Lise Meitner and O. R. Frisch (1969), *Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction*, Nature, 224, Nov. 1

https://www.nature.com/articles/224466a0 This version is a reprint in Nature in 1969 but looks cool – all refernces to page and column refer to this version. An easier to read version can be found here http://www.ymambrini.com/My_World/Physics_files/Meitner%20Frisch.pdf

The paper is presented alongside another. We're going to be reading ***below the horizontal line*** on ***both pages***. So this paper is less than a page long. It's going to be worth having a periodic table available to view whilst looking through this paper.

This paper stems from Fermi and collaborators work where they bombarded each known atom at the time with neutrons and made a note of what happened (you can see that paper here if you're interested: https://royalsocietypublishing.org/doi/pdf/10.1098/rspa.1934.0168). For most of the atoms that Fermi and friends looked at their description of their results is just a couple of lines. Uranium, though, requires half a page and a note to say that it'll get its own paper. At the time, the experimental result was very difficult to understand. Lise Meitner, a physicist, worked in a team of experimental chemists to understand this problem for a long time. Her role was the explain the results that the chemists found. Here, she presents her solution. At the end of the article, we'll look at the events surrounding this work and, ultimately, why Lise Meitner never received a Nobel Prize which she thoroughly deserved.

As always, take a skim-read through the paper first and come up with a few **SKIM-READ QUESTIONS** that you'll need to research to ensure you understand as much as possible when we read it through again in detail, answering the questions below as we go.

(P1, C1) Why do certain atoms emit radiation?	Because their nuclei are unstable and can become *more* stable (but not necessarily completely stable) by emitting radiation. You can think of this from an energy perspective too – by emitting radiation, the resulting nuclei reaches a lower energy state which is more stable (but not necessarily completely stable as the new nucleus could still be radioactive).
(P1, C1) Radioactive substances are those that emit alpha, beta, gamma radiation or neutrons from their nuclei. Discuss what each of these types of radiation is and any of their properties.	Alpha: a helium nucleus (two protons and two neutrons) - it is the most ionising and least penetrating form of radiation. Beta: a fast-moving electron – it is mildly ionising and mildly penetrating Gamma: high energy electromagnetic radiation – it is weakly ionising but highly penetrating Neutrons: single neutrons ejected from the nucleus. They themselves are not ionising as they have no charge and don't interact directly with electrons, but they are *indirectly* ionising as their interactions can lead to further ionising events. Neutrons are more penetrating than alpha and beta radiation. Depending on the material they are travelling through, they can be more penetrating that gamma radiation too (if the atomic number of the material they travel through is large).

(P1, C1) Why do we say that radiation is a random process?	Because we can't predict when a particular nucleus will decay.
(P1, C1) What is the atomic number and mass number for the most common form of uranium? How many protons and neutrons must it have?	Atomic number: 92 Mass number: 238 Number of protons: 92 (atomic number) Number of neutrons: 146 (mass number minus atomic number)

When they say that 'four radioactive substances were produced', this isn't from a single uranium nucleus decaying. The sample of uranium that was bombarded with neutrons contained billions of atoms. The different nuclei could decay in different ways, leading to seemingly four different products that were radioactive (and possibly more that weren't radioactive).

(P1, C1) How might the experimentalists have detected that there were radioactive substances produced?	Using a Geiger counter to monitor the activity over time.
(P1, C1) What is a nuclear isomer?	Two nuclei with the same atomic number and mass number (so the same number of protons and neutrons) but their nuclei are in different states of 'excitation' (which means some of the protons or neutrons have more energy than is typical). Eventually the 'excited' (higher energy) nucleus will decay by giving up its energy in the form of gamma radiation. However, these excited states may be very long-lived such that they are often termed quasi-stable.

At this point in history, scientists were expecting that, when bombarded with neutrons, a nucleus would do one of two things:

- nothing
- absorb the neutron (and possibly even more than one) and then go through a series of decays (alpha, beta, gamma, neutron emission) until we got to something stable.

(P1, C1) "It was always assumed that these radioactive bodies had atomic numbers near that of the element bombarded". Given the two bullet points above, why is this?	Because the only known options were to: • absorb a neutron (so mass number increases by 1) then o Do nothing o Emit alpha radiation (mass number decreases by 4 and atomic number decreases by 2) o Emit beta-minus radiation (atomic number increases by 1) o Emit beta-plus radiation (atomic number decreases by 1) o Emit gamma radiation (no change) o Emit neutron (mass number decreases by 1) All of these would leave the resulting atom very close to the original atom.
(P1, C1) "only particles with one or two charges were known to be emitted"	Predominantly alpha (Charge of +2) and beta (charge of +1 or –1) radiation.

- what are they referring to here?	
(P1, C1) ‘eka-osmium’ is now called Plutonium. Looking at the periodic table, why would osmium and ruthenium be expected to have similar properties?	Because osmium and ruthenium are both in group 8 of the periodic table.
(P1, C1) If something is “isotopic with radium”, then it is an isotope of radium. What does this mean?	An isotope of radium has the same number of protons (88) but a different number of neutrons.
(P1, C1) If bombardment of uranium (Z=92) lead to something “chemically similar to barium” (Z=54), what two reasons would lead them to initially conclude it was an isotope of radium (Z=88)?	Because radium is chemically similar to barium as they’re both in group 2 of the periodic table. Radium is close, in terms of its mass number and atomic number, to uranium, so the decay of uranium could go through known channels (alpha, beta and neutron emission).
(P1, C1&C2) Why were Hahn and Strassman “*forced*” into a conclusion that they probably weren’t happy with?	Because they would have expected the products of the bombardment of uranium to be close to it in the periodic table. They were expecting it to be an isotope of radium, but found that the resulting nucleus could not be distinguished from barium, leading them to conclude that it must be an isotope of barium itself. This is surprising as it would have involved a very long chain of known decays (alpha, beta and neutron emission).

(P1, C2) Meitner and Frisch draw an analogy to a liquid drop. Concentrating simple on a liquid, what keeps a droplet together?	Surface tension. At a liquid-air interface, the liquid molecules are more attracted to one another than to the air, leading to an inward force that makes it seem like the water is encased by some elastic membrane.
(P1, C2) What similarities do Meitner and Frisch draw between the uranium nucleus and a ‘liquid drop’?	If you shake a liquid drop sufficiently violently, it will divide itself into smaller drops. Meitner and Frisch suggest that, rather than emitting nuclear radiation, the nucleus of uranium splits in a similar way to a liquid drop: into two smaller parts.
(P1, C2) What do you think the authors mean by “stability of form”?	Much like a drop of liquid, which can be destabilised into forming two smaller droplets, the uranium nucleus isn’t so strong that it will continue to hold itself in one large piece, but can be disrupted into splitting into two pieces of similar size. It might bring to mind the idea of surface tension.
(P1, C2) Given that we’re discussing nuclear radiation and the behaviour of nuclei, why is it perhaps not surprising that the size of the smaller pieces of uranium may be	Because the laws that govern the nucleus are quantum mechanical laws and are probabilistic by their very nature. The emission of radiation is a random process, so it might not be surprising if the splitting of a nucleus into smaller parts might also have some randomness to it in the size of the resulting pieces.

dictated "partly on chance"?	
(P1, C2) Why will the two nuclei that are formed when uranium splits repel one another?	Because they are nuclei, they contain just protons and neutrons and therefore have positive charge. Like charges repel and so the nuclei will repel one another.
(P1, C2) What is the definition of fission? And hence what is the definition of nuclear fission?	Fission: division or splitting up into two or more parts Nuclear fission: the division of splitting of the nucleus into two or more parts.

Remember that the article continues below the horizontal line on the second page.

(P2, C1) What do they mean when they say "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."	As Uranium has a mass number of 238 and an atomic number of 92, for every proton in uranium, there are ~2.6 neutrons. This ratio is much larger than for lighter elements. So when uranium breaks into two parts, at least one part will have a lot more neutrons than is typical for however many protons there are. This atom will then be unstable and will go through beta decays (neutron turning into a proton and releasing an electron and an antielectron neutrino) to adjust the balance.
(P2, C1) Look at the periodic table and explain why krypton "might decay through rubidium, strontium and yttrium to zirconium"	Each step would be a single beta decay as each step is an increase of 1 in the atomic number (on each step, we might end up at an isotope of each atom though due to the excess neutrons).

In the paragraph that begins "It is possible, and seems to us rather probable", Meitner and Frisch are explaining the previous puzzling experimental evidence through this new lens of nuclear fission. Fermi and friends had previously detected radioactive nuclei with short half-lives as some of the products of the uranium reaction. Rather than having to ascribe these values to new, heavy elements, they are better understood as half-lives of much lighter elements (that were already known) but simply weren't expected to be seen.

The final few paragraphs involved Meitner and Frisch giving their opinions on other confusing experimental results: explaining the neutron bombardment of thorium through a fission paradigm and shining some light onto the isotopes of uranium produced.

It is true of all papers that it's important to understand the work in the context of the time. It's certainly true of this paper and something we're going to do by reading what amounts to a small biography of this particular bit of research.

To do:

1. Read the following paper:

   Ruth Lewin Sime (1989), *Lise Meitner and the Discovery of Fission*, Reflections on Nuclear Fission at Its Half-Century, Journal of Chemical Education, **66**, 5.

   https://pubs.acs.org/doi/pdf/10.1021/ed066p373

2. Within this paper, find up to five key quotes that helped you to better understand the original paper by Lise Meitner and Otto Frisch.

SUMMARY QUESTIONS (submit these, along with your SKIM-READ questions and answers to thomas.millichamp@warwick.ac.uk)

What is nuclear fission?

Describe, in as clear a way as possible, what the troubling results were surrounding the neutron bombardment of uranium, and explain why they were troubling prior to the 'nuclear fission' explanation.

How did the second paper *(Lise Meitner and the Discovery of Fission)* help you to better understand Meitner and Frisch's original paper?

What did you learn from the second paper *(Lise Meitner and the Discovery of Fission)* about the relationship between science and society?

FURTHER INFORMATION

This interactive, 3D model shows the radioactive nuclei on an N-Z graph (mass number vs atomic number). Find uranium and track what the "improbable series of beta decays" would have to have been to achieve barium.

https://people.physics.anu.edu.au/~ecs103/chart3d/

Nuclear fission is now routinely used for electricity generation, this interactive model shows such a reactor and explains what every single part does

https://www.nuclearinst.com/Nuclear-Reactor-Simulator

This article looks at the invention of the nuclear bomb, using the ideas of nuclear fission

https://www.newscientist.com/term/invention-nuclear-bomb/

This short editorial by Robert Oppenheimer discusses another relationship between nuclear physics and society in the creation of the atomic bomb

https://www.nature.com/articles/nphys3287.pdf