

Lise Meitner

and the

Universe of Atoms

– Companion Resource Guide –

Living History • Digital Theater • Science Talk



Anna Frebel & Jen Myronuk



Lise Meitner and the Universe of Atoms – Companion Resource Guide

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Produced by STEM on Stage • www.stemonstage.org • connect@stemonstage.org

About the Program



What if a modern scientist could portray a historic moment of discovery — and then connect it to the science of today?

Lise Meitner and the Universe of Atoms is a new digital theater production created, performed and co-written by MIT astrophysicist Anna Frebel, produced by STEM on Stage.

The program features a living history portrayal of physicist Lise Meitner, set on one day in Stockholm, Sweden in early 1939. The filmed one-act play, 45 minutes, tells the story of Meitner's discovery of nuclear fission.

Frebel follows with a companion science talk, showing how Meitner's discoveries connect directly to Frebel's own research on stars and stellar archaeology, and to today's frontiers in astrophysics. The audience then joins in with questions and conversation, exploring the continuum of scientific discovery, past, present, and future.

Lise Meitner and the Universe of Atoms is a production of STEM on Stage, a humanities-based initiative exploring the history of science and innovation through living history, digital theater, and interactive media.

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This companion resource guide extends the digital theater experience with additional resources and information.

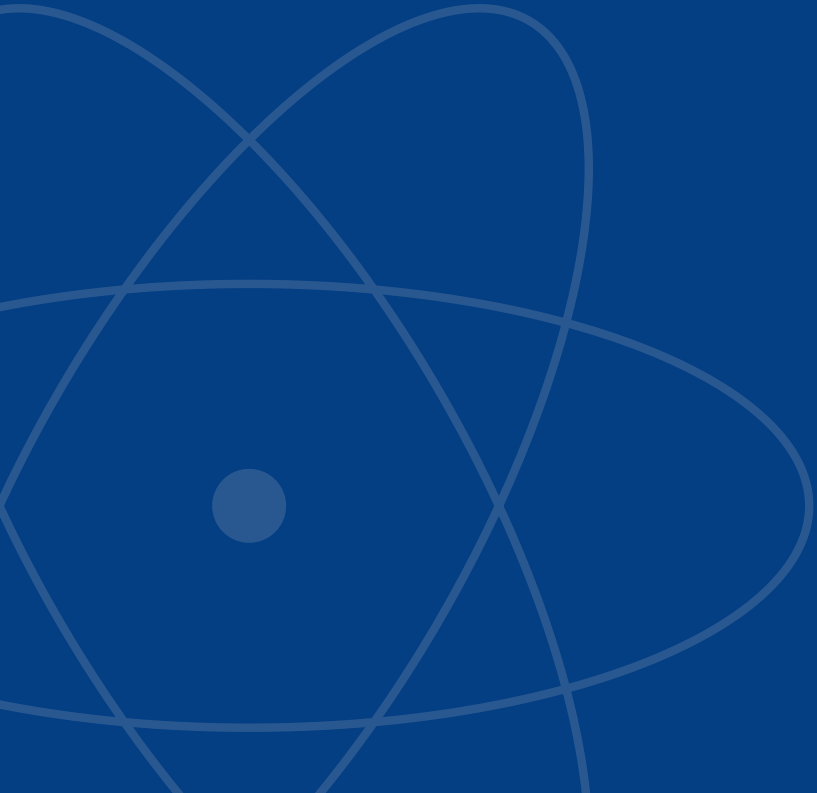
This program is supported by the National Science Foundation under grant AAG-2307436.



PART ONE

Living History & Digital Theater

Recreating scientific discovery on stage





*"Life need not be easy, provided
only that it is not empty."*

– Lise Meitner

(1878 - 1968)

Living History Theater



Living History Theater Production Credits

Created & Performed by
Anna Frebel

Produced & Directed by
Jen Myronuk

Co-Written by
Anna Frebel & Jen Myronuk

Living History Scholar
Susan Marie Frontczak

***Lise Meitner and the Universe of Atoms* is a living history presentation centered on Lise Meitner's pioneering scientific explanation of nuclear fission, one of the great discoveries of modern physics.**

Set on January 14, 1939, exiled in Stockholm after escaping Germany, Meitner reflects on her journey from being a curious child in Vienna to a groundbreaking theoretical physicist in Berlin. She recounts her long collaboration with chemist Otto Hahn and the puzzling experiments that challenged everything scientists understood about the atom.

At the center of the story is Meitner's Christmas 1938 walk in the snow with her nephew, physicist Otto Robert Frisch.

With scraps of paper, a pencil, and her knowledge of physics, Meitner calculated what had seemed impossible: the uranium nucleus had split. Meitner and Frisch soon published the theoretical explanation and gave the process its name: nuclear fission.

A story of scientific brilliance, courage, and discovery, *The Universe of Atoms* reveals how Meitner helped transform our understanding of matter itself.

Performing Science

Over the years on this production journey, I've been asked: *what is it like to portray a historic scientist?*

As an astronomer, nuclear astrophysicist, and science communicator working on the origins of the elements, I've been able to draw on my position as a modern scientist to portray a historic nuclear physicist with accuracy.

Lise Meitner's foundational work made possible the field of nuclear astrophysics, and my own scientific work today: the quest to understand the origins of the heaviest elements in the periodic table.



Anna Frebel, PhD.

Lise and I share this passion, though we take very different approaches in two very different time periods. Lise Meitner and the Universe of Atoms is our way of sharing the scientific method: grounded in facts, driven by the excitement of real discovery, the kind of research that's accessible, and enjoyable, for everyone.

The play spans the distance between past and present, showing science as a communal, peer-reviewed enterprise that builds on the work of earlier generations.

Above all, I want to make science and scientists approachable. I'm inviting you, the audience of every age, to imagine such work for yourself, so you can say, "I could be a scientist, too."

Whether it marks the start of a scientific path or simply a deeper understanding of how science works, I hope everyone comes away from this digital theater performance having stood just a little closer to a moment of human discovery.

Anna Frebel, Creator, Performer & Co-Writer

Lise Meitner and the Universe of Atoms

Background



Susan Marie Frontczak and Anna Frebel, Cambridge Science Festival, 2016

The inspiration for this production began with a different scientist entirely. In 2016, Anna Frebel attended scholar and playwright Susan Marie Frontczak's living history portrayal of **Marie Curie** in *Humanity Needs Dreamers: A Visit With Marie Curie* at the Cambridge Science Festival.

Intrigued by this form of storytelling, Frebel later approached Frontczak and producer/director Myronuk if another pioneering nuclear physicist of the same era could be portrayed: **Lise Meitner**.

Encouraged to take on the role herself, Frebel and Myronuk co-wrote a 15-minute living history monologue set in early 1939. Produced by STEM on Stage under the name *Pursuit of Discovery*, Frebel performed the short play live by reading Meitner's recreated letters and lab books. Several public events were produced from 2017 to 2025 as a work-in-progress.

SELECTED WORK-IN-PROGRESS PERFORMANCES OF “PURSUIT OF DISCOVERY”

NerdNite, Washington, DC – Oct 2017

SciTech Museum, Perth, Australia – Dec 2017

Cambridge Science Festival, MA – Apr 2018

Auburn University, Auburn, AL – Apr 2023

Cambridge Science Festival, MA – Apr 2024

The Foundry, Cambridge, MA – Mar 2025

During 2025, Frebel and Myronuk co-wrote a new, extended script designed for filming the play as digital theater. STEM on Stage produced a live preview performance at The Foundry Cambridge on March 14, 2025 in celebration of Pi Day.



Live preview performance and science talk on March 14, 2025 at The Foundry in Cambridge, MA.

Video Production



During Fall of 2025, the Lise Meitner production was brought into the studio for taping.

Led by producer and director Jen Myronuk, the filmed production featured the same materials that shaped Meitner's own world—her many letters and her lab books— capturing Frebel's performance while preserving the accuracy and immediacy of Meitner's voice.

Rather than a single filmed recording of a stage play, the in-studio production at ACMi Studios was specifically designed as digital theater. In lieu of memorizing a script, Anna Frebel was assisted by two teleprompters while performing. **This unique approach allows a scientist to step into a history role with confidence and success.**



Anna Frebel on set; Meitner's letters and lab books on a table.



Anna Frebel on set with producer & director Jen Myronuk.



In studio taping of the production in October 2025 at ACMi Studios in Arlington, MA. The production integrated the use of letters, lab books and teleprompters to support Frebel's portrayal of Lise Meitner.

EVENT · NOVEMBER 8, 2025

Debut Screening at MIT

The debut digital theater screening of *Lise Meitner and the Universe of Atoms*, followed by Anna Frebel's live science talk, was hosted by the MIT Kavli Institute for Astrophysics and Space Research on November 8, 2025, in Cambridge, Massachusetts.

This presentation also celebrated the shared birthday of Lise Meitner and Marie Curie, who were both born on November 7th, eleven years apart — in 1878 and 1867, respectively.



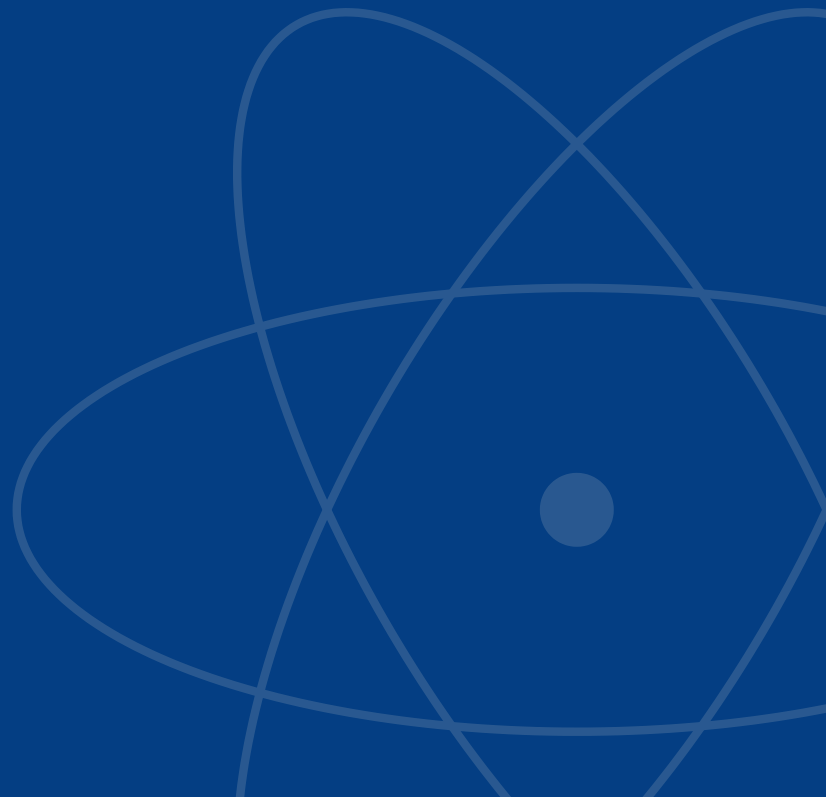
Debut of *Lise Meitner and the Universe of Atoms* and science talk, hosted at MIT, on November 8, 2025.



PART TWO

Biography: Physicist Lise Meitner

1878 - 1968



Timeline

IN HER OWN WORDS

“Science makes people reach selflessly for truth and objectivity; it teaches people to accept reality, with wonder and admiration, not to mention the deep awe and joy that the natural order of things brings to the true scientist.” – Lise Meitner



Portrait of Lise Meitner



A young Lise Meitner



Lise Meitner, circa 1960s

- 1878** Born November 7th in Vienna, third of eight children in a large Jewish family.
- 1905** Earns a physics doctorate at the University of Vienna, only the second woman to do so.
- 1907** Moves to Berlin; begins her collaboration with Otto Hahn.
- 1917** Co-discovers the element protactinium (element 91) with Hahn.
- 1926** Becomes the first woman in Germany to hold a full professorship in physics.
- 1938** Becomes stateless after the annexing of Austria and targeted for being Jewish, Meitner barely escapes Germany, exiled to Stockholm, Sweden.
- 1938** Calculates and discovers nuclear fission with nephew Otto Robert Frisch over Christmas in Kungälv.
- 1939** Meitner and Frisch publish their explanation in *Nature* naming the process “fission.”
- 1944** The Nobel Prize in Chemistry goes to Hahn alone; Meitner is omitted.
- 1966** Shares the U.S. Fermi Award with Hahn and Strassmann.
- 1968** Dies on October 27th in Cambridge, England, aged 89.
- 1997** Element 109 is named meitnerium in her honor.

Lise Meitner

Vienna: An early love of learning

Elise “Lise” Meitner was born in Vienna on November 7, 1878, the third of eight children in a cultured, freethinking Jewish family that shared a love of books, music, and learning. Her father, one of the first Jewish lawyers admitted to practice in Austria, encouraged all of his children—sons and daughters—to think for themselves.

But curiosity alone could not open doors. Girls were banned from further study, and their formal education ended at fourteen. Meitner's path to physics did not open until she was in her 20s when Austria admitted women to its universities.



Lise Meitner as a young woman studying at the University of Vienna.

Meitner compressed eight years of university preparation into two years of intense private study in order to take the university entrance examination. Of the fourteen young women who took it, only four passed, Meitner among them.

At 23, she entered the University of Vienna in 1901 and devoted herself entirely to science. She chose to study under the renowned theoretical physicist Ludwig Boltzmann whose lectures she called “the most beautiful and stimulating” she ever heard. In 1905, she became only the second woman to earn a doctorate in physics.

Berlin: Finding her scientific home

Radioactivity was an exciting new frontier at the time. Inspired by the discoveries of Marie and Pierre Curie, and the Vienna guest lectures by Max Planck, Meitner moved to Berlin in 1907. She set out to join the growing scientific community in Germany, intending to stay only for a limited time. But instead, Berlin became her new adopted home for the next thirty years. In Berlin, as a physicist, she began a lifelong collaboration with the chemist Otto Hahn. Finally, in 1912, Meitner received her first salaried post, at the newly founded Kaiser Wilhelm Institute for Chemistry.



Lise Meitner in her Berlin laboratory.

During the First World War, she served as an X-ray technician in field hospitals. When she returned to the laboratory, while the Great War continued, Meitner and Hahn identified a new element in 1917. Protactinium—element 91— which filled a long-empty gap in the Periodic Table.

In recognition of this discovery, in 1926, Meitner became the first woman in Germany to hold a full professorship in physics.

Stockholm: Escape into exile

When Germany annexed Austria in March 1938, she became stateless. As a scientist of Jewish descent, she was now in danger and forbidden to travel. She was urged to leave to Berlin.

In July 1938, with the quiet help of Dutch and Danish colleagues, she escaped across the border into the Netherlands carrying little more than hand luggage. She eventually reached Stockholm as a scientist in exile. At nearly 60 years old, she was forced to rebuild her life and research.

Kungälv: The walk in the snow

Her scientific collaboration with Hahn continued through frequent letters. For several years, they had been bombarding uranium with neutrons, searching for new elements heavier than uranium, the transuranian elements.

In December 1938, Hahn and the chemist Fritz Strassmann found something in Berlin they could not explain: their experiments pointed not to a heavier element but to barium, barely half the mass of uranium. It seemed impossible. Baffled, Hahn wrote to Meitner in Stockholm: “Perhaps you can suggest some fantastical explanation.”

No. 3615, FEB. 11, 1939

NATURE

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Letters to the Editor

The Editor does not hold himself responsible for opinions expressed by his correspondents. He cannot undertake to return, or to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. No notice is taken of anonymous communications.

NOTES ON POINTS IN SOME OF THIS WEEK'S LETTERS APPEAR ON P. 247.

CORRESPONDENTS ARE INVITED TO ATTACH SIMILAR SUMMARIES TO THEIR COMMUNICATIONS.

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

On bombarding uranium with neutrons, Fermi and collaborators¹ found that at least four radioactive substances were produced, two of which atomic numbers larger than 92 were ascribed. Further investigations² demonstrated the existence of at least nine radioactive periods, six of which were assigned to elements beyond uranium, and nuclear isomerism had to be assumed in order to account for their chemical behaviour together with their genetic relations.

In making chemical assignments, it was always assumed that these radioactive bodies had atomic numbers near that of the element bombarded, since only particles with one or two charges were known to be emitted from nuclei. A body, for example, with similar properties to those of osmium was assumed to be eka-osmium ($Z = 94$) rather than osmium ($Z = 76$) or ruthenium ($Z = 44$).

Following up an observation of Curie and Savitch³, Hahn and Strassmann⁴ found that a group of at least three radioactive bodies, formed from uranium under neutron bombardment, were chemically similar to barium and, therefore, presumably isotopic with radium. Further investigation⁵, however, showed that it was impossible to separate these bodies from barium (although mesothorium, an isotope of radium, was readily separated in the same experiment), so that Hahn and Strassmann were forced to conclude that isotopes of barium ($Z = 56$) are formed as a consequence of the bombardment of uranium ($Z = 92$)

that the surface tension of a charged droplet is diminished by its charge, and a rough estimate shows that the surface tension of nuclei, decreasing with increasing nuclear charge, may become zero for atomic numbers of the order of 100.

It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size (the precise ratio of sizes depending on finer structural features and perhaps partly on chance). These two nuclei will repel each other and should gain a total kinetic energy of *c.* 200 Mev., as calculated from nuclear radius and charge. This amount of energy may actually be expected to be available from the difference in packing fraction between uranium and the elements in the middle of the periodic system. The whole 'fission' process can thus be described in an essentially classical way, without having to consider quantum-mechanical 'tunnel effects', which would actually be extremely small, on account of the large masses involved.

After division, the high neutron/proton ratio of uranium will tend to readjust itself by beta decay to the lower value suitable for lighter elements. Probably each part will thus give rise to a chain of disintegrations. If one of the parts is an isotope of barium⁶, the other will be krypton ($Z = 92 - 56$), which might decay through rubidium, strontium and yttrium to zirconium. Perhaps one or two of the supposed barium-lanthanum-cerium chains are then actually strontium-yttrium-zirconium chains.

Over her Christmas vacation in the Swedish village of Kungälv, Meitner puzzled over Hahn's letter, together with her nephew, the young physicist Otto Robert Frisch.

On a morning walk together in the snow, answers took shape between them.

Meitner calculated how the uranium atom had split into barium and krypton.

Meitner, Lise, and Frisch, O. R., 1939, Nature. "Disintegration of Uranium by Neutrons: A New Type of Nuclear Reaction."

They realized the enormous energy released came from the mass lost in the process, a difference they could account for using Einstein's famous equation relating mass and energy. When Meitner and Frisch wrote up the explanation, they borrowed a term from biology — from the way a living cell divides — and called it "fission." Their short paper appeared in the British journal *Nature* on February 11, 1939, giving the world both the physics and the name of nuclear fission.

Within weeks, laboratories around the world had confirmed it, and Meitner and Frisch followed up with a second paper reporting the experimental evidence behind their theory that Frisch had obtained in his lab. Together, these two papers turned a puzzling laboratory anomaly into an established physical process, laying the theoretical groundwork for continued research.



Lise Meitner, lecturing at Catholic University, Washington, D.C., 1946.

Recognition and Legacy

Lise Meitner was sixty years old when she explained nuclear fission, an achievement made in exile, cut off from her laboratory and her life's work in Berlin. She remained in Sweden in the years that followed, continuing her research under difficult conditions.

Full recognition, however, eluded her. In 1944 the Nobel Prize in Chemistry was awarded to Otto Hahn alone for the discovery of fission, despite their decades of partnership and their joint nominations. Meitner, who had supplied the physical explanation of what Hahn's chemistry experiments had found, did not share it.

Over her lifetime, she was nominated for the Nobel Prize 49 times (30 for physics and 19 for chemistry), yet she was never selected. It stands among the most

discussed omissions in the history of the Prize.

Honor came in other forms. In 1946, she traveled to the United States, where the Women's National Press Club named her Woman of the Year, an award presented at a dinner attended by President Truman. She spent a semester as a visiting professor in Washington, D.C., and toured prominent universities along the East Coast, lecturing to packed halls and mentoring and advising younger scientists.

In 1949, she received the Max Planck Medal, Germany's highest award in theoretical physics, together with Hahn. In 1966, the United States presented her with the Enrico Fermi Award, shared with Hahn and Fritz Strassmann. She was the first woman ever to receive it.



Lise Meitner mentoring young scientists.

In 1960, at the age of 81, she moved to Cambridge, England, to be near her nephew, physicist Otto Robert Frisch, with whom she had gone on that Christmas walk in the snow and who was now a professor at Trinity College.

Meitner died on October 27, 1968, just days short of her 90th birthday. Frisch chose the words carved on her gravestone: “Lise Meitner: a physicist who never lost her humanity.”

In 1997, the newly created synthetic element 109 was named Meitnerium (Mt) in her honor. Only two women, Meitner and Marie Curie, have since had their names written into the periodic table.

In 2023, decades after her death, astronomers found the first evidence of nuclear fission occurring in nature. By analyzing the abundances of heavy elements in ancient stars, they identified a signature of fission fragments produced during a heavy element production event when two neutron stars merged.

The process Meitner explained on a scrap of paper in the Swedish snow continues to contribute to our understanding of heavy element formation in the universe.

*“Lise Meitner: a physicist
who never lost her humanity.”*

HER EPITAPH,
WRITTEN BY OTTO ROBERT FRISCH

109

Mt

Meitnerium

278



PART THREE

Behind the Science: Nuclear Fission

What fission is and how Lise Meitner explained it

Meitner's Discovery: Nuclear Fission

Lise Meitner and Otto Hahn set out to discover elements heavier than Uranium. They wanted to understand why such heavy elements had not yet been found.

In their experiments, they bombarded Uranium, consisting of 92 protons and 146 neutrons, with neutrons in the hopes of creating even heavier, “trans-uranian” elements.

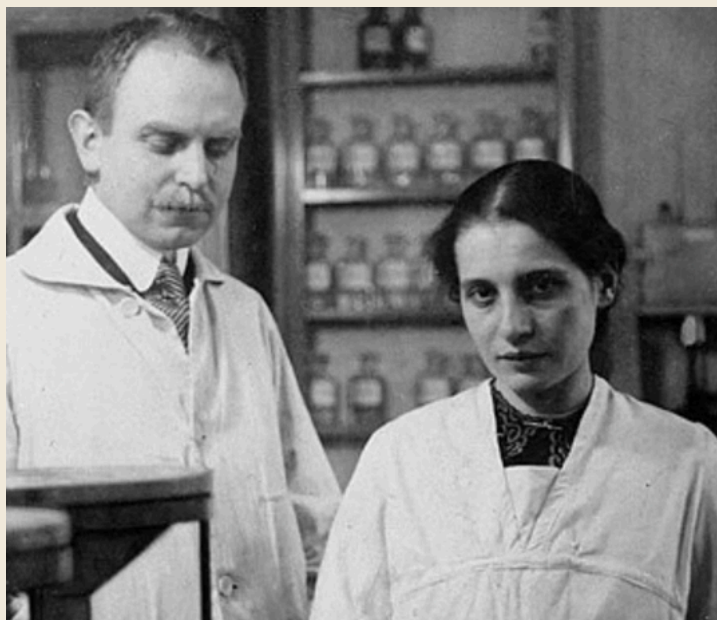
Rather, Hahn found the lighter element Barium to be the outcome – a puzzling observation.

When Meitner, together with her nephew Otto Robert Frisch, explained how and why Barium was, in fact, the correct result, she had discovered fission.

Nuclear fission is the process when a heavy atomic nucleus splits into two lighter ones and releases a large burst of energy.

Instead of a new stable heavy element, they encountered a natural limitation: elements heavier than Uranium are simply too large to be stable, and hence, cannot exist like the other known elements.

Following this discovery, Meitner, immediately predicted that Krypton should also be made in the fission process. The subsequent experimental observation of Krypton by Frisch confirmed Meitner’s breakthrough explanation and that heavy elements must split into two lighter nuclei.

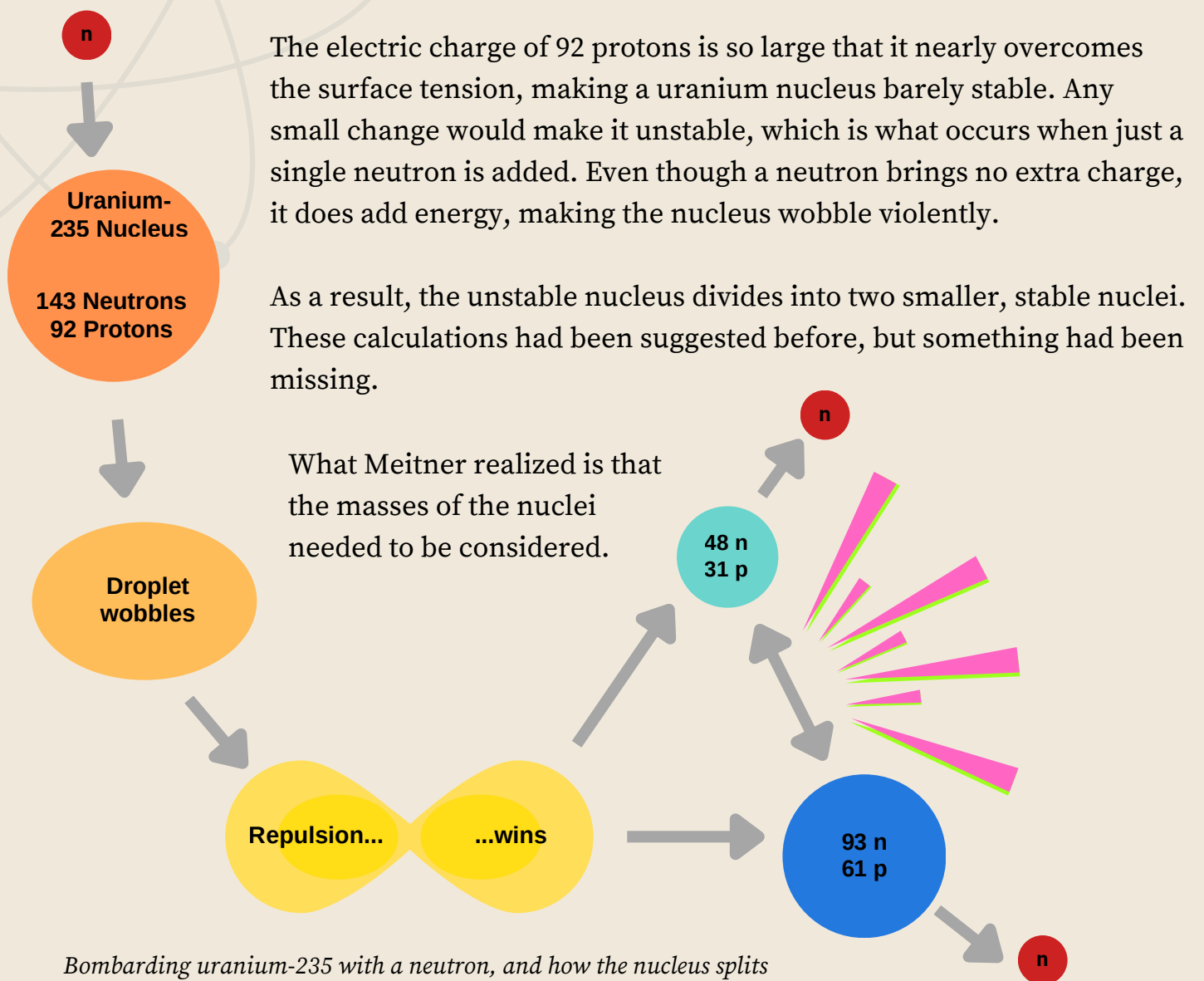


Lise Meitner and Otto Hahn in a laboratory at Emil Fischer's Chemistry Institute in Berlin. 1909. Visual: The Papers of Lise Meitner, Churchill Archives Centre.

A Fantastical Explanation

During her walk in the snow with Frisch, Meitner pictured the nucleus as a liquid droplet, an idea put forward by Niels Bohr. According to Bohr's model, an atomic nucleus is not solid but fluid, held together like a drop of water by surface tension. When bombarded by a neutron, such a drop can elongate, wobble, and eventually divide in two.

She then considered the electric charge of uranium and how it could affect the stability of the nucleus upon bombardment. The atomic number, set by the number of protons, defines the nucleus's charge, since protons are positively charged. That charge drives the electrical repulsion straining against the surface tension holding the nucleus together.



She invoked an empirical formula for calculating nuclear masses that relates a nucleus' size, charge, and the forces that bind it together. The task at hand was to compare the mass of uranium with the combined mass of barium and a plausible second fragment, for which she chose Krypton.

The total mass of Barium and Krypton was a tiny bit less than that of uranium.

Using Einstein's equation $E = mc^2$, she could convert that small mass difference into energy.

The mass was not lost; it was transformed into energy.



Uranium-235 weighs slightly more than Barium-141, Krypton-92 and two neutrons combined.

This led to her immediate prediction: when a Uranium nucleus with 92 protons divides into two parts, and one of them is Barium with 56 protons, then the leftover nucleus must have 36 protons, Krypton.

The proof came about two weeks later, when Frisch indeed observed Krypton in his university physics lab in Denmark. The uranium nucleus had split, and energy was produced.

Meitner showed that just one such fission reaction yields the enormous amount of energy of 200 Mega electron Volts (MeV) – by atomic standards. For comparison, the energy released by a single chemical reaction is 1 to 5 electron Volts (eV) per molecule or atom.

With her calculation came the realization that stable heavier elements could simply not exist in nature.

"No one really thought of fission before its discovery." – Lise Meitner



PART FOUR

Science Talk: Cosmic Origins of the Elements

Where does nuclear fission occur in the universe?

Stellar Archaeology

The oldest stars in the Milky Way are nearly as old as the universe itself. Formed about 12–13 billion years ago, these ancient stars preserve in their atmospheres the chemical composition of the gas clouds from which they were born. Like fossils embedded in rock layers, they provide a direct record of the nucleosynthesis events that produced elements within the first billion years after the Big Bang.

By dispersing starlight into a spectrum, astronomers can measure the abundances of dozens of chemical elements in stars. In this way, the oldest stars serve as cosmic time capsules, allowing us to reconstruct the earliest chapters of chemical evolution.

Frebel's research focuses on discovering and analyzing these ancient stellar relics, identifying the first generations of stars, understanding the origin of the heaviest elements, and tracing how the Milky Way was chemically enriched and assembled over cosmic time.

While nuclear astrophysics investigates the physical processes that create the elements, stellar archaeology seeks to uncover when and where those processes occurred in the early universe. This is Professor Anna Frebel's research, based on spectroscopic data obtained with the world's largest telescopes.



Nuclear Astrophysics

A century ago, scientists such as Marie Curie and Lise Meitner asked what the heaviest elements could be and where they might come from.

Today it is known that uranium is the heaviest long-lived element. Everything heavier simply cannot be held together by the forces that govern the atomic nucleus. The question remains: where do the heavy elements –from Gallium to Uranium– in the bottom half of the Periodic Table come from?

The field of nuclear astrophysics seeks to connect the smallest scales –atoms– with the largest –stars and galaxies– to understand how all the chemical elements are created across the universe. Current research focuses on how atomic nuclei collide and react with each other inside stars, supernova explosions, and neutron star mergers. It is in these energetic astrophysical sites that

all the elements from carbon to uranium are forged.

other inside stars, supernova explosions, and neutron star mergers. It is

in these energetic astrophysical sites that

all the elements from carbon to

uranium are forged.

1 H Hydrogen 1.0078																	2 He Helium 4.0026		
3 Li Lithium 6.9410	4 Be Beryllium 9.0122													5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305													13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.380	31 Ga Gallium 69.723	32 Ge Germanium 72.640	33 As Arsenic 74.922	34 Se Selenium 78.960	35 Br Bromine 79.904	36 Kr Krypton 83.798		
37 Rb Rubidium 85.468	38 Sr Strontium 87.620	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.950	43 Tc Technetium 98	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.90	54 Xe Xenon 131.29		
55 Cs Caesium 132.91	56 Ba Barium 137.33	57 La Lanthanum 138.91	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.84	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.20	83 Bi Bismuth 208.98	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222		
87 Fr Francium 223	88 Ra Radium 226	89 Ac Actinium 227	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 269	107 Bh Bohrium 264	108 Hs Hassium 269	109 Mt Meitnerium 278	110 Ds Darmstadtium 281	111 Rg Roentgenium 282	112 Cn Copernicium 285	113 Nh Nihonium 286	114 Fl Flerovium 289	115 Mc Moscovium 289	116 Lv Livermorium 293	117 Ts Tennessine 294	118 Og Oganesson 294		
			58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium 145	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.5	67 Ho Holmium 164.93	68 Er Erbium 167.27	69 Tm Thulium 168.93	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.97			
			90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium 237.05	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 252	100 Fm Fermium 257	101 Md Mendelevium 257	102 No Nobelium 259	103 Lr Lawrencium 262			

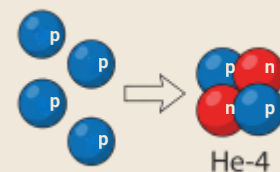
Periodic Table of the elements.

Periodic Table of
the elements.

The field of nuclear astrophysics seeks to connect the smallest scales, atoms, with the largest, stars and galaxies, to understand how all the chemical elements are created across the universe.

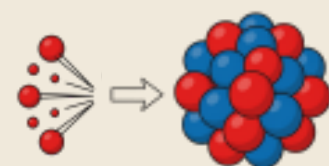
How Elements Are Formed

Lighter elements up to iron are made through fusion processes in the cores of stars during their lives and when they explode as supernovae. Energy is gained by fusing two lighter nuclei into one heavier one.



Fusion of lighter nuclei leads to heavier elements.

Fusing any of the heavier elements beyond Iron, including Silver, Gold, Platinum, and all the way to Uranium, would require energy. Instead, they are built up, within seconds, when existing nuclei are bombarded with countless neutrons. This rapid (r-) neutron-capture process occurs in merging neutron stars when a strong neutron flux occurs during the collision. Fission plays a role: arbitrarily heavy stable elements cannot be made, so fission enforces the limits of stable element creation.



Neutron-capture to build up heavier elements.

This is where Professor Anna Frebel picks up Meitner's thread: by studying the elemental compositions preserved in the oldest stars, she traces where and how these elements were created in the early universe. It is the origin of the “star stuff” we are all made from.

By combining astronomical telescope observations, laboratory accelerator experiments, and theoretical nucleosynthesis calculations, physicists and astronomers continue in Meitner's quest to learn about elements and their formation across the cosmos.



The twin Magellan telescopes in Chile, each equipped with a 6.5 meter mirror. The bright center of the Milky Way towers above the telescopes. The bright spots on the left telescopes are star light reflections.

Signature of Nuclear Fission, Found in Stars

In 1939, Lise Meitner explained a process nobody had imagined: that a heavy nucleus could split into two pieces. In the decades since, fission has been studied in laboratories and reactors here on Earth to better understand its conditions and consequences. But in the cosmos, it turns out, fission has been operating all along, as part of the rapid (r-) process that creates the heaviest elements in the Periodic Table.

When two small, dense orbiting neutron stars collide, an enormous amount of neutrons are set free. Existing lighter nuclei are bombarded with neutrons so quickly that, within seconds, extremely neutron-rich, unstable nuclei are built up. Once the neutron flux stops, these nuclei decay into stable atoms, releasing energy in the form of fast photons. That leads to a powerful glowing aftermath – observed by astronomers as a so-called Kilonova that shines for several weeks.

During the collision, the heaviest neutron-rich nuclei do exactly what Meitner described: they split. Not just one nucleus is splitting, but astronomical numbers of them. The merger itself marks one of the most extremes cosmic explosions and fission shapes the production of certain lighter stable elements.

In 2023, a team of astronomers around Anna Frebel found the fingerprints of fission written in ancient stars. Studying the heavy-element abundances of old stars that formed from gas previously enriched by one of these neutron star mergers, the team identified a distinctive pattern for the first time: certain element abundances were slightly larger than anticipated.

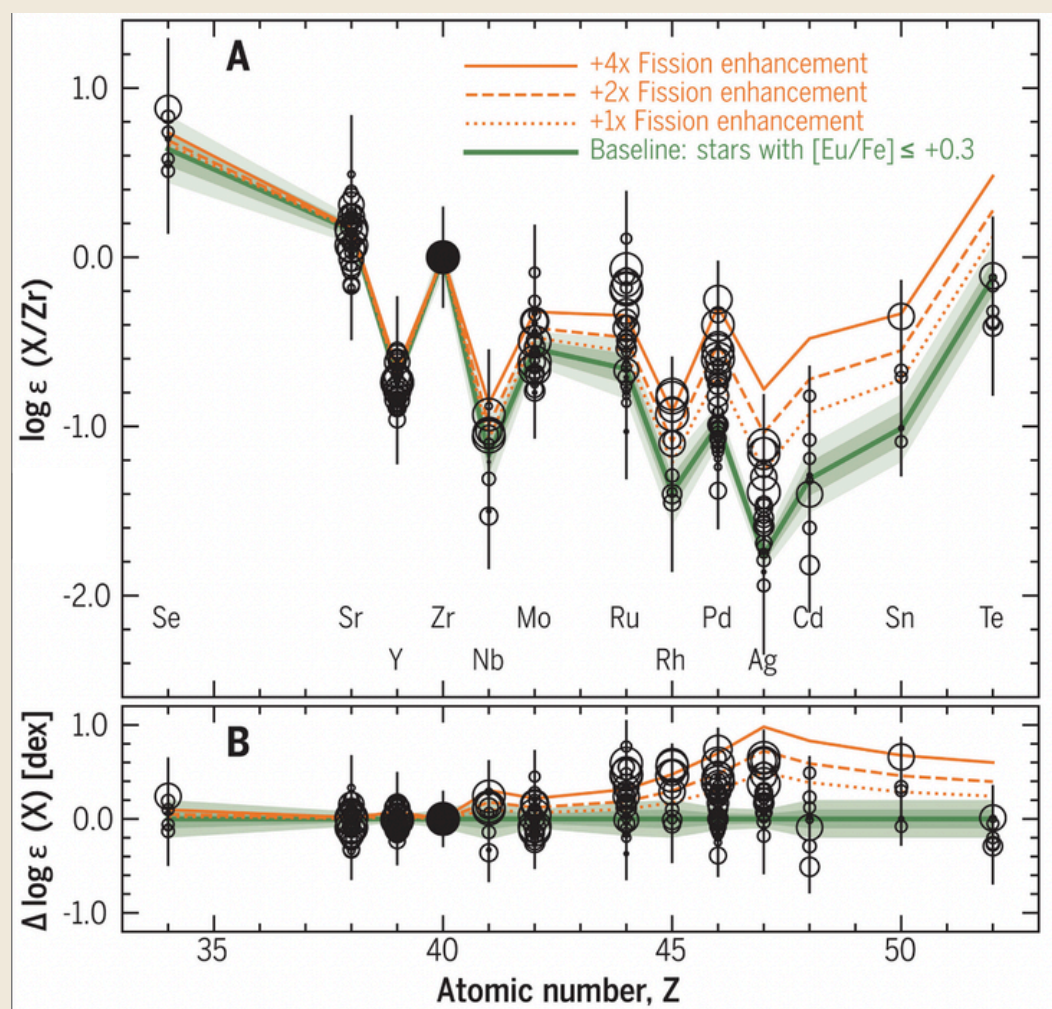
Meitner's discovery, calculated with just a pencil on a walk in the snow, is not a closed chapter. The story of the heaviest elements is still unfolding, most recently in the light of stars nearly as old as the universe.

Element Abundance Patterns in Stars

Using very detailed spectroscopic data from the Hubble Space Telescope, the astronomers found a small observed excess of the elements Ruthenium ($Z=44$), Rhenium ($Z=45$), Palladium ($Z=46$), Silver ($Z=47$) and Cadmium ($Z=48$). The little “extra” in the abundances of these elements, implies that a process in addition to the contribution from the direct r-process must have contributed those elements to the stars' birth gas cloud.

The astronomers then theoretically modeled the effects of fission as part of the r-process and the production of heavy elements. The excess is consistent with these elements being fission fragments of nuclei heavier than uranium.

This marks the first evidence that fission is naturally occurring in stars. It also contributes to our understanding of how each element is made across the universe.



Comparison of elemental abundance data of 42 ancient stars with fission model predictions. The abundances of Ru, Rh, Pd, Ag, and Cd are slightly higher than the baseline model (green line) suggests. This excess has been modeled with a fission contribution (orange lines) which matches the data.

Figure taken from Roederer et al., “Element abundance patterns in stars indicate fission of nuclei heavier than uranium,” 2023, *Science* 382, 1177

Group Discussion Topics

Use these prompts after the screening, in class, or at the kitchen table – in small groups or by yourself. There are no single right answers; the goal is to think, discuss and collaborate to explore the inquiry itself.

1 • THE ANALOGY

Meitner compared the nucleus to a wobbling drop of liquid. Why is a good analogy so useful in science? Where does this one break down?

2 • CREDIT AND FAIRNESS

Meitner was left off the Nobel Prize for a discovery she helped make. Why does it matter who gets credit in science? Who might be overlooked today?

3 • LETTERS AS LABORATORY

Meitner solved the puzzle by post, hundreds of miles away from the experiment. What does that tell you about how science actually gets done?

4 • PAST AND PRESENT

A modern scientist plays a historic one. What can a working physicist teach you about Meitner that a professional actor might not be able to show you?

Explore More: Activities

Find Meitnerium

Look up element 109 in the Periodic Table. Note its neighbors, every one of them named for a person or a place. What are their stories? Whose names are missing?

Weigh the difference

Look up the masses of Uranium-235, Barium-141 and Krypton-92. Add the masses of the fragments, subtract them from the Uranium mass. The difference times c^2 is the energy Meitner calculated.

Read the gold in your hand

Find one gold or silver object nearby. Every atom in it was forged in a neutron star collision billions of years ago. Share this cosmic journey with family and friends.

Further Resources

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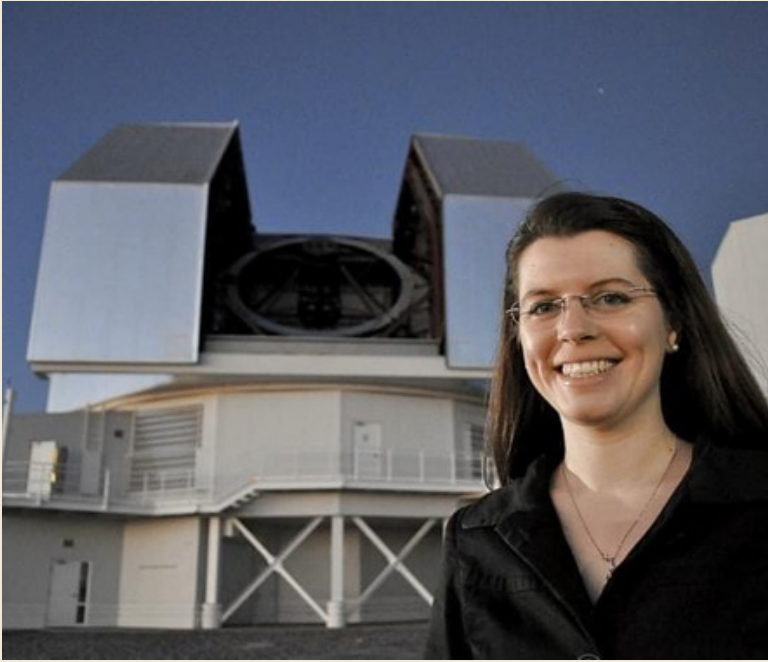
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Anna Frebel



Anna Frebel, PhD, is an observational astronomer and Professor of Physics at the Massachusetts Institute of Technology. She also heads the Astrophysics Division.

Frebel received her PhD from the Australian National University's Mt. Stromlo Observatory in 2007, and did postdoctoral work as a WJ McDonald Fellow in Austin, TX (2006-2008) and as Clay Fellow at the Center for Astrophysics | Harvard & Smithsonian (CfA), in Cambridge, MA (2009-2012).

Frebel has received numerous honors and awards including the 2010 Annie Jump Cannon Award (American Astronomical Society), a 2013 CAREER Award from the National Science Foundation, and in 2016 she was named one of ScienceNews Magazine's "Ten Scientists to Watch". In 2022, she was elected Fellow of the American Physical Society. She was promoted to Associate Professor with tenure in 2018 and to full Professor in 2022.

Frebel has authored more than 200 papers in various refereed journals, including *Nature* and *Science*. She enjoys communicating science to the public through regular public lectures, magazine articles, interviews as well as her popular science book "*Searching For The Oldest Stars: Ancient Relics from the Early Universe*" (Princeton University Press). Since 2016, Frebel has portrayed physicist Lise Meitner on stage and in an accompanying digital theater production to bring the discovery process to a wider audience.

She also teaches STEM Leadership and Professional Strategies to grad students, postdocs and faculty at MIT as well as STEM professionals to empower them in their career journeys.

www.annafrebel.com

Jen Myronuk

Jen Myronuk is a public humanities producer focused on bringing the history of science to life through digital theater and interactive storytelling.

As co-founder and creative director of STEM on Stage, a humanities-based initiative advancing stories of science through living history and digital theater, her productions have been presented at science festivals, museums, libraries, schools, and universities.



She produced and directed the living history digital theater productions *Humanity Needs Dreamers: A Visit With Marie Curie* and *Lise Meitner and the Universe of Atoms*, both part of NSF-supported outreach programs. Meitner was developed in collaboration with Anna Frebel (MIT Department of Physics) and Curie with Susan Marie Frontczak (Storysmith.org) and Daniel Steinberg (Princeton Center for Complex Materials).

Her STEM public outreach work also includes *Pop! Astronomy* and *Pop! Astronomy Explorer*. Her latest production, *Through Field and Woodland: The Legacy of Alice Rich Northrop Memorial Camp*, is an oral history documentary exploring place, memory, and seven decades of a nature camp in the Berkshire Mountains of Western Massachusetts, named after notable botanist and Hunter College professor Alice Rich Northrop.

She serves on the board of Design With Us, a nonprofit empowering youth with disabilities to explore their lived experiences through design and innovation.

www.stemonstage.org

Susan Marie Frontczak

Susan Marie Frontczak is a scholar, playwright, and living history performer who has spent more than two decades bringing history and literature to life on stage. Through Storysmith®, she has created and performed some ten different living history programs across more than forty U.S. states and nine countries.

Frontczak is best known for her acclaimed living history portrayal of Marie Skłodowska Curie, presented over 600 times, as the one-woman stage show *Manya: The Living History of Marie Curie*, and as digital theater *Humanity Needs Dreamers: A Visit With Marie Curie*, produced by STEM on Stage.



Susan Marie Frontczak as Marie Curie

Frontczak came to performance from an earlier career in engineering, a B.S. from Swarthmore College, a master's in software engineering, and fourteen years at Hewlett-Packard before turning to writing and performing full time.

She has also trained a generation of living history scholars in the Chautauqua tradition through Colorado Humanities Young Chautauqua program.

For *Lise Meitner and the Universe of Atoms*, Frontczak served as living history scholar and script consultant, lending her many years of living history expertise.

www.storysmith.org
www.humanityneedsdreamers.org

Digital Theater Production Credits



Lise Meitner and the Universe of Atoms

Created & Performed by
Anna Frebel

Produced & Directed by
Jen Myronuk

Co-Written By
Anna Frebel & Jen Myronuk

Living History Scholar
Susan Marie Frontczak

Costume
Anna Frebel

Camera
Stuart Roelke
Michael Bosik

Sound
Iasmina Birleanu

Post Production
Jen Myronuk

ACMi Studios
Arlington, MA



Acknowledgements

We want to extend a heartfelt Thank You to our production team and the ACMi Studios, Arlington, MA, for the studio time, and their wonderful staff of volunteers.

With special thanks to Susan Marie Frontczak, Melanie Wallace, and David Kaiser for their guidance, input and support during script development, and Harry Mattison for photography during the shoot. We are grateful to our families and friends who have supported this project and the community who has participated in our live presentations.

We thank the *MIT Kavli Institute for Astrophysics and Space Research* and Erika Reinfeld for hosting the debut screening event on November 8, 2025.

This program was supported by the MIT Department of Physics, and the National Science Foundation (under NSF-AAG 2307436).



**Sign up to learn more about opportunities to bring
Lise Meitner and the Universe of Atoms as a digital
theater screening with a science talk and Q&A
to your school, museum, festival or university.**

**Email: connect@stemonstage.org
www.stemonstage.org**