Prehistoric Nuclear Reactors?

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Outline

Review of U238 & U235 Fission:

- Fast neutrons induce U238 fission, but that releases no replacement neutrons
- Slow neutrons induce U235 fission, which **does** release new neutrons, but they're fast

Before they can chain react with more U235, they must be slowed down ("moderated")

- If moderator is water, need > 3% U235 (in U238) to sustain chain reaction

From half-lives: U235 would have exceeded that abundance > 1.7 billion years ago

The alarming data, that was then reinterpreted as evidence for such reactors in Africa

How they likely formed:
- Water flow concentrated Uranium by first dissolving, then re-depositing, its oxides
- But for those oxides to form, there had to be a lot of oxygen in earth's atmosphere
  - Oxygen which was only liberated by spread of cellular life on earth

Before 1.7 billion years ago: Not enough life => Not enough O$_2$ => No natural reactors

But with life, geology suggests reactors pulsed on-and-off for hundreds of thousands of years!

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Prehistoric Nuclear Reactors?

Could **GEOLOGY** ever produce a naturally occurring nuclear reactor?

Scientists believe this **MIGHT** have occurred

Long long ago . . . right here on Earth

The explanation comes right out of my preceding lecture:

**Nuclear Power – But they blow up!**

So I just had to share this fascinating story

Ideally, you should review the first half of that preceding lecture

But, in case you're in a hurry, I'll provide a quick review:
On earth, uranium now has TWO significant isotopes:

**Uranium 238 (\(^{238}\text{U}\)):**

- It makes up 99.27% of the earth's current supply of uranium.
- It spontaneously falls apart, but extremely slowly: "half-life" = 4.6 billion years.

But if a \(^{238}\text{U}\) atom is struck by a fast (high kinetic energy) neutron:

- It tends to absorb that fast neutron.
- But it then becomes extremely unstable.
- And most quickly fall to pieces.

But none of those pieces are free/lone neutrons:
The second significant uranium isotope is:

**Uranium 235 (\(^{235}\text{U}\))**:

- It makes up 0.72% of the earth's current supply of uranium.
- It spontaneously falls apart a bit more quickly: "half-life" = 703.8 million years.

But if a \(^{235}\text{U}\) atom is struck by a **slow** (low kinetic energy) neutron:

- It tends to absorb that slow neutron.
- But it then also becomes extremely unstable.
- And most quickly fall to pieces.

But its pieces include 1-3 fast neutrons:
But neutrons, of any speed, aren't usually flying around

So it's normally extremely boring:

After 4.6 billion years, half of the $^{238}\text{U}$ atoms will have fallen apart

After 704 million years, half of the $^{235}\text{U}$ atoms will have fallen apart

But when a $^{235}\text{U}$ DOES fall apart, it can get briefly exciting

because its liberated hot neutrons can cause 1-3 $^{238}\text{U}'s$ to fall apart

And then it goes back to being extremely boring
UNLESS there is some **water** hanging around!

Then, a **fast "hot"** neutron can bounce off water's H atoms

Which, because H has about the same mass, will be kicked aside

taking away some of the incident neutron's kinetic energy

After multiple collisions, a **fast "hot"** neutron thus becomes a **slow "cool"** neutron

Which can THEN cause another $^{235}$U to fall apart

And **THIS** is the start a nuclear chain reaction!
The environment of a nuclear reactor promotes this chain reaction

But nuclear reactors also require:

That the uranium atoms are packed rather tightly together

Thus oxides of $^{235}\text{U}$ and $^{238}\text{U}$ are refined and compressed inside fuel rods

And light-water moderated nuclear reactors additionally require:

That the $^{235}\text{U}$ concentration must be jacked up from 0.72% to 3-5%

Difficult because ALL uranium atoms have the same number of electrons

So they bond to the same things ruling out "chemical" purification

Nuclear enrichment plants thus use exotic "gas-diffusion" or "ultra-centrifuges"

As first developed for bomb manufacture in the World War II Manhattan Project

But those bombs required much more intense $^{235}\text{U}$ enrichment

To levels of $\geq 80\%$ $^{235}\text{U}$ (rather than just 3-5%)
Here we need to reflect on what a "radioactive half-life" really implies:

\[ 235\text{U} \text{ half life} = 703.8 \text{ million years} \quad \text{vs.} \quad 238\text{U} \text{ half life} = 4.6 \text{ billion years} \]

Right now, for every 9927 \( 238\text{U}'s \), there are 72 \( 235\text{U}'s \) (from: 99.27\% vs. 0.72\%)

But, 1 billion years ago, the numbers were (based on the meaning of "half-life"):

\[ 235\text{U} = (72) \times 2 \left( \frac{1 \text{ billion}}{703.8 \text{ million}} \right) = 192 \]

\[ 238\text{U} = (9927) \times 2 \left( \frac{1 \text{ billion}}{4.6 \text{ billion}} \right) = 11,541 \]

And 2 billion years ago the numbers were:

\[ 235\text{U} = (72) \times 2 \left( \frac{2 \text{ billion}}{703.8 \text{ million}} \right) = 516 \]

\[ 238\text{U} = (9927) \times 2 \left( \frac{2 \text{ billion}}{4.6 \text{ billion}} \right) = 13,418 \]
So the 3% nuclear chain reaction threshold was met about . . .

1.7 billion years ago:

\[
\begin{align*}
\text{235U} &= (72) \times 2 \left( \frac{1.7 \text{ billion}}{703.8 \text{ million}} \right) = 384 \\
\text{238U} &= (9927) \times 2 \left( \frac{1.7 \text{ billion}}{4.6 \text{ billion}} \right) = 12,825
\end{align*}
\]

\[\text{235U} = 2.9\%\]

But in the earth's crust uranium atoms are normally way too far apart

So now mix in some oxygen gas

Which reacts with uranium to form oxides

Which are somewhat soluble in water

THEN, flowing water can pick up both \text{235U} and \text{238U} ("leeching" it from the rocks)

And if that water flow happens to dry up in one place,

it will leave a residue of concentrated \text{235U} and \text{238U}
Which completes the requirements for a natural nuclear reactor

Scientists recognized this possibility as early as the 1950's

Indeed, one theorist, Paul Kuroda, published a supporting calculation in 1956 ¹

But his paper got largely ignored - Until a French security agency got involved

Why? Because security agencies worry a LOT about missing $^{235}$U!

After all, $^{235}$U is THE essential ingredient for making a fission nuclear bomb

In 1972, ore from the "Oklo" Gabon Africa mine was being processed in France

EVERYWHERE else in the world, uranium ore contains 0.72% $^{235}$U

But for Oklo, the concentration was found to be significantly lower ²

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The French Atomic Energy Commission (CEA) was thus called in:

They quickly calculated the total amount of $^{235}\text{U}$ that could be missing from Oklo.

They didn't like the answer: Enough to build a half dozen nuclear bombs.

But the CEA also knew just how hard it is to selectively remove $^{235}\text{U}$.

And they found no evidence that the Oklo ore had been diverted through one of the aforementioned nuclear enrichment plants.

The CEA was thus reportedly "perplexed" for several weeks until someone remembered those predictions of natural nuclear reactors.

Which provided a much less alarming answer to where the $^{235}\text{U}$ had gone:

It had long ago fissioned away into other things:  

The "things" that are produced when atoms fall apart, making other atoms

Otherwise known as the "daughters" produced in nuclear chain reactions

As only partially enumerated this figure from my introductory lecture:

And this all occurred, quite naturally, about 1.7 billion years ago
That seems to wrap things up & tie it in a bow, right?

NO, there are still some loose ends to be explained:

Tracking radioactive half-lives backward, we calculated historic $^{235}$U percentages of:

<table>
<thead>
<tr>
<th>Time</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Now: -1.0x10^9 BCE</td>
<td>0.72%</td>
</tr>
<tr>
<td>-1.7x10^9 BCE</td>
<td>1.6%</td>
</tr>
<tr>
<td>-2x10^9 BCE</td>
<td>2.9%</td>
</tr>
<tr>
<td>-2x10^9 BCE</td>
<td>3.7%</td>
</tr>
</tbody>
</table>

Indicating that nuclear chain reactions could be sustained 1.7 billion years ago

But, at 3.7%, they would have worked even better 2 billion years ago

And they would have worked even better before that . . .

So why say natural nuclear reactions ONLY occurred ~ 1.7 billion years ago?

Because that was about the time life was getting started on earth
And it took **life** to liberate large amounts of gaseous oxygen

Which, recall, was essential for doing this:

**Oxygen gas** reacted with widely dispersed uranium, to form oxides

Those oxides were somewhat water soluble

Allowing **flowing water** to pick up both $^{235}\text{U}$ and $^{238}\text{U}$

Which, if it then dried up in one place,

would leave concentrated residues of $^{235}\text{U}$ and $^{238}\text{U}$

So, getting even weirder, scientists suggest that prehistoric nuclear reactors
could not be formed **until** oxygen-liberating life began populating the earth

But it gets even **stranger**:
When they carefully analyzed those chain reaction products:

They concluded that these prehistoric reactors fired up 1.7 billion years ago, and "operated" intermittently for hundreds of thousands of years.

But that intermittent operation was not random - reaction products instead suggest:

The chain reaction ran for ~ 30 minutes
It was then extinguished for ~ 2 ½ hours
And then that cycle was repeated over and over and over . . .
All because sustained fission still requires neutron "moderation"

That is, fast/hot neutrons from $^{235}$U must be transformed into slow/cool neutrons.

In manmade nuclear reactors, neutrons do this by ricocheting off liquid water.

Prehistoric reactors apparently used the same process.

But when those soggy-stuff-buried-in-the-ground-reactors (SSBGR) fired up:

That patch of ground would start to get really hot.

And after ~ 30 minutes, almost all of the liquid water would boil away.

Then, deprived of that neutron "moderating" liquid water,

the nuclear chain reaction would be quenched.

But THEN the ground would start to cool back down.

And after about 2 ½ hours enough liquid water could seep back in

that the nuclear chain reaction would start back up!

And so on, and so on, and so on . . .
But how did they come up with the exact 30 minute / 2 ½ hour timing?

The $^{235}\text{U} / ^{238}\text{U}$ chain reactions are known to release multiple isotopes of Xenon. Some isotopes are released very early, some are released later.

However, as a gas, Xenon doesn't normally stick around. But at Oklo, hot water slowly oxidized aluminum & silicon-containing minerals, which could trap Xenon, at least if it hung around long enough.

But while late-emerging Xe isotopes were found, early-emerging Xe was not!

Suggesting the ground was VERY hot when the early Xe emerged.

Because extreme heat would pressurize that Xe, driving it out and away.

But that the ground was cooler when the late Xe emerged.

Allowing it to hang around long enough to be trapped by mineralization.

Known timing of Xe generation then indicated: "30 minutes on + 2 ½ hour off" \(^{3, 5}\)


Experts OR particularly observant readers of my introductory nuclear lecture might figure out that I have not really chosen the most appropriate type of "ghost reactor" to depict in my figure above.

(HINT: Note type of reactor suggested by figure's reactor containment structure)

top: http://mashable.com/category/nuclear-reactor/  
Other WeCanFigureThisOut.org note sets on nuclear energy:

Note set introducing nuclear energy & its accidents:

Nuclear Energy – But they blow up!

Note three sets on the possible future of nuclear energy:

Gen III/III+ Reactors: Confronting Cost & Operational Safety

Gen IV Reactors: Two Designs that Might Radically Reduce Nuclear Waste

Other Gen IV Nuclear Reactors

For links to these note sets (and their accompanying resources webpages) visit:

www.WeCanFigureThisOut.org/ENERGY/Energy_home.htm
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This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.

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