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Maria Babiuc-Hamilton

Joseph I. Powell

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EDITED BY
Francesca M. Civano,
National Aeronautics and Space Administration, United States

REVIEWED BY
Jocelyn Samantha Read,
California State University, Fullerton, United States
Carlos Frajuca,
Federal University of Rio Grande, Brazil

*CORRESPONDENCE
Maria C. Babiuc Hamilton,
babiuc@marshall.edu

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How do nuclear isomers influence the gamma-ray bursts in binary neutron star mergers?

Maria C. Babiuc Hamilton* and Joseph I. Powell

Department of Mathematics and Physics, Marshall University, Huntington, WV, United States

Neutron star mergers are astrophysical “gold mines,” synthesizing over half of the elements heavier than iron through rapid neutron capture nucleosynthesis. The observation of the binary neutron star merger GW170817, detected both in gravitational waves and electromagnetic radiation, marked a breakthrough. One electromagnetic component of this event, the gamma ray burst GRB 170817A, has an unresolved aspect: the characteristics of its prompt gamma-ray emission spectrum. In this work, we investigate that gamma-ray spectra in such GRBs may be influenced by de-excitations from isomeric transitions. Our study begins with a review of current knowledge on GRB structure and of r-process nucleosynthesis in neutron star collisions, focusing on the role of nuclear isomers in these settings. We then test our hypothesis by developing criteria to select representative isomers, based on known solar element abundances, for modeling GRB spectral characteristics. We integrate these criteria into an interactive web page, facilitating the construction and analysis of relevant gamma-ray spectra from isomeric transitions. Our analysis reveals that three isomers—$_{90}$Zr, $_{207}$Pb, and $_{89}$Y—stand out for their potential to impact the prompt GRB spectrum due to their specific properties. This information allows us to incorporate nuclear isomer data into astrophysical simulations and calculate isomeric abundances generated by astrophysical r-processes in neutron star mergers and their imprint on the detected signal.

KEYWORDS

binary neutron mergers, gamma-ray bursts, rapid neutron capture nucleosynthesis, nuclear isomers, isomeric transition

1 Introduction

The collision of two neutron stars injects massive amounts of matter at high energy into the surrounding environment and release an enormous amount of energy that can be detected as gravitational waves and light, emitted across the electromagnetic spectrum on various timescales (Friedman and Stergioulas, 2020).

The first detection of gravitational waves (GW) from a binary neutron star (BNS) collision, named GW170817 (Abbott et al., 2017a), was accompanied by a weak, off-axis γ-ray burst (GRB 170817A) (Abbott et al., 2017b), matter outflow (Moharana and Piran, 2017) and an optical-to-infrared transient (AT2017gfo), called a kilonova (Arcavi et al., 2017), that emitted a broad array of electromagnetic (EM) radiation (Nakar et al., 2018), in accord with the predictions for radioactive decay of elements. Analysis of the data gathered from this collision provided us with a wealth of new insights into many yet unknown aspects of a neutron star (Potekhin, 2010), such as its internal structure and radius (Abbott et al., 2018), the amplification of the magnetic fields during merger (Abdalla et al., 2020), and the outflow of matter during the collision process (Wu and MacFadyen, 2018). Further theoretical studies of this twin detection in GW and EM radiation allowed scientists to identify for the first time an element heavier than iron, namely strontium (Watson et al., 2019), thus confirming BNS mergers as sites where heavy elements are formed (Hotokezaka et al., 2018). These discoveries established neutron star mergers as veritable "gold mines," because more than half of all the elements heavier than iron can be forged in the collision (Nedora et al., 2021) through the rapid-process (r-process) nucleosynthesis, the dominant mechanism through which neutrons are promptly captured by seed nuclei to build up heavier elements before they radioactively decay (Cowan et al., 2021).

The detection of the accompanied GRB 170817A signal (Goldstein et al., 2017; Savchenko et al., 2017) also unambiguously confirmed compact binary mergers as sources of gamma-ray bursts (GRB) (Beniamini et al., 2019; Wu and MacFadyen, 2019). However, one of the puzzling questions that still remains is the mechanism of the highly collimated short GRB (Kisaka et al., 2018; Nathanail, 2018; Matsumoto et al., 2019).

During the collision, a large amount of highly relativistic matter is projected outwards, along the axis of rotation. These particles are trapped, collimated and accelerated to near-light speed by strong magnetic fields amplified during the merger, and are carried to long distances, spanning entire galaxies. In their travel, these particles might convert kinetic energy into γ-ray (EM) energy through synchrotron emission, inverse Compton processes and dissipation due to internal shocks. Although great strides have been made in understanding the nature of GRB emission, one open issue remaining is the interpretation of the radiative mechanisms responsible for the prompt GRB spectrum. At the beginning, the γ-ray energies have a different origin than the synchrotron radiation, suggesting that a more complex model is required to fit the data. This emission might contain as well γ-ray photons from nuclear decay of the heavy elements produced in the ejecta (Janiuk, 2014). The heavy nuclei produced in this outflow of matter by the r-process nucleosynthesis are stripped of electrons, and many of them are unstable. While still in excited nuclear states, some of these nuclei can be trapped by the strong magnetic field and beamed to high velocities. The radioactive decay of these unstable isotopes will release nuclear energy in form of γ-ray, neutrino and particle products in the jet. While the neutrino will escape freely, the electrons will annihilate with the positrons, and the other particles will be thermalized through collisions, Coulomb forces and inverse Compton scattering, producing additional γ-rays.

A portion of these newly formed, highly excited heavy isotopes will be in isomeric, metastable nuclear states with lifetimes long enough to enable them to be distinguished from other nuclear states. The nuclear isomers that retain their metastable characteristics in highly energetic astrophysical environments such as BNS mergers are called astromers (Misch et al., 2021a) and may play a significant role in determining not only the abundance of the elements in the Universe (Misch et al., 2021b), but also the spectral appearance of GRBs from such events. Scientists have started to consider the influence of astromers in the r-process nucleosynthesis in connection with the light-curve of the EM signal from the ejecta of BNS mergers (Reifarth et al., 2018; Si and Ma, 2020). However, this aspect is still in its infancy, and none has explored their connection to GRB γ-ray emission.

One aspect that remains unexplained is the non-thermal γ-ray spectrum of the prompt emission. Our research aims to bridge this gap by investigating whether γ-ray de-excitations from isomeric transitions of excited nuclei created in the r-process nucleosynthesis during BNS mergers can contribute to the spectrum of the GRBs associated to these events. An accurate understanding of this γ-ray emission through isomeric transition is challenging because we have limited knowledge of the nuclear physics that operates the r-process nucleosynthesis of heavy elements during a BNS collision in the presence of isomers. Similar to the stable elements, isomers are thought to conglomerate around the "magic numbers" of neutron shell closure and can lead to a change in the elemental abundances produced in nucleosynthesis, or even influence the path of the nuclear reactions (Misch et al., 2021c). Our endeavor to connect isomeric γ-ray de-excitations with the observed GRB spectrum is feasible, although ambitious. To calculate the emission from such transitions, we must know the species of nuclides inside the merger ejecta, and their abundances. Moreover, the fate of the γ-ray photons generated through isomeric decay will be sensitive to the thickness of the ejecta, and will be affected by superpositions with the γ-rays generated through fission, annihilation radiation, synchrotron emission and thermalization, as well as by the line broadening caused by the Doppler effect during the relativistic expansion of the jet.

Our paper is organized as follows: we begin with a discussion on GRB properties, and continue with introducing known facts about the r-process nucleosynthesis in BNS collisions, as well as the concept of isomeric transition. We continue with presenting our compilation of the relevant isomeric elements likely to be created during the r-process, from Garg et al. (2023). We explain our criterion of selecting representative isomers, accounting for the typical time of the r-process, the time necessary for the jet to form and break through the ejecta surrounding the merger, and the time of the GRB burst. We carefully cross-correlate the identified isomers with the cosmic abundance of elements observed in the Solar System (Lodders, 2019) and estimate the number of isomers created relative to the number of baryons in the ejecta. We implement our selection criteria in a Python program embedded into an interactive web page, accessible as an open-source shareable data application. We analyze this data, constructing a set of relevant γ-ray spectra and light-curves associated with the most promising isomers. In a later work, we will refine our model and will compare our results with GRB170817A as well as with other GRBs thought to have originated from double neutron star mergers.

Our new connection between the GRB emission from known astrophysical sites of r-process nucleosynthesis such as BNS mergers and the γ-ray signature of isomeric transition might be a step forward towards explaining spectral features in past and future GRB detections from compact sources. The information we provide can be also incorporated into detailed astrophysical simulations, in order to calculate with accuracy the characteristic isomeric abundance produced by BNS collisions and to generate light curves that can be then validated by comparison with detected GRB data. This is just the beginning and much remains to be learned about the impact of isomers on the creation of heavy elements in astrophysical nucleosynthesis r-processes and on the physics of GRB. Our study could contributes to the elucidation of the intriguing mechanism behind the spikes in the spectrum of the GRB. Although besides strontium, there is currently no reported detection of elements created during BNS mergers in the light curves from GRB 170817A (Savchenko et al., 2017), future combined GW/GRB detections, with more sensitive instruments, will occur. These detections will be needed to elucidate the mechanisms behind γ-ray emission in the GRB spectrum, and distinguish the role played by isomeric transition, thus validating or disproving our hypothesis.

2 GRB structure

Gamma ray bursts (GRBs) have been a focal point of research since their initial observation in 1973 by the Vela satellite (Klebesadel et al., 1973). It is agreed that their γ-ray emission follows roughly the same pattern, starting with a short, spectrally hard burst, followed by a longer tail of spectrally softer emission, and ending with a long-lasting multi-wavelength afterglow (Li and Paczynski, 1998; Lamb et al., 2022). Despite the detection of over 12,000 GRBs since their discovery, and extensive research on this topic, the jet formation mechanism remains elusive (Burns and Fryer, 2023; Valverde et al., 2023).

Based on the observed time frame of the γ-ray emission, astronomers have categorized GRBs in two groups: long ($>$ 2s) and short ($<$ 2s) bursts. The short-duration GRBs are considered to originate when two compact objects merge, while long GRBs could result from a collapsing massive star, or supernova. However, recent discoveries of long-duration bursts such as GRB 211211A (Mei et al., 2022; Rastinejad et al., 2022) and GRB 230307A (Dai et al., 2023) show evidence that they are consistent with the detection of an associated kilonova. Their spectra present extreme variability, flares and quasi-periodic substructure, characteristic to the formation of a neutron star remnant prior to the final collapse (Chirenti et al., 2023; Most and Quataert, 2023; Veres et al., 2023). These discoveries point towards a new class of long GRBs originating from mergers of neutron stars.

The mainstream explanation of the GRB engine is centered on the Blandford-Znajek mechanism. This theory requires the existence of a black hole (BH) surrounded by an accretion disk. The accretion disk supports large-scale aligned magnetic fields, which thread through the central black hole. This magnetic field extracts spin energy from the black hole, directing it into a low-mass jet, and accelerating it to relativistic speeds (Blandford and Znajek, 1977). Numerical simulations do report that during the collision of two neutron stars, the jet is formed after the remnant collapses to a black hole (Pavan et al., 2021). An alternative explanation for the GRB engine is a fast-spinning, strongly magnetized neutron star, called a magnetar, that can dump its rotational energy into the Poynting flux, who transports the energy of the magnetic fields in form of electromagnetic radiation from the star to the jet. This mechanism could accelerate a small amount of matter to very high energies, producing the relativistic jet. Indeed, other numerical simulations prove that magnetars formed as remnants of BNS mergers are viable engines able to launch GRBs and power kilonovae (Salafia et al., 2019; Mösta et al., 2020).

The current understanding of GRB production involves a compact star (either a magnetar or a black hole with an accretion disk) generating a large amount of highly relativistic particles. These particles extract energy from the compact object through the Poynting flux, carrying them over large distances. During their travel, the stream of particles become optically thin and might experience shocks, and convert their kinetic energy into internal energy. The observed γ-rays are subsequently emitted through synchrotron radiation or inverse Compton processes when relativistic electrons are being accelerated in magnetic fields (Salafia et al., 2019; Burgess et al., 2020).

The GRB 170817A jet was detected at t_0 = 1.75s after the peak in the GW signal, and lasted around t_j = 2s, starting with an initial spike in γ-ray energy of about 0.5s, followed by a broader and less intense tail (Burgess et al., 2020). Its γ-ray emission was less luminous than known short-duration GRBs, leading scientists to infer that the emission was off-axis (He et al., 2018), and subsequently scattered while passing through the merger ejecta, with a peak in photon energy of about 5MeV and a narrow half-opening of $\approx 2.1^{+2.4}_{-1.4}$ degrees, viewed at an angle of 23^{+5}_{-3} degrees (Cao et al., 2023; Hayes et al., 2023; Salafia et al., 2023). This model classified GRB 170817A as a typical short GRB, favoring a quasi-universal jet structure, with the differences being caused by extrinsic factors, such as density of the particles in the jet, viewing angle or interaction with the surrounding medium (Salafia et al., 2019).

Numerical simulations showed that the time delay between the merger and the start of the jet was due to 1) the time necessary for engine activation and 2) the time for the jet to break out of the surrounding environment (Pavan et al., 2021). After a careful examination, it was shown that the time delay should include three terms, namely 1) the time to launch the jet, 2) the time for the jet to break out from the surrounding medium and 3) the time to reach the emission site. The fact that the time delay for GRB 170817A correlates with the pulse duration was interpreted to indicate that the time delay is dominated by the duration for the jet to travel to the emission radius, estimated to be at large distance ($\approx 10^{15}$cm) from the progenitor (Zhang, 2019). As consequence, the time delay cannot be used to diagnose the jet launching mechanism.

In this model, the γ-rays are produced far away from the engine, in the circumstellar region populated by the outflow of gas ejected during the merger, driven by magnetic fields. The radiation was released from a broad outflow with a large opening angle, and subsequently collimated, partly by the large-scale, ordered magnetic field, and partly due to the ultra-relativistic motion of the particles in the jet (Cao et al., 2023). Relativistic outflows are strongly beamed, such that the observer sees only the beaming angle, proportional to $1/\Gamma$, where Γ is the Lorentz factor, a measure of the relativistic effects experienced by objects moving close to the speed of light. The estimated values for the Lorentz factor of the bulk matter in the jet are very large, between 100 and 1,000 (Ravasio et al., 2023). Particles accelerated to such relativistic speeds posses extremely high energy and emit synchrotron radiation in strong magnetic fields.

Nonetheless, many GRB spectra deviate from the expectations of this synchrotron emission. For example, the light-curves of the prompt emission are irregular. One of the hypothesis is that this variability is due to internal shocks (Kisaka et al., 2018; Salafia et al., 2019; Lazzati, 2020). Relativistic jets can generate shock waves because the inner engine produces inhomogeneities, and shells of particles in the jet travel at different velocities. However, the internal shock model of GRBs is inefficient in converting the kinetic energy of the particles in the jet into γ-ray radiation, known as the "low-efficiency problem." This was replaced with a model in which a "fireball," moving at a relativistic speed, is launched by a fast-rotating black hole or magnetar. In this case, the internal shocks are supplemented with the external shock mechanism (Piran, 1999; Beniamini et al., 2016; Cao et al., 2023). Because the velocity of the particles in the jet is larger than the speed of sound, the beamed ejecta will form a cocoon when it plows through the surrounding medium and this interaction modulates the synchrotron radiation (Gottlieb et al., 2018). The jet and cocoon combination forms a "structured" jet, which avoids the underlying mechanism. A structured jet has a uniform, ultra-relativistic core, surrounding by a power-law decaying wind, forming a two-jet component, with a relativistic core and a slightly slower outer jet (Salafia and Ghirlanda, 2022). To explain photon energies greater than 10GeV, this double-jet picture is modified into a narrow, off-axis jet with a high Lorentz factor, and a wide, on axis jet with a small Lorentz factor, the interaction between them forming reverse shock regions that could explain the GeV flares observed in some GRBs (Fraija et al., 2023a).

This way, a unified picture of both short and long GRBs from compact binary mergers emerges, based on a structured jet launched by a common central engine, which avoids the underlying mechanism (Kasliwal et al., 2017; Gottlieb et al., 2023). The peak luminosity distribution of the long and short GRBs could be also fitted to a triple power law, implying that both types of GRBs could be produced by the same mechanism (Fraija et al., 2023b; Li et al., 2023). But if indeed the γ-ray emission took place in an optically thin region, far away from the central engine, the shock emission components are suppressed, and some other mechanisms may be at play (Ravasio et al., 2023). For example, recent simulations show that before the emergence on the jet from the neutron star remnant formed after the BNS merger, a UV/blue precursor signal is generated, that can "seed" the ultra relativistic GRB jet (Combi and Siegel, 2023).

Spectral data alone might not be enough to discern between various models and to assess their viability. Polarization measurements of the GRB prompt emission, in principle, have the potential to address many of these questions. However, such measurements have only been obtained for a limited number of bursts and thus have limited statistical significance (Wang and Lan, 2023). Looking ahead, joint detections of GW/GRB events, coupled with polarization data from the accompanying GRB, will help understand these astrophysical phenomena.

3 r-process nucleosynthesis and isomers

The r-process consists of a series of reactions in which nuclei capture neutrons rapidly, leading to the creation of heavy elements. This process is believed to occur at high temperatures, in extremely neutron-rich environments. While the r-process was long associated with supernovae, recent studies indicate that BNS mergers, with their more neutron-rich environments, are likely the predominant sites for heavy r-process element production (Just et al., 2015; Perego et al., 2021; Rosswog and Korobkin, 2022). More than half of the heavy elements found in nature are produced through the r-process, some elements forming exclusively or almost so by this mechanism (Cowan et al., 2021). The detailed pathways of producing these heavy elements are still unsettled (Pogliano and Larsen, 2023) and the lack of confidence in the neutron capture rate predictions makes the calculation of final abundances in the r-process difficult (Kajino et al., 2019).

The r-process operates in two distinct phases: an initial period in which neutron captures dominate, and a subsequent state characterized by β-decay, leading to the creation of new elements with increasingly heavier proton numbers. The timescale for neutron capture is significantly faster than that of β-decay. Neutrons are absorbed rapidly until a statistical equilibrium is reached, a point known as "neutron drip line," where neutron separation energy becomes zero. Here, a neutron shell closure is reached, known as "freeze-out," where rapid neutron capture ceases (Just et al., 2015). This occurs when the neutron-rich environment becomes depleted, and the neutron capture rate drops significantly. At this stage, the nucleus is no longer able to capture neutrons effectively, marking the end of the rapid neutron capture phase and leading to a shift towards β-decay, where neutrons in the nucleus transform into protons, creating new elements. These nuclei, formed post freeze-out, act as seeds for subsequent r-processes, continuing to capture neutrons and forming increasingly heavy nuclei. "Kinks" in the r-process occur at neutron number shell closures, specifically around $N = 50, 82$, and 126. At these points, nuclei are more stable and resist further neutron capture, leading to an accumulation of material. These kinks influence the distribution of elements produced in the r-process, leading to observable patterns in the abundance of elements. The r-process culminates at the "magic number" $N = 184$, that marks the third r-process peak, signaling the completion of neutron capture and β-decay. This happens at about $t_r = 1.34$s since the beginning of the process, when unstable elements with large atomic mass, $A \approx 240$, are created (Eichler et al., 2015). This instability leads to fission, where the heavy nuclei split into smaller ones, typically in the $A < 140$ range, releasing additional neutrons and a significant amount of energy, detected as observable electromagnetic emission associated with neutron star mergers.

The r-process produces a variety of heavy elements, in agreement with the Solar System abundance. Within the energetic collision environment of BNS mergers, a diverse range of conditions leads to various nuclear nucleosynthesis products. Extremely high densities favor the formation of heavy nuclei, while high temperatures tend to produce lighter nuclei. During the coalescence phase, matter is dynamically ejected due to angular momentum conservation within milliseconds, moving at mildly relativistic speeds. This tidal ejecta, dense and moderately heated, retains its original low electron fraction, facilitating the "strong" r-process nucleosynthesis leading to heavier elements (Just et al., 2015). The production of heavy elements in this ejecta competes with its rapid expansion, that reduces the neutron density and temperature. During collision, temperatures reach values high enough to dissociate nuclei into free nucleons, and neutrinos become the primary cooling mechanism. At this point, amplified magnetic fields and neutrino winds eject neutron-rich material along the rotation axis, potentially enhancing the production of heavy elements that can be trapped in the jet (Perego et al., 2014; Shibata and Hotokezaka, 2019). The remnant formed after the merger acquires a neutron rich accretion disk, heated to high temperature by friction and irradiation with neutrinos, favoring the continuation of the r-process (Curtis et al., 2022).

Considering all components—dynamic ejecta, neutrino winds, and outflows from accretion disks—compact binary mergers produce the heaviest r-process nuclei, contributing significantly to the solar r-process abundance (Fujibayashi et al., 2023). The early dynamic ejecta, emerging from the spiral arms, stay very neutron rich and lead to strong r-processes, while the late ejecta will produce weaker r-processes. Simulations suggest that the mass ratio of the binary affects the range of elements produced, leading to variations in the r-process products across different events (Pogliano and Larsen, 2023; Ristić et al., 2023). If the magnetic field is amplified to large values, it will drive winds toward the disk, enhancing the production of heavier elements. These studies also show that the outflow from the remnants can produce a blue kilonova, indicating the presence of heavy elements (Curtis et al., 2024). Observations of kilonovae suggest also that the amount and distribution of r-process products can differ from event to event (Gompertz et al., 2018). As astrophysical models of compact binary mergers become more sophisticated and our understanding of neutron-rich nuclei improves, we move closer to accurately predicting the variety and abundance of heavy elements produced in these cosmic events, shedding light on their contribution to the universal abundance of elements (Banerjee et al., 2020; Perego et al., 2021; Rosswog and Korobkin, 2022; Kobayashi et al., 2023; Ristić et al., 2023).

Predictions indicate that γ-ray emissions from neutron star mergers might include photons from the radioactive decay of heavy isotopes produced in the r-process (Li, 2019; Gillanders et al., 2023). Those isotopes can find their way in the GRB jets, carried by neutrino cooling winds and by the magnetic field (Fujimoto et al., 2004; Janiuk, 2014; Janiuk, 2019). They can power the γ-ray bursts and extend the plateau of their γ-energy emission (Ishizaki et al., 2021). Direct measurements of these photons could potentially serve as a probe for the r-process nucleosynthesis (Korobkin et al., 2019; Terada et al., 2022). This must be supplemented with more robust knowledge of the properties of exotic, neutron-rich nuclei to reduce present nuclear uncertainties, that make it difficult to definitely measure the distribution of heavy isotopes (Sun et al., 2005).

The GW170817/GRB 170817A/AT2017gfo event was identified as a site of r-process nucleosynthesis, observed in the kilonova's electromagnetic spectrum (Hotokezaka et al., 2018; Domoto et al., 2021). Although the r-process nucleosynthesis was confirmed by the observations of this event, no trace of individual elements has been identified, except for strontium (Watson et al., 2019). The high density of the spectroscopic lines of the photons expected to be emitted during the r-process, together with the large velocity of the material ejected during the collision produces line blending and smooths the spectra. This uncertainty complicates the accurate quantification of the heavy element abundances associated with a GRB (Gillanders et al., 2023). Nuclear data is essential to predict the specific elements that are created in an observed astrophysical environment, and to connect observed abundances and kilonova features to astrophysical conditions and constrains on the nucleosynthesis sites (Terada et al., 2022).

Isomers, which are metastable excited states of the same atomic nucleus, can significantly influence γ-ray emission, and not accounting for them may lead to underestimations of the emission (Chen et al., 2021). If the corresponding lifetimes are of the same order of magnitude as the timescales of the environment, isomers must be treated explicitly (Reifarth et al., 2018). In the energetic environment of the collision, isomers may either accelerate their decay, slow it down and act as energy storage, or remain unaffected in their half-life (Misch et al., 2021a; Misch et al., 2021b; Misch et al., 2021c). Particularly, isomers could contribute to the early, blue component of kilonova emissions, as observed in GW170817 (Si and Ma, 2020), potentially allowing outflow towards heavier masses via isomeric branches (Sun et al., 2005). Near the magic numbers $A \approx 80, 130, 195$ marking the "waiting point" where the r-process temporarily slows down, the excitation energy and the number of isomers increase (Garg et al., 2023). As a result, these points accumulate a higher concentration of nuclei, including isomeric states, that become preferentially populated at these three main peaks of the r-process (Sun et al., 2005; Sun, 2008). An important question to answer is how do isotopes reach the isomeric excited state, because promoting nucleons to excited states is hindered due to nuclear recoil (Mossbauer effect, Jain et al., 2021). To achieve excitation, the energy of the γ-ray photon must exceed the transition band energy. Isomer activation can occur either through the capture of higher-energy γ-ray photons or via nuclear excitation through thermal excitation at high temperatures (Crawford et al., 2023; Misch and Mumpower, 2024). Moreover, when nuclei move at relativistic speeds, they can reach isomeric states by absorbing radiation in ultraviolet and X-rays (Budker et al., 2021). Internal conversion, involving the ejection of an inner orbital electron, competes with γ-ray emission, unless the nuclei are in a completely ionized state, a condition found in the atmosphere of the merger (Misch et al., 2021a).

Understanding these intricate nuclear processes in the astrophysical environment of a neutron star merger and their imprint in the emitted EM radiation from BNS mergers not only sheds light on the complex mechanisms of r-process nucleosynthesis but could also enhance our knowledge of GRB's γ-ray emission.

4 Methods

Although uncertainties persist in the r-process calculations and their dependency on the astrophysical environment, there is a general agreement that it occurs within a few seconds. Reference Eichler et al. (2015) indicates that at $t = 1.34$s, the timescale for neutron capture exceeds that of β-decay, marking the end of the r-process. The γ-rays emitted following the r-process are initially trapped within the ejecta and can only be detected after they successfully diffuse through it (Barnes, 2020). Most of these photons transfer heat and become thermalized, losing their characteristic spectral information. However, the similar timing observed between the completion of the r-process ($t_r \approx 1.34$s) and the delay in the γ-ray burst GRB 170817A ($t_0 = 1.75$s) offers a compelling suggestion: the γ-ray emission from this event may include photons from the de-excitation of heavy elements formed via r-process nucleosynthesis, from parts of the ejecta exposed to the jet funnel.

It has been previously suggested that emissions from binary neutron star mergers may include gamma rays from nuclear decay (Wang et al., 2020). Additionally, it has been shown that β-decaying isomer states are more strongly populated than the ground states in stellar environments (Banerjee et al., 2018). We propose that a large fraction of these heavy elements is excited into isomeric states and subsequently ejected within the magnetically and neutrino driven wind outflows from the jet engine, contributing to the collimated jet. This de-excitation process is likely to contribute to the γ-ray spectrum observed in GRBs. Thus, we put forth the hypothesis that a BNS collision serves as an efficient γ-ray “factory,” where the primary “raw materials” are the heavy isotopes in their isomeric states, synthesized through r-process nucleosynthesis within the highly energetic and neutron-rich environment of the ejecta. Their presence may be observed in the γ-ray emissions through distinct multipolarity signatures, influenced by the spin angular momentum carried by the radiation.

To test this hypothesis, we utilized the Atlas of Nuclear Isomers (Garg et al., 2023), a comprehensive database of experimental data for all known isomers to date. This resource includes known properties of each isomer, such as excitation energies, half-lives, decay modes, spins and parities, and energies and multipolarities of isomeric transitions. In our analysis, we processed over 2,500 isomers and identified which isotopes produced in the r-process are likely to have significant isomeric states that are relevant for γ-ray production, based on the following two initial criteria:

- We start by converting the digital database for the known isomers (Garg et al., 2023) from its original format into an Excel file to enable compatibility with Python.
- We focus only on heavy elements produced in r-process nucleosynthesis and limit our choice to isotopes heavier than iron, starting with an atomic mass number greater than 56.
- From these isomers, we select only those that decay via 100% isomeric transitions, because such decays are most relevant for γ-ray emission and do not alter the chemical properties.

Our next task was to determine the initial quantity of individual isotopes for each element produced and to correlate this value with the respective isomeric form. To achieve this, we relied on estimations of the various types of ejecta present in a neutron star collision (Fujimoto et al., 2004; Just et al., 2015):

- The early dynamic ejecta emerging from the tidal interaction of the merging neutron stars, typically ranges between $10^{-4}M_{\odot}$ and $10^{-2}M_{\odot}$, depending on the mass ratio and composition (Abbott et al., 2017c; Dietrich and Ujevic, 2017).
- The neutron-rich mass ejected along the rotational axis by the magnetized wind from the merger remnant, is estimated to about $3.5\times10^{-3}M_{\odot}$, based on an outflow mass rate of $0.1M_{\odot}/s$ (Perego et al., 2014; Nedora et al., 2021).
- The post-merger ejecta surrounding the remnant is calculated to be around $0.1M_{\odot}$ (Shibata and Hotokezaka, 2019; Fujibayashi et al., 2023).

To approximate the mass contributing to isomeric decay, we focused on the mass of the magnetized wind. Additionally, we incorporated a proportion of the mass from both the early dynamic ejecta and the post-merger outflow, that aligns with the jet. The exact angular distribution of the ejecta within the jet remains uncertain, varying with the parameters of the merger. However, the multi-wavelength afterglow of GW170817 suggests a stratified geometry of the ejecta, as indicated in (Lazzati et al., 2018). Models range from a top-hat to isotropic fireball geometry, but evidence increasingly supports a structured composition (Kasliwal et al., 2017; He et al., 2018; Lazzati et al., 2018). The post-merger ejecta, which constitutes the majority of the material, is propelled primarily by the shock at the contact surface during the merger of the two neutron stars. Due to the accumulation of tidal ejecta near the equatorial plane of the binary, this outflow is predominantly directed along the polar axis (Salafia et al., 2018). Considering an isotropic ejecta as a starting point, with matter uniformly distributed around the merger site, the mass encompassed within the half-opening angle θ_0 corresponds to the fraction of the spherical surface area covered by the jet $A_j = \Omega r_0^2$, where $\Omega = 2\pi(1-\cos\theta_0)$ is the solid angle of the jet's cone and r_0 is the radius from the central engine at which the jet forms. Thus, the effective mass in the jet is:

$$M_{\mathrm{eff}} = M_{\mathrm{ejecta}}\left(1-\cos\theta_0\right), \tag{1}$$

where M_{ejecta} is the ejecta mass. This formula takes into account that the jets emanate from both poles.

After calculating the quantity of material expected to influence γ-ray production in the jet, our next step is to calculate the initial number of isotopes. This involves the following steps:

- We rely on the atomic abundances and the mass fractions for the specific isotopic composition in our Solar System, as detailed in Table 9 of Lodders (2019), We start with the heavy elements that begin forming near the first peak of the r-process, around atomic weight $A = 80$, namely with strontium.
- We estimate the fraction of each element produced in merging neutron stars (see Table 1), based on Supplementary Table S1 in the Supplementary Material from Johnson (2019). A revised estimation is found in Busso et al. (2022).
- We calculate the quantity of baryons for each element, rescaled to the abundance of heavy elements baryons, assuming that neutron star collision produce mainly these heavy elements.
- We rescale this quantity back to only 10% of the matter in the jet assumed to be converted into heavy elements through the r-process (Abbott et al., 2017c).
- From the calculated number of baryons for each element produced via the r-process in the jet, we determine the number of atoms and the corresponding mass abundance, in terms of solar mass.
- We normalize the number of atoms for each element to the total number of atoms in the jet. This normalization eliminates the dependence on the effective mass, and will allow to simply scale

TABLE 1 The estimated fractions of each element created in merging neutron stars (Johnson, 2019).

Fraction	Element
0.25	Se, Br, Kr, Rb, Sr, Y, Zr, Nb, Sn, Ba, Ce, Tl, Bi
0.50	Mo, Pd, Cd, Te, La, Pr, Nd, Hf, Ta, W, Hg
0.75	Ru, In, Sb, Sm, Yb, Lu
1.00	Rh, Ag, I, Xe, Cs, Eu, Gd, Tb, Dy, Ho, Er, Tm, Re, Os, Ir, Pt, Au, Pb, Th, U

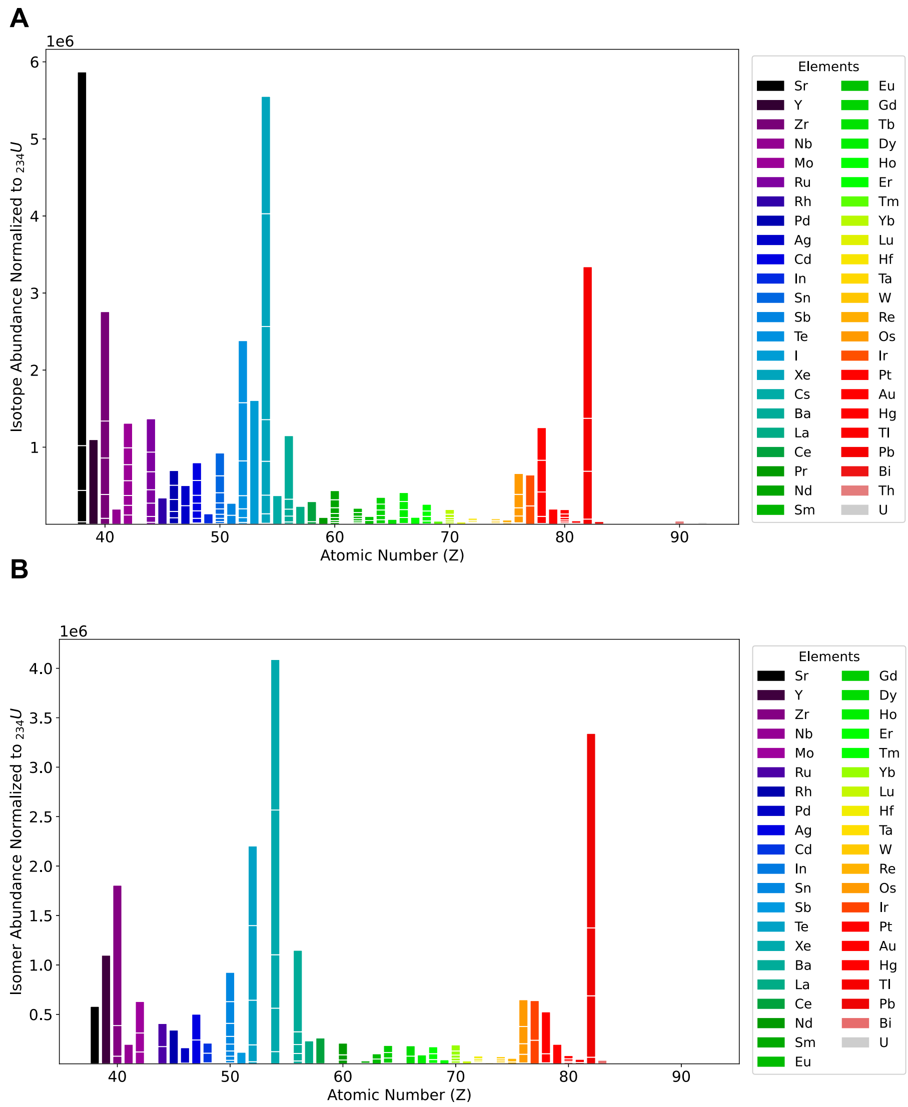

FIGURE 1
Abundances of heavy elements in BNS merger ejecta starting with strontium, plotted against atomic number Z, normalized to the lowest number of atoms ($^{92}_{234}U$), and stacked by atomic mass number. **(A)** Isotopes abundance per atom of ($^{92}_{234}U$) created in BNS merger ejecta. Note: vertical axis $\times 10^6$. **(B)** Isomer abundance per atom of ($^{92}_{234}U$) created in BNS merger ejecta. Note: vertical axis $\times 10^6$.

the contribution of each isotope to the γ-ray production in the jet.

- Lastly, we select among these heavy elements the atoms that admit the previously identified isomeric states, to obtain the type and number of isomers relevant for γ-ray production.

Research on mass ejection and nucleosynthesis in BNS mergers indicates that the temperature of the dynamical ejecta typically exceeds 10GK (Fujibayashi et al., 2023), equivalent to approximately 0.86 MeV. Moreover, during the merger process, shock heating can generate temperatures as high as 100MeV at the contact layer between the colliding stars. The collision dislodges neutron-rich material, which is subsequently carried into the jet by the neutrino cooling winds and magnetic fields from the polar region. The post-merger ejecta undergo heating due to temperature inversion caused by differential rotation, reaching temperatures around 40MeV. Isomeric states of the r-processes elements created in the ejecta of neutron star mergers could be populated due to these high temperatures, according to the Boltzmann distribution:

$$N_{i,0} = N_{\text{count}} e^{-\frac{\Delta E}{kT}}. \tag{2}$$

here, ΔE represents the energy difference between the isomeric and ground states, k is the Boltzmann constant, and T denotes the temperature of the ejecta. Besides nuclear excitation at high temperatures, the isomeric states can also be activated through absorption of γ-ray photons, or interaction with ultraviolet and X-rays, for nuclei moving at relativistic speeds. In a future work, after a more detailed analysis of the properties of the matter in the jet, we will refine the number of isomers at specific excitation energies.

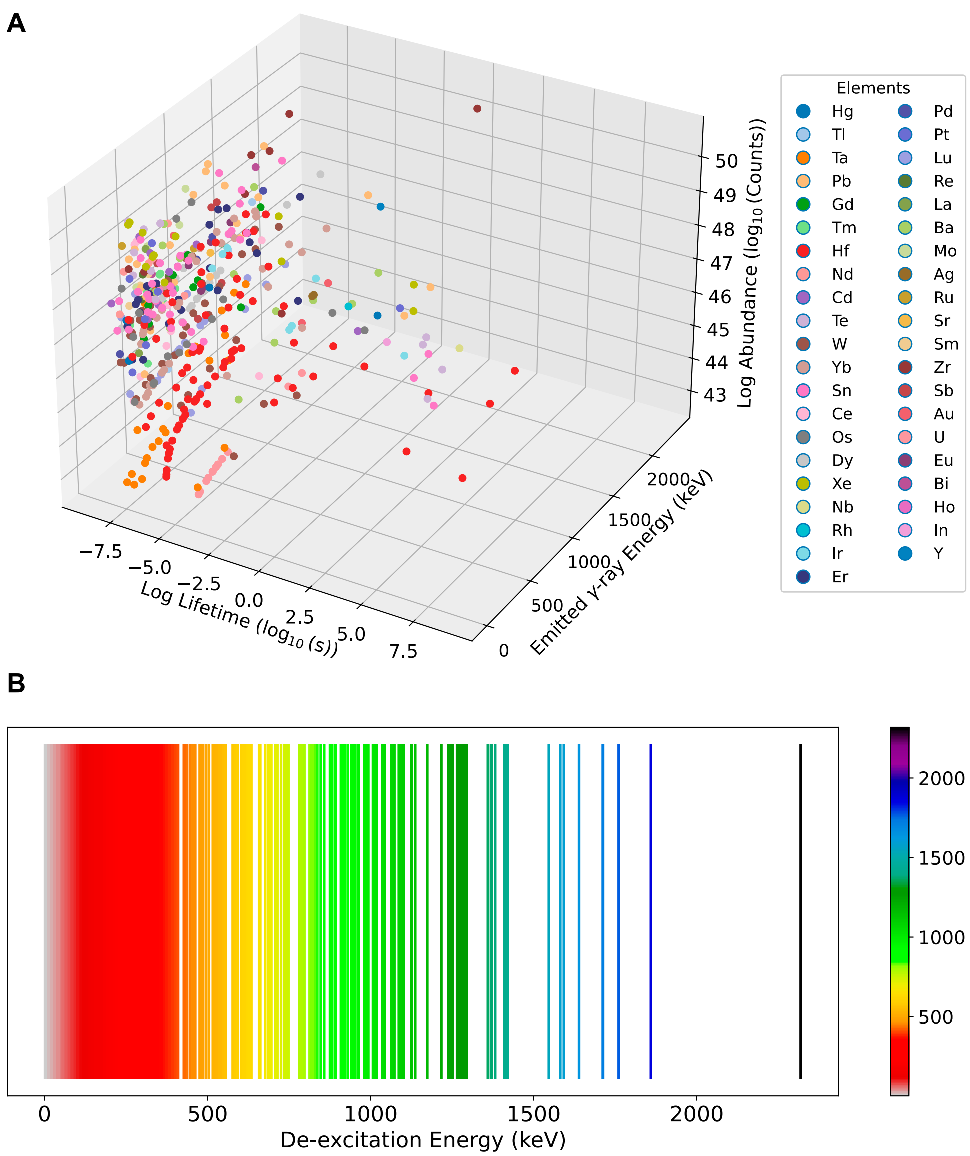

FIGURE 2
(A) Logarithmic abundance of isomers in the jet vs. logarithm of the lifetime ($T_{1/2}$) and the corresponding emitted E_γ. **(B)** The spectra of the emitted γ-ray radiation for all the isomers in the jet.

- In the cases where an isotope admits an isomer that has multiple decay pathways, the energy contribution from each decay is weighted according to the probability P_i of that specific pathway,

$$P_i = \frac{1}{N}\frac{E_{\gamma,i}}{\langle E_\gamma \rangle}, \quad (3)$$

where N is the total number of isomeric decays allowed for a particular isotope in isomeric state, i is the decay path, $E_{\gamma,i}$ the energy of the decay path, and $\langle E_\gamma \rangle$ the mean value of the energies. This holds, because the probability of each decay path is proportional to its γ-ray energy (Garg et al., 2023).

- We calculate the number of γ-ray radiation events ΔN_i occurring within a chosen time interval Δt for each isomer identified, using the decay law:

$$\Delta N_i = N_{i,0} e^{-\lambda t}\left(1 - e^{-\lambda \Delta t}\right) \quad (4)$$

here, $\lambda = \ln(2)/T_{1/2}$ is the decay constant, with $T_{1/2}$ being the half-life of the isomer. We focus on isomers with terrestrial half-life between

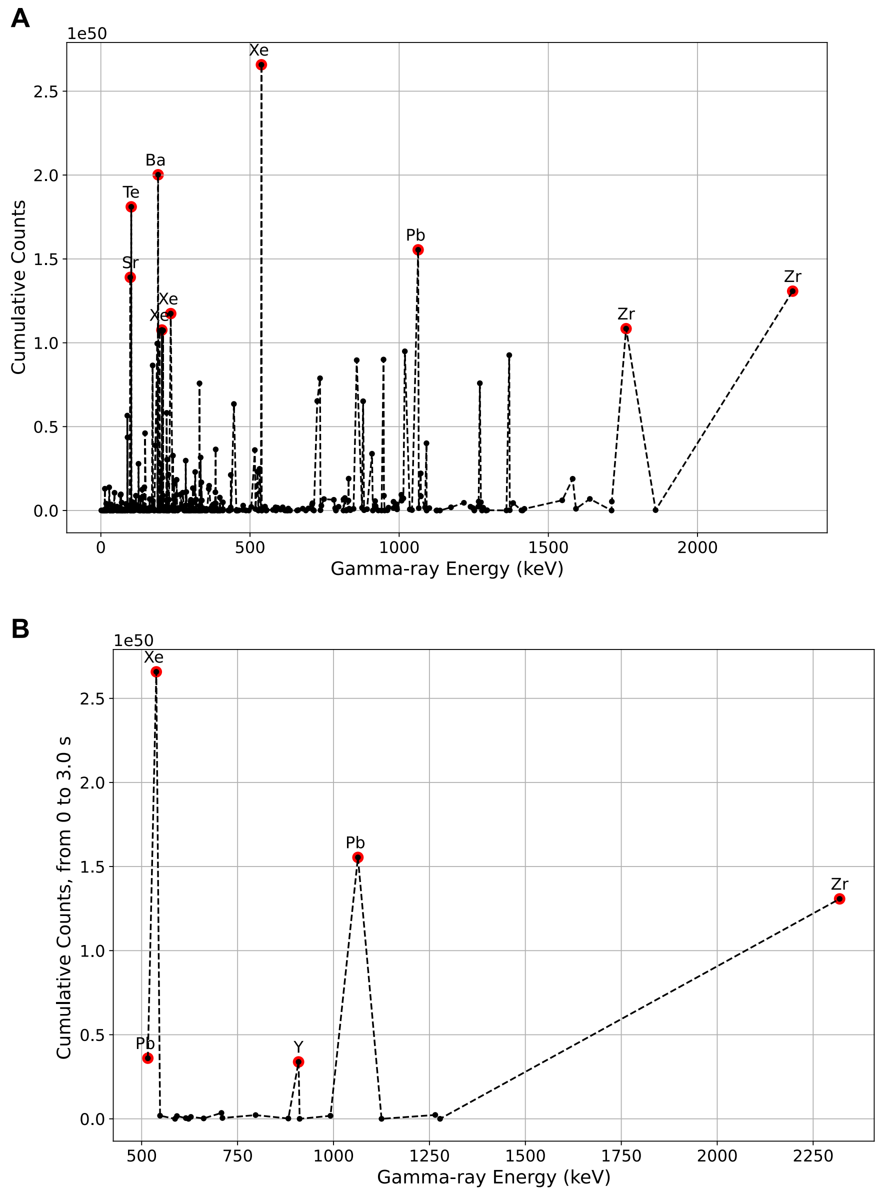

FIGURE 3
Isomer de-excitations spectra, represented as cumulative counts vs. γ-ray energy, $t \leq 3$s. **(A)** Isomer de-excitations spectra for $t \leq 3$s, with top elements highlighted. Vertical axis $\times 10^{50}$. **(B)** Selected isomer γ-ray spectra ($T_{1/2} \geq 10$ μs, $E_\gamma \geq 500$ keV). Vertical axis $\times 10^{50}$.

$t_0 - t_r \leq T_{1/2} \leq t_j$, assuming that the γ-rays emitted by isomeric de-excitation between the end of the r-process and the start of the jet will be reabsorbed.

- Finally, we combine the number of decays (or counts) ΔN_i for all the isomers within a given time interval to obtain the cumulative output from all isomeric decays for each specific de-excitation energy.

To construct the light curve that captures the contribution of isomeric γ-ray de-excitation to the temporal evolution of the GRB's intensity, we proceed as follows:

- For each isomer, we multiply the number of counts ΔN_i calculated with Eq. 4, by the γ-ray energy released per decay for consecutive time intervals, to obtain the evolution of the intensity in time, in increments of Δt.
- Then, we calculate the luminosity emitted for each time bin, by summing the emitted intensities for all the isomers and dividing by Δt.
- We calculate the specified emission area as $A = \Omega_j r^2$, where r is the estimated radius at which the jet is emitted, and its collimation angle is $\theta_j = (1/r)^p$, where $p \approx 0.22$ (Lloyd-Ronning et al., 2020).
- Lastly, we divide the luminosity calculated by the relevant area, to obtain the flux of γ-ray.

TABLE 2 The isomers within the selected criteria.

Fraction	Element	Lifetime (s)	Energy (keV)
206	Pb	1.25×10^{-4}	516.18
132	Xe	8.37×10^{-3}	538.2
89	Y	15.66×10^{-3}	908.96
207	Pb	0.805×10^{-4}	1,063.656
90	Zr	0.809	2,319

We have outlined the methods employed for building an interactive tool for analyzing data related to the complex process behind the contribution of isomeric transitions to the GRB spectrum, and to construct the light curve that captures the contribution of isomers to the temporal evolution of the GRB's intensity.

5 Results

To facilitate the data analysis of nuclear isomers with γ-ray emission relevant to GRBs, we developed an interactive web interface using Streamlit, an open-source Python library designed for creating shareable data applications. Our application, retrievable at https://isomersearchengine.streamlit.app, allows users to filter the data according to specific criteria through interactive sidebars. It also provides functionalities to plot relevant graphs and download the selected data for further analysis. This streamlined approach significantly enhances the efficiency and accessibility of our nuclear isomer data analysis tool.

We started our data analysis by estimating the amount of matter containing r-process elements that can contribute to the overall γ-ray decays occurring within the jets from neutron star mergers, a crucial quantity necessary to calculate the isotope count. We considered a jet of typical geometry, with an initial half opening angle of approximately $\theta_0 = 20°$ when the jet forms (Dai et al., 2023). Using Eq. 1 with this value for θ_0, we found that the effective mass in the jet is $M_{\mathrm{eff}} \approx 6\% M_{\mathrm{ejecta}}$. In this case, the early ejecta contributes minimally, with a mass of maximum $6 \times 10^{-4} M_\odot$. The more significant contribution, of $6 \times 10^{-3} M_\odot$ arises from the post-merger ejecta. Therefore, adding the mass of the magnetized wind to the dynamic and post-merger ejecta expected to impact the jet, we obtain an effective mass $M_{\mathrm{eff}} \approx 10^{-2} M_\odot$. This effective mass contains 1.2×10^{55}baryons, among which we assume that only 10% contribute to the formation of heavy elements (Abbott et al., 2017c). This approach allowed us to determine the amount of matter containing r-process elements that can contribute to the overall decay processes occurring within the jet. Our assumption is based on the premise that the ejecta is spherically-symmetric and that relevant γ-ray emission influencing the GRB's energetic output comes from the matter within this conical section of the jet. This model provides only an approximate estimate of the matter distribution within the jet. A detailed investigation of the matter distribution as a function of the angle, which is essential for a more precise understanding, is beyond the scope of this study and will be the subject of future work.

We determine the initial number of isotopes in M_{eff} and select among these heavy elements the isotopes that admit isomers with 100% isomeric transitions, then calculate their abundance. Our analysis of the ejecta impacting the jet revealed that approximately 35% of the mass comes from the wind, about 5% originates from tidal interactions, and the remaining 60% is attributed to the outflow. Considering the different contributions to the ejecta and their respective temperatures, the average temperature of the ejecta is approximately $T = 59$MeV. We infer from Eq. 2 that for this average temperature, more than 96% of the heavy isotopes formed in the ejecta will have their isomeric energy levels populated. This provides only a rough estimate, because we did not account for the isomers activated through other processes. We mediate the number of isomers for each emitted γ-ray energy with the probability of de-excitation using Eq. 3.

We plot in Figure 1 the abundances of heavy elements, starting with strontium, as a function of the atomic number Z according to the predicted Solar System abundances, first for the isotopes (Figure 1A), and then for their corresponding isomers (Figure 1B). These are shown relative to the abundance of $^{92}_{234}U$, which has the lowest number of atoms ($^{92}_{234}U = 2.51662 \times 10^{44}$ atoms). The number of different isotopes for each Z is indicated within each bar, and the legend on the right lists the type of atoms. Strontium is the most abundant isotope, followed by xenon and lead, while in isomeric state only xenon and lead keep their contribution.

In Figure 2A, we present the abundance of isomers on a logarithmic scale, plotted against the emitted γ-ray energy and the logarithm of the de-excitation time, providing an intuitive overview of all the isomers created in a BNS merger ejecta. This is complemented by the complete de-excitation spectra shown in Figure 2B. We observe that the majority of isomers de-excite in less than (10μs) and have their de-excitation energies below 500keV. These emissions are likely reabsorbed by the medium within the jet, and are most likely not contributing to its overall energy budget. Observational data and models of GRBs indicate that the peak γ-ray energy ranges between 500keV and 2MeV. Consequently, isomers emitting within this energy range merit further investigation. In Figure 3A, we present the isomers energy spectrum as cumulative counts of de-excitations occurring within a time interval of 3s, highlighting all the isomers with the largest de-excitations counts, over 10^{50}. We note that $_{132}Xe$, with a de-excitation energy of 538.2 provides the most substantial contribution to the overall emission. We further narrow down our selection to isomers with de-excitation times exceeding 10μs and energies greater than 500keV, and present them in Figure 3B, highlighting now the five isomers with the largest de-excitations counts. We list the identified isomers in Table 2, detailing their lifetimes, atomic mass number, and their emitted γ-ray energies.

We proceed to illustrate in Figure 4A the γ-ray intensity emitted over time, by the de-excitation of the five isomers selected, from 0 to 3s, calculated as $Intensity(t) = E_\gamma \times Counts(t)$. We observe minimal intensity contribution from the $_{206}$Pb isomer, while $_{132}$Xe peaks around $t \approx 5$ms before steeply declining. Both of these isomers have de-excitation energies around 500keV. Factoring in the electron-positron annihilation process, expected to be frequent within the

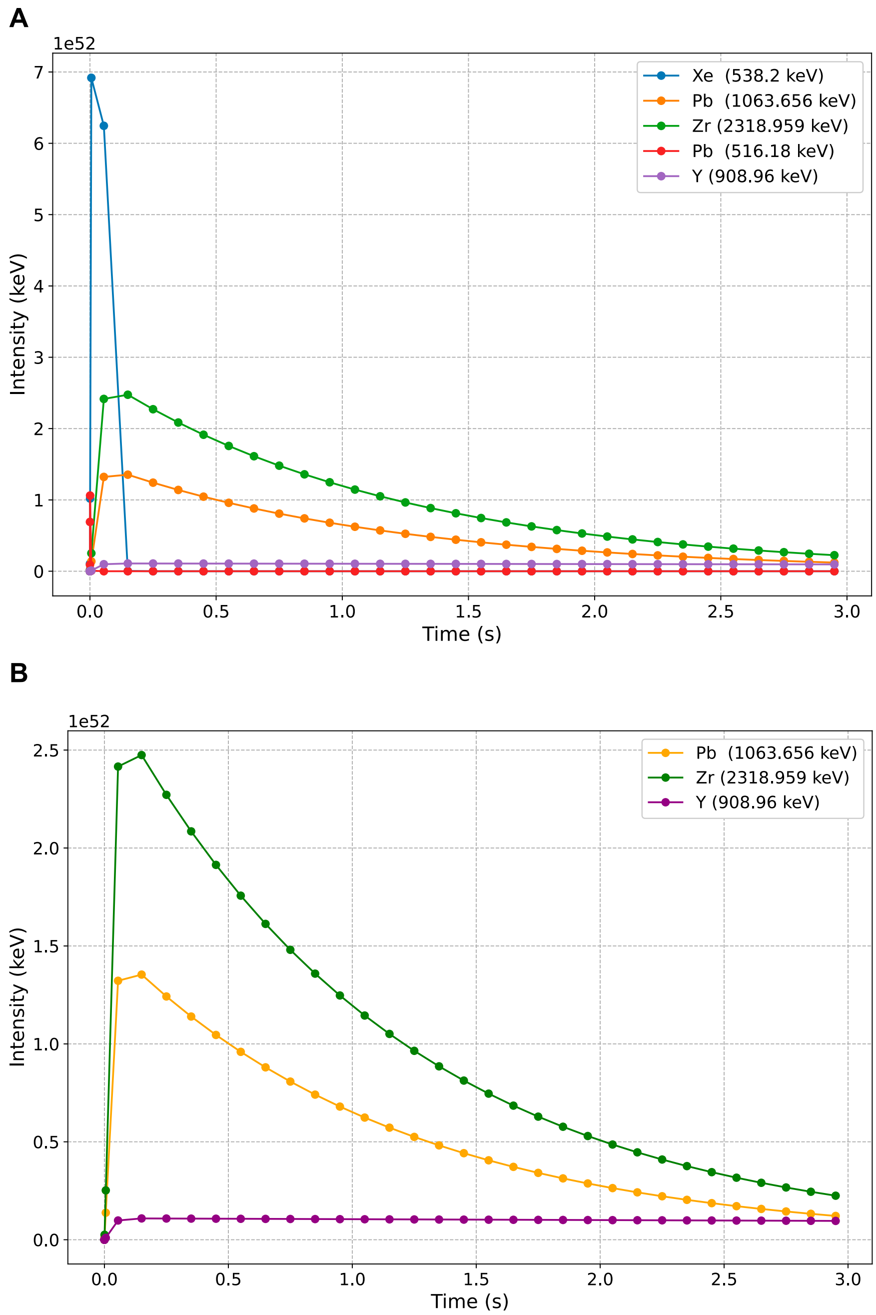

FIGURE 4
Evolution of the emitted γ-ray intensity, for the isomers relevant to GRBs, up to $t \leq 3$s. **(A)** Evolution of the intensity for top 5 isomers, with $E_\gamma \geq 500$ keV. Vertical axis $\times 10^{52}$. **(B)** Evolution of the intensity for top 3 isomers ($E_\gamma \geq 1{,}000$ keV). Vertical axis $\times 10^{52}$.

jet and releasing 1.022MeV, it becomes challenging to differentiate the signal from these isomers from that of the annihilation process. Consequently, our focus will shift to isomers with de-excitation energies above 1MeV and de-excitation times of seconds, specifically $_{89}$Y, $_{207}$Pb, and $_{90}$Zr, as these characteristics make their signals more distinguishable and relevant to our study. In Figure 4B, we show the intensity evolution of these three isomers. Notably, all three exhibit a peak at approximately 0.15s, followed by a rapid decline. Based on these observations, we identify $_{90}$Zr, $_{207}$Pb and $_{89}$Y as prime candidates to account for the hard prompt γ-ray emission observed in GRBs.

Lastly, we construct the light curves, which requires estimating the radius at which the jet originates from the central engine, which is still uncertain (Cao et al., 2023). In Figure 5, we compare the evolution of the total luminosity over time from all isomers against the luminosity specifically from the three selected isomers, displayed on a logarithmic scale. Initially, there is a notable burst in luminosity, attributed to the rapid de-excitation of isomers with lifetimes under

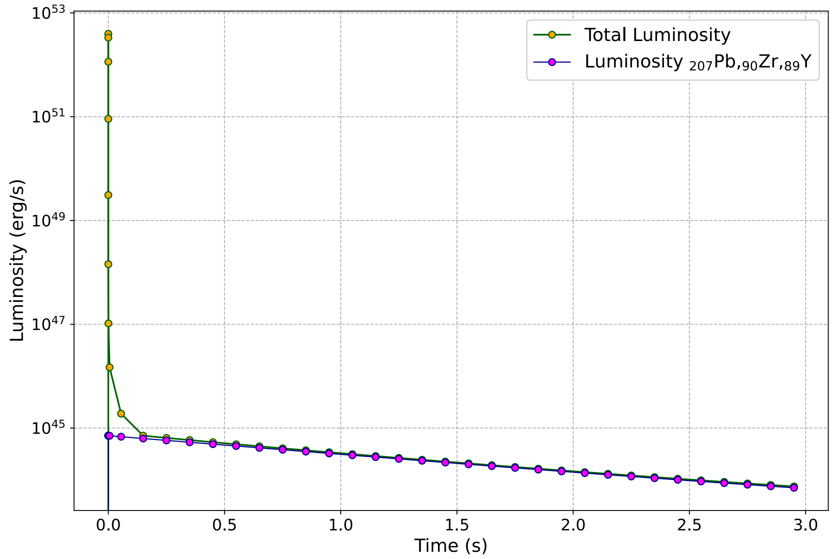

FIGURE 5
Comparison of total luminosity from all isomers against the luminosity specifically from the three selected isomers, displayed on a logarithmic scale.

1μs. However, after about 0.1s, the emission comes prominently from $_{132}$Xe and the three key isomers, $_{90}$Zr, $_{207}$Pb, and $_{89}$Y, indicating their potential significant contribution to the jet. We note that the peak luminosity emitted by the selected isomers is $L^{max}_{(Pb,Zr,Y)} \approx 7.15 \times 10^{44}$erg/s lower than that of the peak luminosity of typical GRB ($L^{max}_{GRB} \approx 10^{50}$erg/s). This value represents the 'true' luminosity of the γ-ray photons that are emitted by isomeric transitions within the jet, and no further adjustment with the beaming factor is necessary. To calculate the flux at the GRB emission (in CGS units), we adopt the assumption that the jet forms at a distance of 5×10^6cm from the central engine (Salafia et al., 2020), with a half-opening angle of $\theta_0 = 20°$ and the emission occurs once the jet extends to about 10^9cm from the central engine. By this stage, the collimation angle of the jet is approximately 6.23°, covering a surface area of $A_{jet} = 3.72 \times 10^{16}$cm^2. For these values, we obtain a peak flux of $F^{max}_{(Pb,Zr,Y)} \approx 1.92 \times 10^{28}$erg/(s · cm^2).

Our findings present an analysis of isomeric abundances and their energy spectrum within the jet. We identify the top three relevant isomers with the potential to influence GRB gamma-ray emission. By examining the luminosity and flux generated by these isomers, we provide a foundational understanding of their contribution to the prompt emission phase of GRBs. It is important to note that our calculations while not accounting for the Doppler boost, likely present an upper-bound estimate. This is because we have assumed that all elements within the jet are in isomeric states that de-excite exclusively through isomeric transitions. Additionally, we treated the ejecta as isotropic and structurally uniform, without considering the diverse components and their respective r-process element abundance. This study paves the way for deeper investigations into the complex dynamics of these cosmic phenomena.

6 Conclusion

In this study, we relied on the knowledge that neutron star mergers play a crucial role in creating elements heavier than iron through r-process nucleosynthesis. The starting point of our investigation was the binary neutron star (BNS) merger GW170817, a milestone event observed both in gravitational waves and electromagnetic radiation. The prompt gamma-ray emission spectrum of the accompanying gamma ray burst (GRB 170817A) continues to be an open question. We proposed a novel idea, namely that the γ-ray spectrum of such GRBs may include contributions from γ-ray de-excitations due to isomeric transitions.

Our research starts with a comprehensive examination of the current understanding of GRB structure, coupled with an investigation into r-process nucleosynthesis during neutron star collisions. We make a case for the addition of isomers within these astrophysical phenomena. To investigate the role played by isomeric transitions within the GRB emission, we created an interactive web page designed to facilitate a thorough analysis of their potential impact on the GRB γ-ray spectra. This platform allows for interactive data filtering, detailed visualization of radiation spectra, and light curve modeling. We began by selecting representative isomers and estimating their initial quantities, using known solar element abundances and factoring in the quantity of matter expected to influence on gamma-ray production. Subsequently, we computed the number of gamma-ray radiation events for each isomer. This data was then utilized to construct both the radiation spectrum and the light curve, tailored specifically to the time interval of GRB 170817A. We identified three isomers, $_{90}$Zr, $_{207}$Pb, and $_{89}$Y, whose abundance, de-excitation energy, and lifetime make them prime candidates for contributing to the prompt GRB spectrum. This approach provides a comprehensive method for examining the γ-ray characteristics of GRBs from similar astrophysical events.

Moving forward, our next goal is to refine our methods and compare the theoretical spectra and light curves predicted by our model against actual observations of GRBs from r-process sites. This comparison will be crucial in testing our assumptions and validating our model, thus deepening our understanding of the GRB emission spectra. In upcoming work, we plan to expand our selection of nuclear isomers to include elements lighter than strontium, and to pursue a more detailed analysis of the matter distribution and temperature in the jet. These improvements will allow us to achieve a more precise calculation of isomeric abundance in the major production sites of elements, apply our model to long GRBs, and incorporate these findings into astrophysical simulations. This last step will provide us with accurate calculations of isomeric abundance in astrophysical r-processes and will enable us to identify the precise contribution of isomeric transitions to the γ-ray signatures of GRBs, thus enhancing our understanding these astrophysical events.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://github.com/Powell222/Isomer_Search_Engine.

Author contributions

MH: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing–original draft, Writing–review and editing. JP: Data curation, Formal Analysis, Funding acquisition, Software, Writing–review and editing.

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Conflict of interest

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