1 and 2 is better understood with numerical values. We show this in Table 1 with cross sections for neutron evaporation (σ_{-1n} , σ_{-2n} , σ_{-3n} , and σ_{-4n}), fission, total cross sections, and branching ratios to fission channels. The cross sections are given in barns at the LHC and in millibarns at the EIC, and it is clear that at the LHC the number of events in these channels is about a factor of 10^3 larger than at the EIC. The isotope distribution in both cases shows a dominance of neutron emission. Some fragments originate from the emission of light nuclei and the mass distribution drops dramatically. For ^{238}U , fission fragments are produced in both laboratories.

At the EIC, the integrated luminosities for electron-nucleus collisions are expected to range between $10^{33} - 10^{34} \text{ cm}^2 \text{ s}^{-1}$. Assuming a luminosity of $\mathcal{L} = 10^{34} \text{ cm}^2 \text{ s}^{-1}$, approximately 10^8 neutrons per second can be produced from electron-uranium nucleus fragmentation. Event rates for the production of uranium fission fragments are anticipated to fall within a similar range. These neutrons and fragments will predominantly travel in the forward direction with negligible transverse momenta, making their detection challenging without specialized equipment. A possible solution is to utilize a setup similar to the Zero Degree Calorimeter (ZDC) employed with the ALICE detector at CERN [30]. The specifics of detection techniques, however, lie beyond the scope of this work [31]. Notably, many low-energy processes in relativistic heavy-ion collisions were predicted as early as the 1980s [10] when suitable detectors were unavailable, yet they were eventually observed experimentally decades later. It is highly plausible that the low-energy processes described in this study will also become experimentally accessible at the EIC.

The isotope production cross sections for tin (open red squares), xenon (filled blue circles), and lanthanum (open black triangles) at the EIC are shown in Fig. 3. The electromagnetic interaction induces a small excitation energy of the nucleus - around 15 MeV - compared to the large excitation due to strong interactions [25]. Because of this small excitation energy, the cross sections for the production of neutron-rich isotopes are much smaller than those for stable isotopes, as displayed in Fig. 3. Strong lepton-nucleus interactions can also be treated in terms of initial lepton-parton hard scattering (primary interaction) followed by an intra-nuclear cascade collision model, as described in [2]. This leads to the production of numerous neutron-deficient isotopes in the $Z = 89 - 94$ region [3]. However, as remarked earlier, the cross sections are smaller than those calculated here because the initial lepton-parton cross section is smaller than the collective excitation of giant resonances, which yields a very large nuclear response to the electromagnetic field.

Our results suggest that the study of nuclear fragmentation in UPCs at the LHC might be better suited for nuclear physics investigations, provided that proper experimental conditions are met. The EIC has the advantage that the electron is a cleaner probe of the nucleus and that the fragments might be more easily identified.

4. Conclusions

We have compared low-energy nuclear excitation in Ultraperipheral Collisions at the LHC with eA scattering at the future EIC. Our study confirms the applicability of the equivalent photon method for the energy regime of the EIC. In UPCs at the LHC, careful experimental separation of purely electromagnetic interactions from hadronic interactions is required. In contrast, at the EIC, nuclear fragmentation is predominantly driven by electromagnetic interactions, providing a clearer probe of nuclear excitation followed by particle emission or nuclear fission.

Table 1

Cross sections (in barns at the LHC and milibarns at the EIC) for numerous decay channels of lead and uranium nuclei in collisions at the LHC and at the future EIC. Neutron (-1n, -2n, -3n and -4n) evaporation and fission channels are shown, as well as the total cross sections and the percentage of fission branching channels.

Cross sections	LHC Pb + Pb [b]	LHC U + U [b]	EIC e-Pb [mb]	EIC e-U [mb]
σ_{-1n}	33.93	33.20	20.24	15.58
σ_{-2n}	18.89	30.59	11.45	14.88
σ_{-3n}	2.546	3.537	1.416	1.591
σ_{-4n}	1.091	0.784	0.5933	0.2934
$\sigma_{fission}$	0	18.24	0	8.867
σ_{total}	55.74	85.48	33.90	41.32
Fission b.r.	0%	19.54%	0%	21.45%

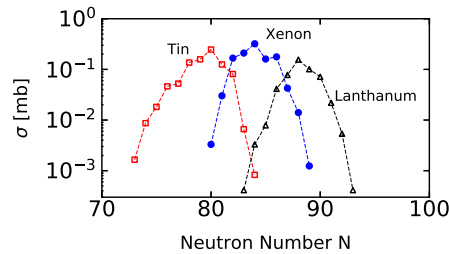


Fig. 3. Cross sections for the production of tin (open red squares), xenon (filled blue circles) and neodymium (open black triangles) isotopes at the EIC.

We applied our theoretical framework to describe the nuclear fragmentation of ^{208}Pb and ^{238}U ions at the EIC and in UPCs at the LHC. Our results indicate that the cross sections and number of events at the EIC are smaller than at the LHC by about a factor 10^3 . We considered only electromagnetic interactions through the excitation of giant resonances, which predominantly decay via neutron emission and, for ^{238}U , by fission. Most isotopes produced are near the stability line due to the small excitation energy imparted by the electromagnetic interaction. Notably, about 21% of events involving fragmentation of ^{238}U at the EIC result in a large number of isotopes with masses around $A = 100$ and $A = 140$. The cross sections for neutron emission are so significant that they can be utilized for monitoring the degradation of the ion beam at the EIC.

At the EIC, the contribution of initial photo-nucleon interactions followed by parton-parton or nucleon-nucleon cascades results in the excitation and decay of the nucleus. But their cross sections are small compared to the collective excitation of giant resonances. In heavy ion colliders at the LHC, nuclear fragmentation can also arise from central collisions, potentially forming a fireball with a QCD phase transition and subsequent hadronization. Our comparison of electromagnetic fragmentation at the EIC and the LHC highlights two extreme conditions for such processes and also underscores the potential of complementary studies at future high-power laser facilities to explore similar phenomena [32,33].

In contrast to eA collisions at the EIC, in UPCs we may have pomeron exchange, which is a long range strong interaction and competes with photon induced processes. In principle, pomerons can also cause nuclear fragmentation. There are also clear differences between the two processes as pomerons are 0^{++} particles and the photon is 1^{--} . In the EIC all processes are free of pomerons and it is an ideal laboratory to isolate pure electromagnetic from strong interactions processes in studies of low excitation energy nuclear physics.

CRediT authorship contribution statement

C.A. Bertulani: Investigation. **Y. Kucuk:** Investigation. **F.S. Navarra:** Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Carlos Bertulani reports financial support was provided by US Department of Energy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work has been supported by the Turkish Council of Higher Education (YOK) under Mevlana Exchange Program, and by the U.S. DOE grant DE-FG02-08ER41533 and the U.S. NSF Grant No. 1415656.

Data availability

No data was used for the research described in the article.

References

- [1] A. Accardi, et al., Electron ion collider: the next QCD frontier - understanding the glue that binds us all, arXiv:1212.1701, 2014.
- [2] N. Magdy, M. Hegazy, A. Rafaat, W. Li, A. Deshpande, A.M.H. Abdelhady, A.Y. Ellithi, R.A. Lacey, Z. Tu, A study of the nuclear structure of light nuclei at the electron-ion collider, arXiv:2405.07844, 2024.
- [3] B. Schmookler, A study of the nuclear structure of light nuclei at the electron-ion collider, in: *Electron-Ion Collider User Group Meeting*, July 23-31, University of Warsaw, 2023.
- [4] K.-H. Schmidt, M. Ricciardi, A. Botvina, T. Enqvist, Production of neutron-rich heavy residues and the freeze-out temperature in the fragmentation of relativistic ^{238}U projectiles determined by the isospin thermometer, *Nucl. Phys. A* 710 (1) (2002) 157–179, [https://doi.org/10.1016/S0375-9474\(02\)01120-X](https://doi.org/10.1016/S0375-9474(02)01120-X).
- [5] B. Jurado, K.-H. Schmidt, J. Benlliure, Time evolution of the fission-decay width under the influence of dissipation, *Phys. Lett. B* 553 (3) (2003) 186–190, [https://doi.org/10.1016/S0370-2693\(02\)03234-3](https://doi.org/10.1016/S0370-2693(02)03234-3).
- [6] B. Jurado, C. Schmitt, K.-H. Schmidt, J. Benlliure, A. Junghans, A critical analysis of the modeling of dissipation in fission, *Nucl. Phys. A* 747 (1) (2005) 14–43, <https://doi.org/10.1016/j.nuclphysa.2004.09.123>.
- [7] D. Pérez-Loureiro, et al., Production of neutron-rich nuclei in fragmentation reactions of ^{132}Sn projectiles at relativistic energies, *Phys. Lett. B* 703 (5) (2011) 552–556, <https://doi.org/10.1016/j.physletb.2011.08.037>.
- [8] X. Roca-Maza, N. Paar, Nuclear equation of state from ground and collective excited state properties of nuclei, *Prog. Part. Nucl. Phys.* 101 (2018) 96–176, <https://doi.org/10.1016/j.ppnp.2018.04.001>.
- [9] A. Tamii, et al., Complete electric dipole response and the neutron skin in ^{208}Pb , *Phys. Rev. Lett.* 107 (2011) 062502, <https://doi.org/10.1103/PhysRevLett.107.062502>.
- [10] C. Bertulani, G. Baur, Electromagnetic processes in relativistic heavy ion collisions, *Phys. Rep.* 163 (1988) 299–408, [https://doi.org/10.1016/0370-1573\(88\)90142-1](https://doi.org/10.1016/0370-1573(88)90142-1).
- [11] E. Fermi, Über die Theorie des Stoßes zwischen Atomen und elektrisch geladenen Teilchen, *Z. Phys.* 29 (1) (1924) 315–327, <https://doi.org/10.1007/BF03184853>.
- [12] E. Fermi, Sulla teoria dell'urto tra atomi e corpuscoli elettrici, *Il Nuovo Cimento* (1924–1942) 2 (2) (1925) 143–158, <https://doi.org/10.1007/BF02961914>.
- [13] C.F.v. Weizsäcker, Ausstrahlung bei Stößen sehr schneller Elektronen, *Z. Phys.* 88 (9) (1934) 612–625, <https://doi.org/10.1007/BF01333110>.
- [14] E.J. Williams, Nature of the high energy particles of penetrating radiation and status of ionization and radiation formulae, *Phys. Rev.* 45 (1934) 729–730, <https://doi.org/10.1103/PhysRev.45.729>.
- [15] G. Nordheim, L.W. Nordheim, J.R. Oppenheimer, R. Serber, The disintegration of high energy protons, *Phys. Rev.* 51 (1937) 1037–1045, <https://doi.org/10.1103/PhysRev.51.1037>.
- [16] R.H. Dalitz, D.R. Yennie, Pion production in electron-proton collisions, *Phys. Rev.* 105 (1957) 1598–1615, <https://doi.org/10.1103/PhysRev.105.1598>.
- [17] D. Isabelle, G. Bishop, Study of the giant resonance in α by inelastic electron scattering, *Nucl. Phys.* 45 (1963) 209–234, [https://doi.org/10.1016/0029-5582\(63\)90795-8](https://doi.org/10.1016/0029-5582(63)90795-8).
- [18] V. Budnev, I. Ginzburg, G. Meledin, V. Serbo, The two-photon particle production mechanism. Physical problems. Applications. Equivalent photon approximation, *Phys. Rep.* 15 (4) (1975) 181–282, [https://doi.org/10.1016/0370-1573\(75\)90009-5](https://doi.org/10.1016/0370-1573(75)90009-5).
- [19] T. de Forest Jr., J. Walecka, Electron scattering and nuclear structure, *Adv. Phys.* 15 (57) (1966) 1–109, <https://doi.org/10.1080/00018736600101254>.
- [20] T.W. Donnelly, J.D. Walecka, Electron scattering and nuclear structure, *Annu. Rev. Nucl. Part. Sci.* 25 (1975) 329–405, <https://doi.org/10.1146/annurev.ns.25.120175.001553>.
- [21] J. Eisenberg, W. Greiner, *Excitation Mechanisms of the Nucleus*, North-Holland, 1988.
- [22] J.M. Blatt, V.F. Weisskopf, *Theoretical Nuclear Physics*, Dover Books, NY, 2010.
- [23] T. Aumann, et al., Few-neutron removal from ^{238}U at relativistic energies, *Z. Phys. A, Hadrons Nucl.* 352 (2) (1995) 163–169, <https://doi.org/10.1007/BF01298903>.
- [24] C. Bertulani, V. Ponomarev, Microscopic studies on two-phonon giant resonances, *Phys. Rep.* 321 (4) (1999) 139–251, [https://doi.org/10.1016/S0370-1573\(99\)00038-1](https://doi.org/10.1016/S0370-1573(99)00038-1).
- [25] C.A. Bertulani, Y. Kucuk, R. Lozeva, Fission of relativistic nuclei with fragment excitation and reorientation, *Phys. Rev. Lett.* 124 (2020) 132301, <https://doi.org/10.1103/PhysRevLett.124.132301>.
- [26] M.N. Harakeh, A. Van der Woude, *Giant Resonances: Fundamental High-Frequency Modes of Nuclear Excitation*, Oxford Studies in Nuclear Physics, Oxford Univ. Press, Oxford, 2002.
- [27] A. Kelic, M.V. Ricciardi, K.-H. Schmidt, ABLA07 - towards a complete description of the decay channels of a nuclear system from spontaneous fission to multi-fragmentation, arXiv:0906.4193, 2009.
- [28] W.J. Huang, G. Audi, M. Wang, F.G. Kondev, S. Naimi, X. Xu, The AME2016 atomic mass evaluation (I). Evaluation of input data; and adjustment procedures, *Chin. Phys. C* 41 (3) (2017) 30002.
- [29] R. Bass, *Nuclear Reactions with Heavy Ions*, Texts and Monographs in Physics, Springer Verlag, Heidelberg, 1980.
- [30] R. Arnaldi, et al., The neutron zero degree calorimeter for the Alice experiment, *Nucl. Instrum. Methods Phys. Res., Sect. A* 564 (2006) 235, <https://doi.org/10.1016/j.nima.2006.03.044>.
- [31] Yuji Goto, Physics and detector requirements at zero degree of EIC, in: *Proceedings of the Workshop on Forward Physics and QCD at the LHC, the Future Electron Ion Collider and Cosmic Ray Physics*, Guanajuato, Mexico, 2019.
- [32] F. Negoita, et al., Laser driven nuclear physics at ELINP, arXiv:2201.01068, 2022.
- [33] A. Martens, et al., Design of the optical system for the gamma factory proof of principle experiment at the CERN super proton synchrotron, *Phys. Rev. Accel. Beams* 25 (2022) 101601, <https://doi.org/10.1103/PhysRevAccelBeams.25.101601>.