# Introduction to Nuclear forensics

28th October 2020

https://www.iaea.org/newscenter/news/crime-scene-to-court-room-implementing-nuclear-forensic-science

# Nuclear forensics


**Nuclear forensics** involves the laboratory analysis of seized illicit nuclear materials or debris from a nuclear detonation to identify the origins of the material or weapons.

# What is Nuclear Forensics?

- Nuclear Forensics is defined as a methodology that aims at re-establishing the history of nuclear material of unknown origin.
- Extract the historical information from the nuclear evidence
  - What? Where? When?
  - Radioactive material
    - Isotopic composition
    - Place of origin
    - Trafficking route
    - Age

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# Nuclear forensic science—From cradle to maturity

K. Mayer, M. Wallenius, T. Fanghänel *

*European Commission—Joint Research Centre, Institute for Transuranium Elements, 76125 Karlsruhe, Germany*

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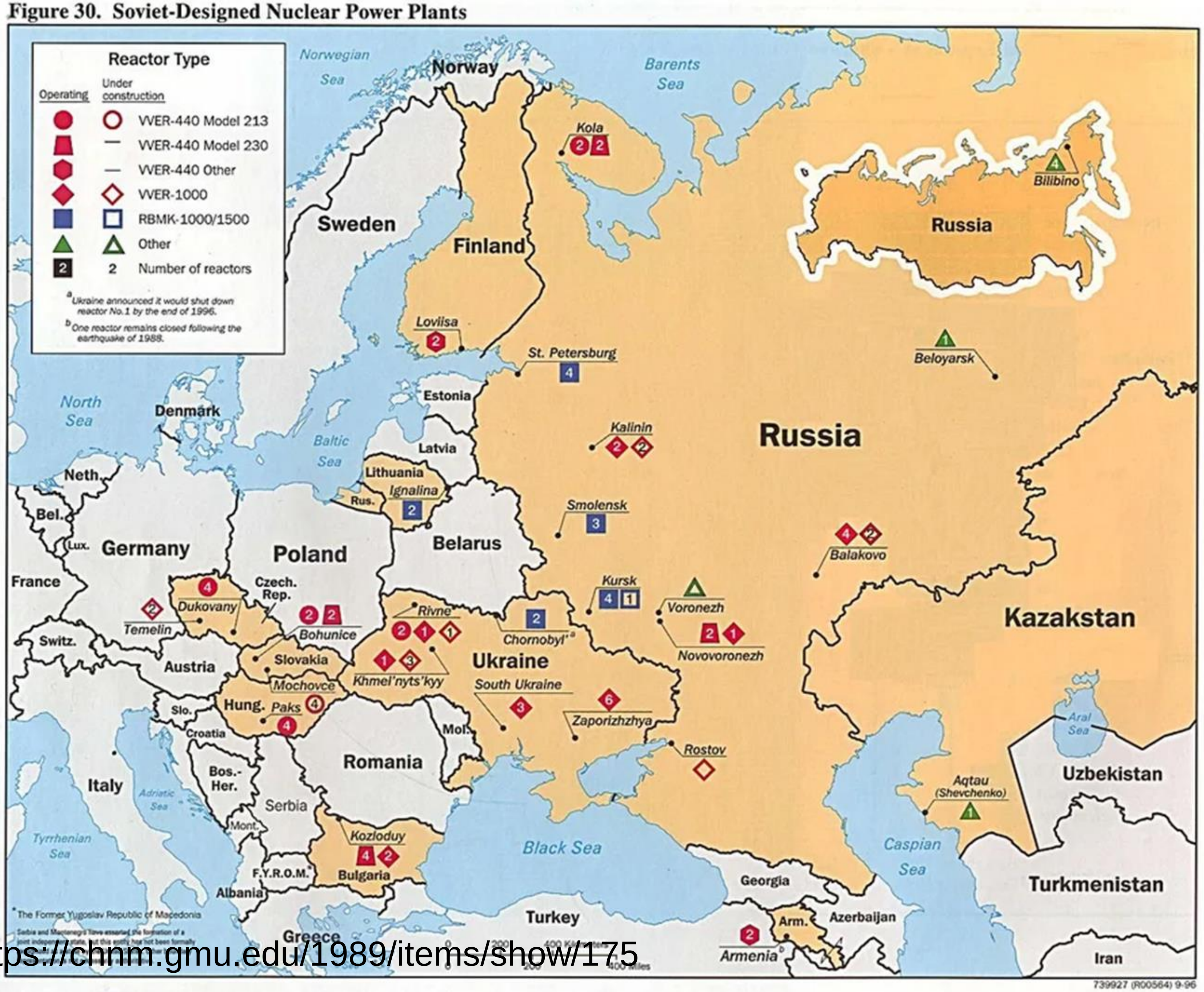
**Abstract**

Since the beginning of the 1990s, when the first seizures of nuclear material were reported, the IAEA recorded more than 800 cases of illicit trafficking of nuclear or other radioactive materials. Despite the decreasing frequency of seizures involving nuclear materials (i.e. uranium or plutonium), the issue continues to attract public attention and is a reason for concern due to the hazard associated with such materials. Once illicitly trafficked nuclear material has been intercepted, the questions of its intended use and origin are to be addressed. Especially the origin is of prime importance in order to close the gaps and improve the physical protection at the sites where the theft or diversion occurred. To answer the questions, a dedicated nuclear forensics methodology has been developed. In this paper, an overview is given on the methodologies used, the measurement techniques that are applies and on the characteristic parameters that help in the identification of the origin of the material. Some selected examples shall illustrate the challenges and the complexity associated with this work. In particular the past and on-going developments in this new area of science will be highlighted and special attention is attributed to the challenges ahead.


*Keyword:* Nuclear forensics




https://chnm.gmu.edu/1989/items/show/175

# What is this?

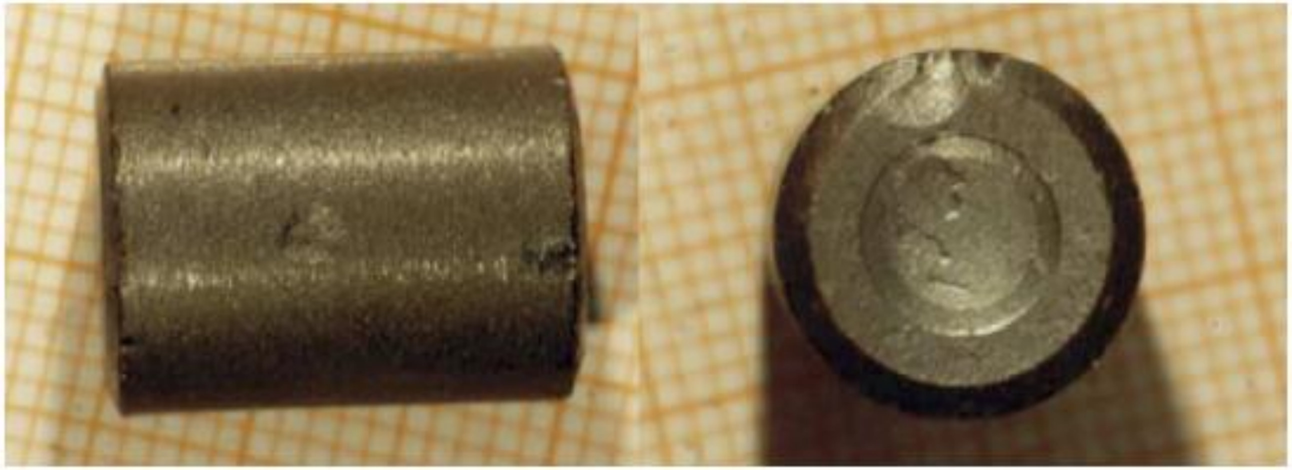
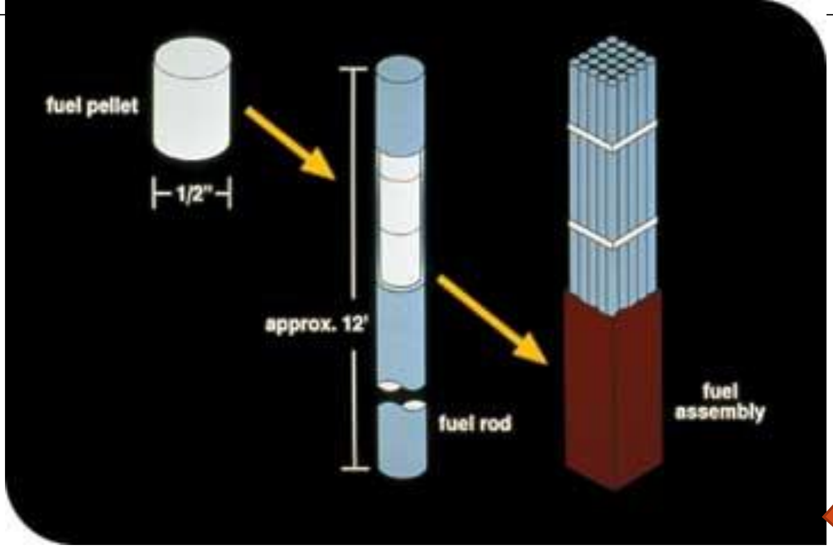


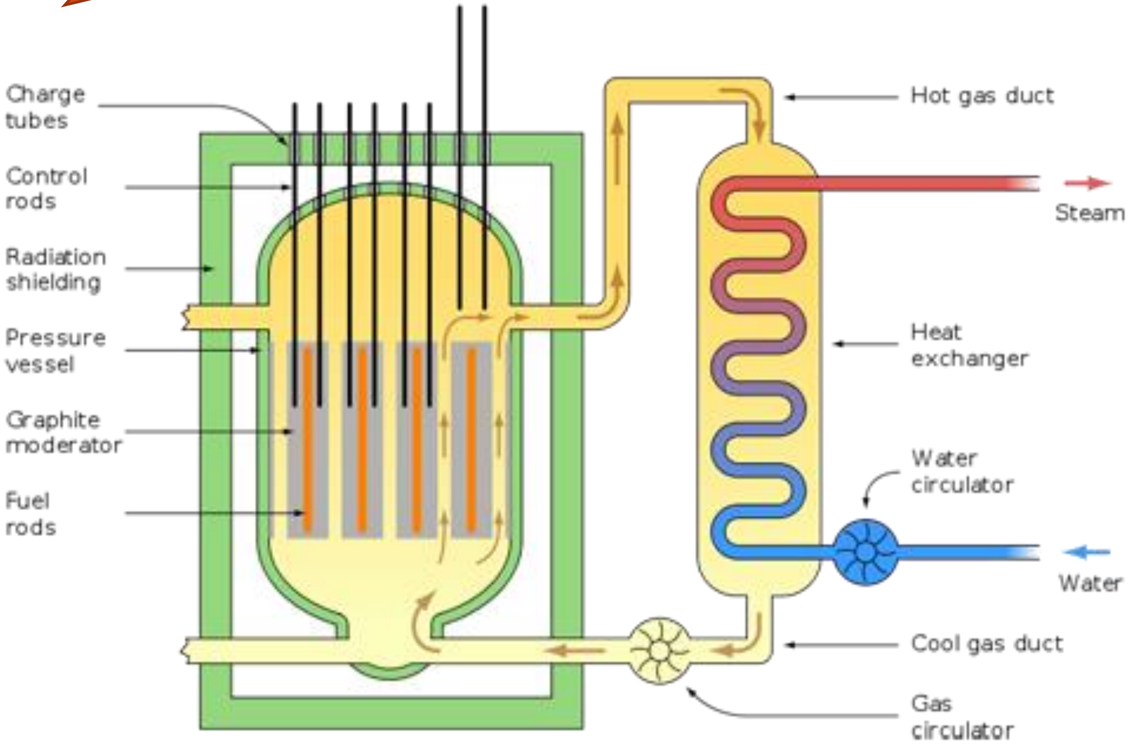
Fig. 1. Photo of a U pellet of "Find-1".

- In March 1992, uranium fuel pellets were seized in Germany.
- The **nuclear materials** were analyzed and investigated their measurable properties such as isotopic compositions, physical dimensions and chemical impurities. The analysis aims to identify the origin and intended use.
- The seizure consists of 72 uranium pellets so called "Find 1."

**Nuclear material** refers to the metals uranium, plutonium, and thorium, in any form.




Fuel pellets are inserted into fuel rods, which are grouped together in a fuel assembly.




Fuel rods are placed into the reactor to start nuclear reaction.

https://panthersgetnuclear5.wikispaces.com/Types+of+Nuclear+Reactors

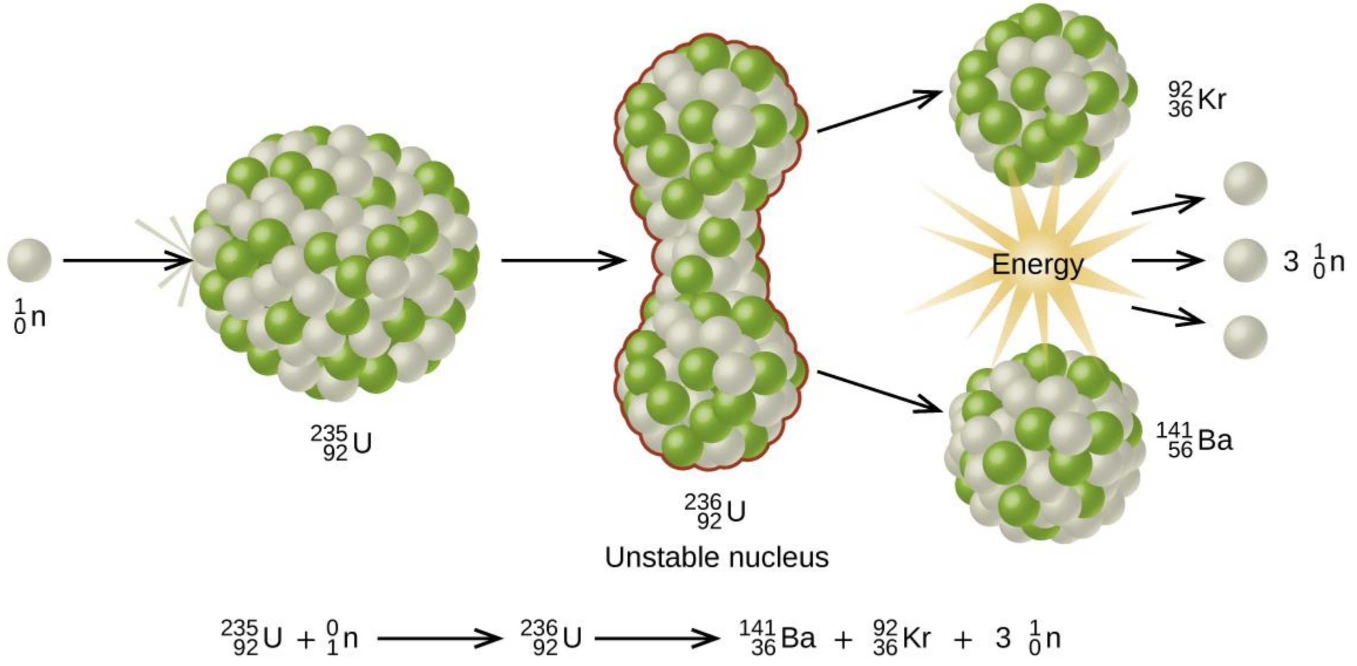
# Analysis of “Find 1”

Table 1
Analytical results of “Find-1” (average of three pellets ±1 s)

| Parameter | Dimension | U-isotope (wt.%) | U-concentration (wt.%) |
|---|---|---|---|
| Ø (mm) | 11.45 ± 0.01 | U-232 (8.27$E$−8 ± 6.5$E$−9) | 87.98 ± 0.03 |
| Height (mm) | 14.42 ± 0.24 | U-234 (0.034 ± 0.002) | |
| Weight (g) | 15.454 ± 0.315 | U-235 (2.507 ± 0.014) | |
| | | U-236 (0.449 ± 0.051) | |
| | | U-238 (97.011 ± 0.067) | |

- Preliminary results in terms of the physical dimensions and isotropic composition pointed out that the materials were intended to be used as **fuel pellets for a nuclear reactor**.
- The materials were low-enriched uranium fuel pellets (~ 5% of U-235 concentration).

# Isotopes from the nuclear fission




- In a nuclear reactor, when a slow neutron hits a fissionable U-235 nucleus, it is absorbed and forms an unstable U-236 nucleus.
- The U-236 nucleus then rapidly breaks apart into two smaller nuclei (in this case, Ba-141 and Kr-92) along with several neutrons (usually two or three), and releases a very large amount of energy.

- The presence of U-236 in the fuel shows that the uranium has been exposed to neutrons, thus having been previously in a reactor.
- This information can be used to confirmed its intended use.

# Dimensions

**Table 1:** Dimensions of $UO_2$ pellets used in commercial reactor types in Europe [6].

| Reactor type | Name (model) | Diameter (mm) | Length (mm) | Central hole (mm) |
|---|---|---|---|---|
| PHWR | Cernavoda in Romania (Candu 6) | 12.16 | 16 | – |
| AGR | HeyshamA1# in UK | 14.5 | 15.2 | 6.39 |
| PWR | Loviisa in Finland (VVER-440) | 7.6 | 10 | 1.2 |
| PWR | Kalinin in Russia (VVER-1000) | 7.55 | 11–12 | 2.2–2.4 |
| PWR | Philippsburg 2 in Germany | 9.11 | 11 | – |
| PWR | Gravelines in France (CP2) | 8.19 | 13.3 | – |
| BWR | Gundremmingen in Germany (BWR 72) | 8.67/9.11 | 10.5/11 | – |
| BWR | Oskarshamn 3 in Sweden | 10.44 | 11 | – |
| LWGR | Chernobyl in Ukraine (RBMK-1000) | 11.5 | 15 | – |
| LWGR | Ignalina in Lithuania (RBMK-1500) | 11.5 | 12–15 | 2.0 |

- The shape of the pellet depends on the type of reactor the fuel is produced for.
- The dimensions indicates that the pellets were highly likely used for **RBMK reactor** can used to traced back to the nuclear reactor.



https://doi.org/10.1515/ract-2018-3068

# Dimensions of the pellet

**Figure 1:** Photos of one of the analysed RBMK-1500 pellets from Lithuania.
Dimensions: ∅ 11.44 ± 0.01 mm, inner hole 2.0 ± 0.1 mm. The dimensions were identical (within measurement uncertainty) for all pellets from the different seizures.

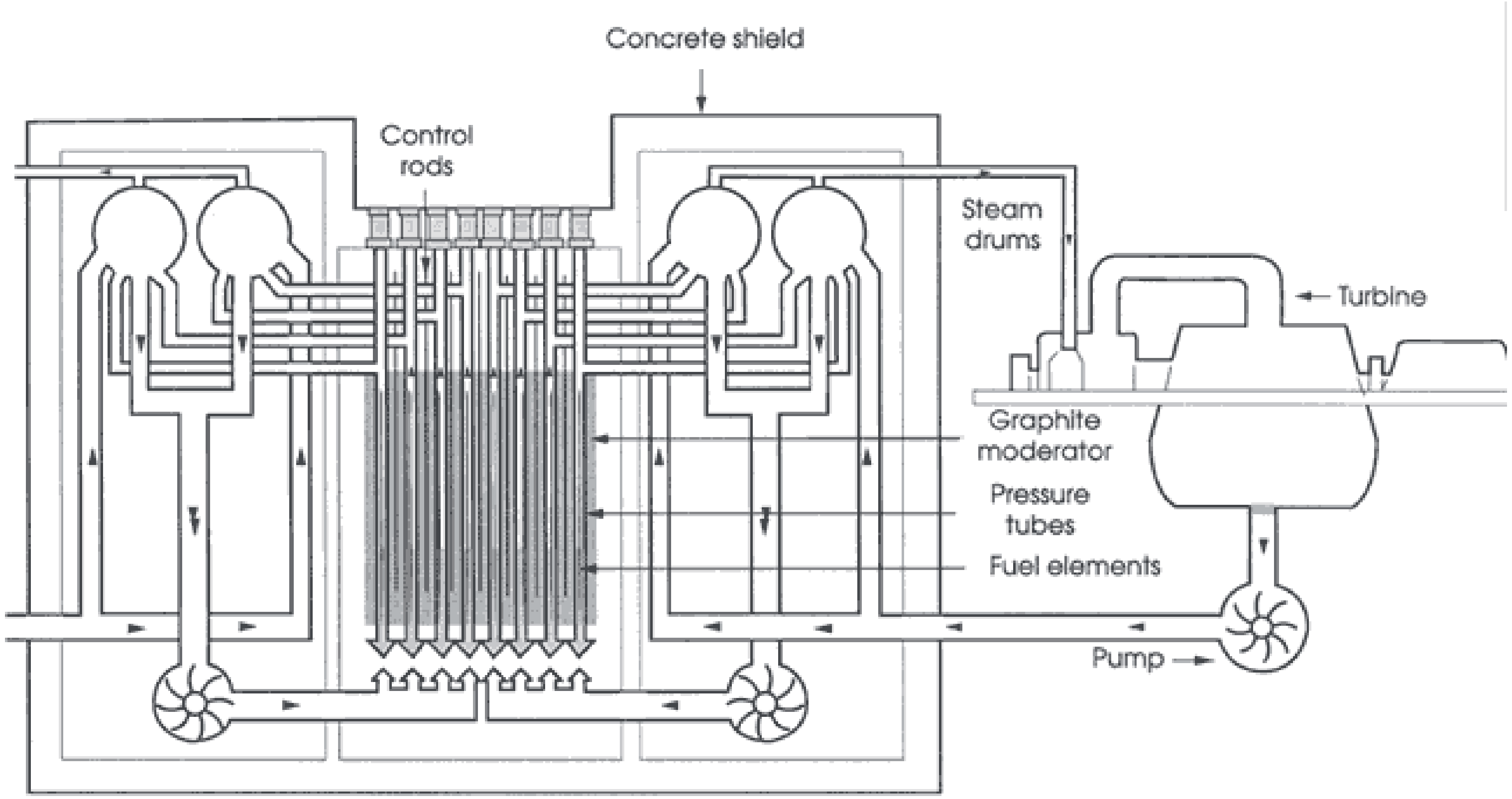
•Because the dimensions are characteristics for different reactor types, varying significantly from reactor type to another.

•The intended use of the pellet was for a Russian type graphite moderated reactor (RBMK).



https://doi.org/10.1515/ract-2018-3068

# Nuclear power plant RBMK type in Russia




RBMK (reaktor bolshoy moshchnosti kanalniy  means reactor (of) large power (of the) channel type)

# Techniques used for analyzing seized nuclear material

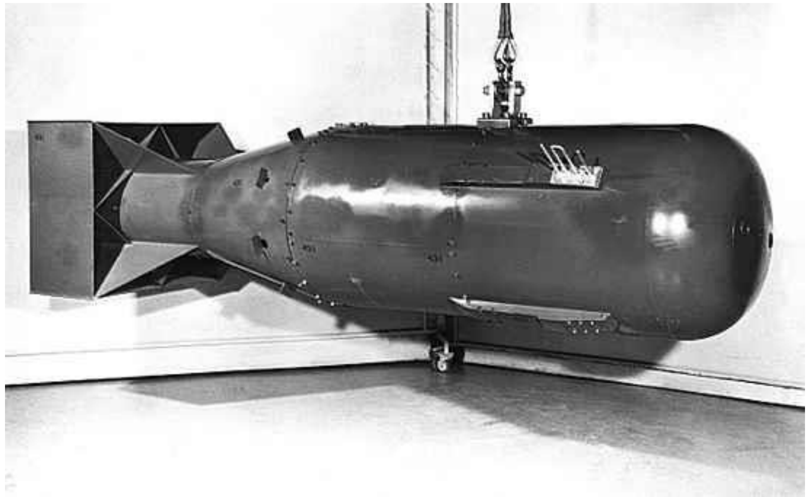
**Table 1** Techniques used for analysing seized nuclear material

| Techniques/methods | First analysis | Information | Detailed analysis | Information |
|---|---|---|---|---|
| Radiological | Estimated total activity<br>Dose rate (α, γ, n)<br>Surface contamination | Radiological hazard<br>Precautions | | |
| Physical characterization | Visual inspection<br>Photography<br>Size measurement<br>Optical microscopy<br>Radiography<br>Weighing | Macroscopic dimensions<br><br>Mass | SEM (EDX)<br><br>XRD<br>TEM | Microstructure and elemental composition<br>Crystal structure<br>Microstructure |
| Traditional forensic analysis | Fingerprints, fibers | | | |
| Isotope analysis | γ-Spectroscopy | Isotopic composition | Mass spectrometry (SIMS, TIMS, MC-ICP-MS)<br>Radiochemical separations<br>α-spectrometry | Accurate isotopic composition |
| Elemental/Chemical analysis | | | ICP-MS<br>XRF<br>Assay (titration, IDMS)<br>GC-MS | Chemical impurities<br>Chemical composition |

# Enriched Uranium Classes

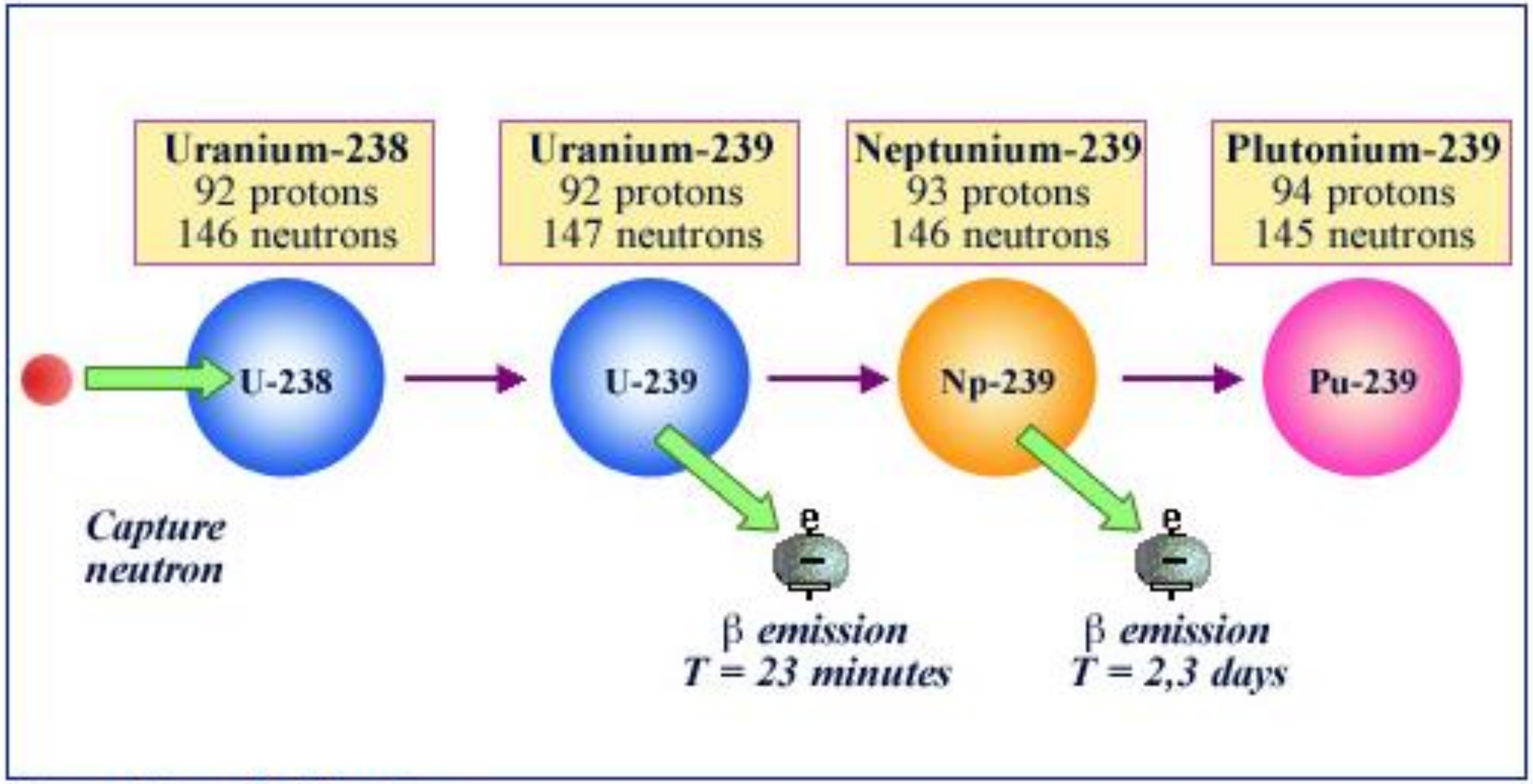
- **Low Enriched Uranium (LEU)** 0.72-20% U 235
  - LEU is primary fuel for nuclear reactors

- **High Enriched Uranium (HEU)** >20% U 235
.
  - HEU is used primarily in weapons.
  - Atomic weapons of WWII used HEU of about 93.5% U 235



www.hep.fsu.edu/~wahl/phy3091/f03/talk4/BLynchTalk4.p

# Production of Pu-239 from U-238




**Generation of plutonium**
The capture of a neutron by a nucleus of uranium-238 leads to the formation within a few days of a nucleus of fissile plutonium-239. The nucleus of uranium-239 resulting from the capture of the neutron is radioactive beta-minus. By emitting an electron and an antineutrino, it becomes neptunium-239, which being itself unstable transforms in its turn the same way into plutonium-239.




http://www.radioactivity.eu.com/site/pages/Plutonium_239_Formation.htm

# Death by Polonium-210

By Robin B. McFee, DO, MPH, FACPM, &
Jerrold B. Leikin, MD, FACEP, FAACT, FACP, FACOEM, FACMT

## Lessons learned from the murder of former Soviet spy Alexander Litvinenko


Alexander Litvinenko in the ICU on Nov. 20, 2006.

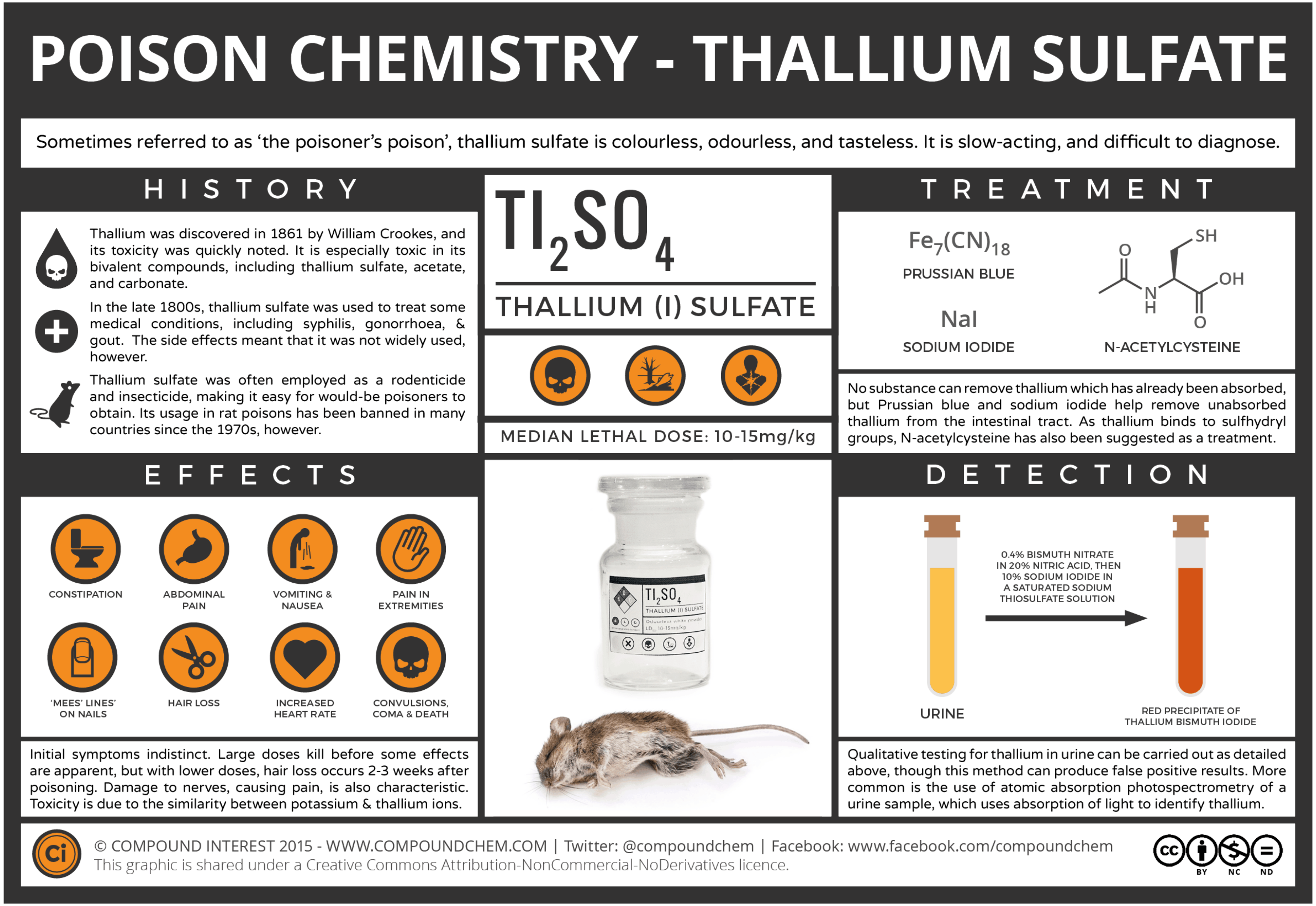
PHOTO NATASJA WEITSZ/GETTY IMAGES

# Case report

- On Nov. 1, 2006, a former KGB agent named **Alexander Litvinenko** presented to a North London hospital with acute, severe, progressive gastrointestinal symptoms.

- Litvinenko's health rapidly deteriorated : his hair fell out and a reduction in the number of red and white blood cells, as well as platelets. The latter symptoms indicates the condition of **pancytopenia**.

- The symptoms were consistent with radiation **or thallium toxicity**.
- However, the patient's urine and blood samples were negatively tested.


POISON CHEMISTRY - THALLIUM SULFATE
Sometimes referred to as 'the poisoner's poison', thallium sulfate is colourless, odourless, and tasteless. It is slow-acting, and difficult to diagnose.
HISTORY
Thallium was discovered in 1861 by William Crookes, and its toxicity was quickly noted. It is especially toxic in its bivalent compounds, including thallium sulfate, acetate, and carbonate.
In the late 1800s, thallium sulfate was used to treat some medical conditions, including syphilis, gonorrhoea, & gout. The side effects meant that it was not widely used, however.
Thallium sulfate was often employed as a rodenticide and insecticide, making it easy for would-be poisoners to obtain. Its usage in rat poisons has been banned in many countries since the 1970s, however.
$Tl_2SO_4$
THALLIUM (I) SULFATE
MEDIAN LETHAL DOSE: 10-15mg/kg
TREATMENT
$Fe_7(CN)_{18}$
PRUSSIAN BLUE
NaI
SODIUM IODIDE
SH
O
OH
N
H
O
N-ACETYLCYSTEINE
No substance can remove thallium which has already been absorbed, but Prussian blue and sodium iodide help remove unabsorbed thallium from the intestinal tract. As thallium binds to sulfhydryl groups, N-acetylcysteine has also been suggested as a treatment.
EFFECTS
CONSTIPATION
ABDOMINAL PAIN
VOMITING & NAUSEA
PAIN IN EXTREMITIES
'MEES' LINES' ON NAILS
HAIR LOSS
INCREASED HEART RATE
CONVULSIONS, COMA & DEATH
Initial symptoms indistinct. Large doses kill before some effects are apparent, but with lower doses, hair loss occurs 2-3 weeks after poisoning. Damage to nerves, causing pain, is also characteristic. Toxicity is due to the similarity between potassium & thallium ions.
$Tl_2SO_4$
THALLIUM (I) SULFATE
DETECTION
0.4% BISMUTH NITRATE IN 20% NITRIC ACID, THEN 10% SODIUM IODIDE IN A SATURATED SODIUM THIOSULFATE SOLUTION
URINE
RED PRECIPITATE OF THALLIUM BISMUTH IODIDE
Qualitative testing for thallium in urine can be carried out as detailed above, though this method can produce false positive results. More common is the use of atomic absorption photospectrometry of a urine sample, which uses absorption of light to identify thallium.
Ci
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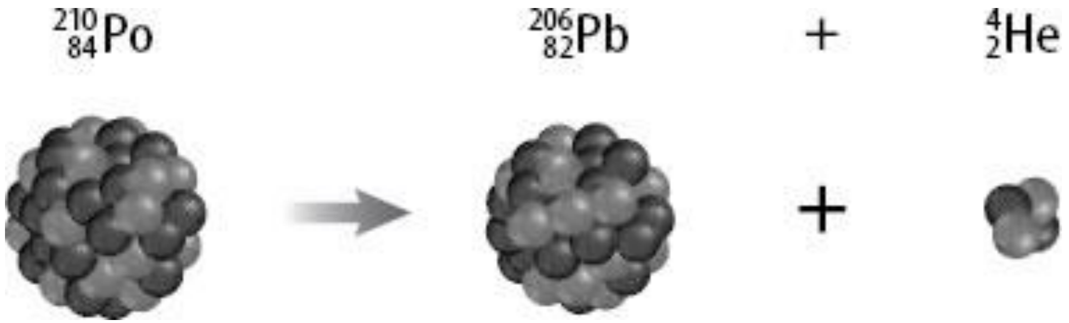
# Positive test for Po-210

- Advanced tests by Britain's Atomic Weapons Establishment revealed significant amount of **alpha particle radiation**.




- This indicated the poisoning to the patient by Polonium-210 ($^{210}Po$).
- Litvinenko died of internal contamination from the radioactive.
- Traces of polonium were found in several locations where Litvinenko had visited shortly before becoming ill.



https://socratic.org/questions/what-is-the-nuclear-equation-for-the-alpha-decay-of-po210


http://www.itv.com/news/update/2016-01-21/images-released-of-teapot-used-to-poison-litvinenko/

- An image of the teapot used to poison Russian dissident Alexander Litvinenko have been released.
- Traces of polonium 210 were discovered in the teapot in the Pine Bar at the Millennium Hotel.

Note : cps = counts per second, the indicator used to measure radiation levels.

# Understanding Polonium-210

- Polonium is a rare radioactive metalloid, and was discovered in uranium ores by Marie and Pierre Curie in 1897.
- Polonium may now be made in milligram amounts in nuclear reactors.
- Polonium is a solid but dissolves readily in dilute acids.

**Polonium Characteristics**

*http://en.wikipedia.org/wiki/Polonium*

**Most stable isotopes**

Main article: Isotopes of polonium

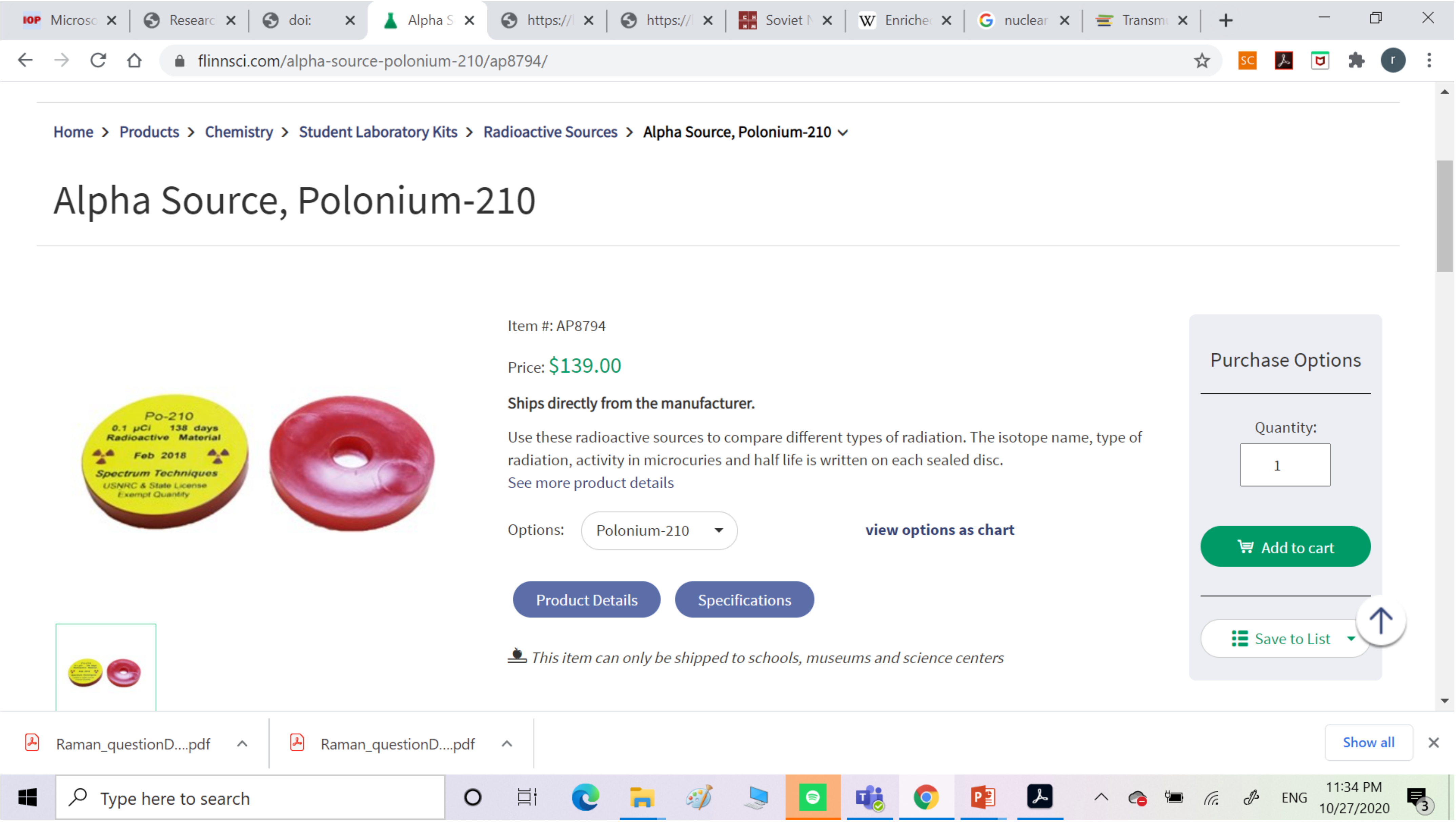
| iso | NA | half-life | DM | DE (MeV) | DP |
|---|---|---|---|---|---|
| $^{208}Po$ | syn | 2.898 y | α | 5.215 | $^{204}Pb$ |
| | | | $β^+$ | 1.401 | $^{208}Bi$ |
| $^{209}Po$ | syn | 103 y | α | 4.979 | $^{205}Pb$ |
| | | | $β^+$ | 1.893 | $^{209}Bi$ |
| $^{210}Po$ | trace | 138.376 d | α | 5.307 | $^{206}Pb$ |

$h_{Po210} := 138.376\,\mathrm{day}$ *Polonium-210 half life.*

$E_{\alpha} := 5.307\,\mathrm{MeV}$ *Polonium-210 alpha decay energy*

http://mathscinotes.com/2014/01/radiation-exposure-from-cigarette-smoking/

# Polonium 210 on sale from internet



# Quantifying Radioactive Decay

Measurement of **Activity** (**กัมมันตภาพ**) in disintegrations per second (dps);

- 1 **Becquerel** (Bq) = 1 dps;
- 1 **Curie** (Ci) = 3.7 x $10^{10}$ Bq (dps) ;
- **Specific activity of substances are expressed as activity per weight or volume (e.g., Bq/gm or Ci/l).**

# Radioactivity

Activity = decay constant $\times$ number of radioactive nuclei

$$A = \lambda N$$

$$= \frac{\ln 2}{half-life} N$$

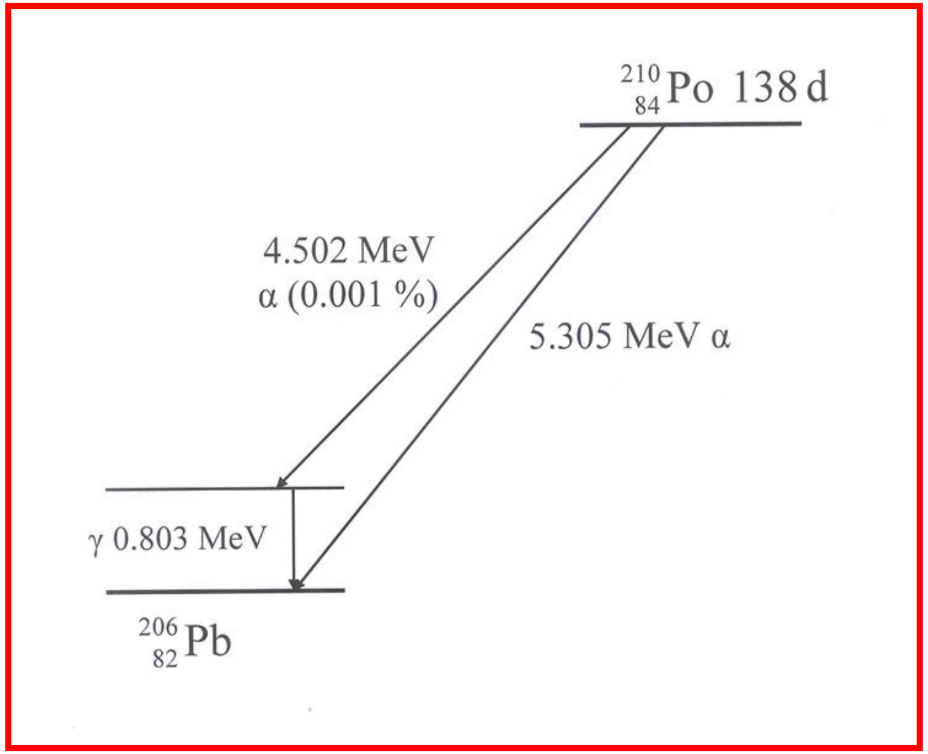
- According to experts' estimation, about 1 μg of the Po-210 could have been response for Mr Litvinenko's death.
- What should be the activity of this amount of the Po-210?

http://news.bbc.co.uk/2/hi/science/nature/6190144.stm

# Calculation

# Alpha emitter

- A single gram of $^{210}Po$ generates energy at the rate of 150 watts.
- Since nearly all alpha radiation can be easily stopped by ordinary containers and upon hitting its surface releases it energy.
- $^{210}Po$ has been used as a lightweight heat source for artificial satellites.

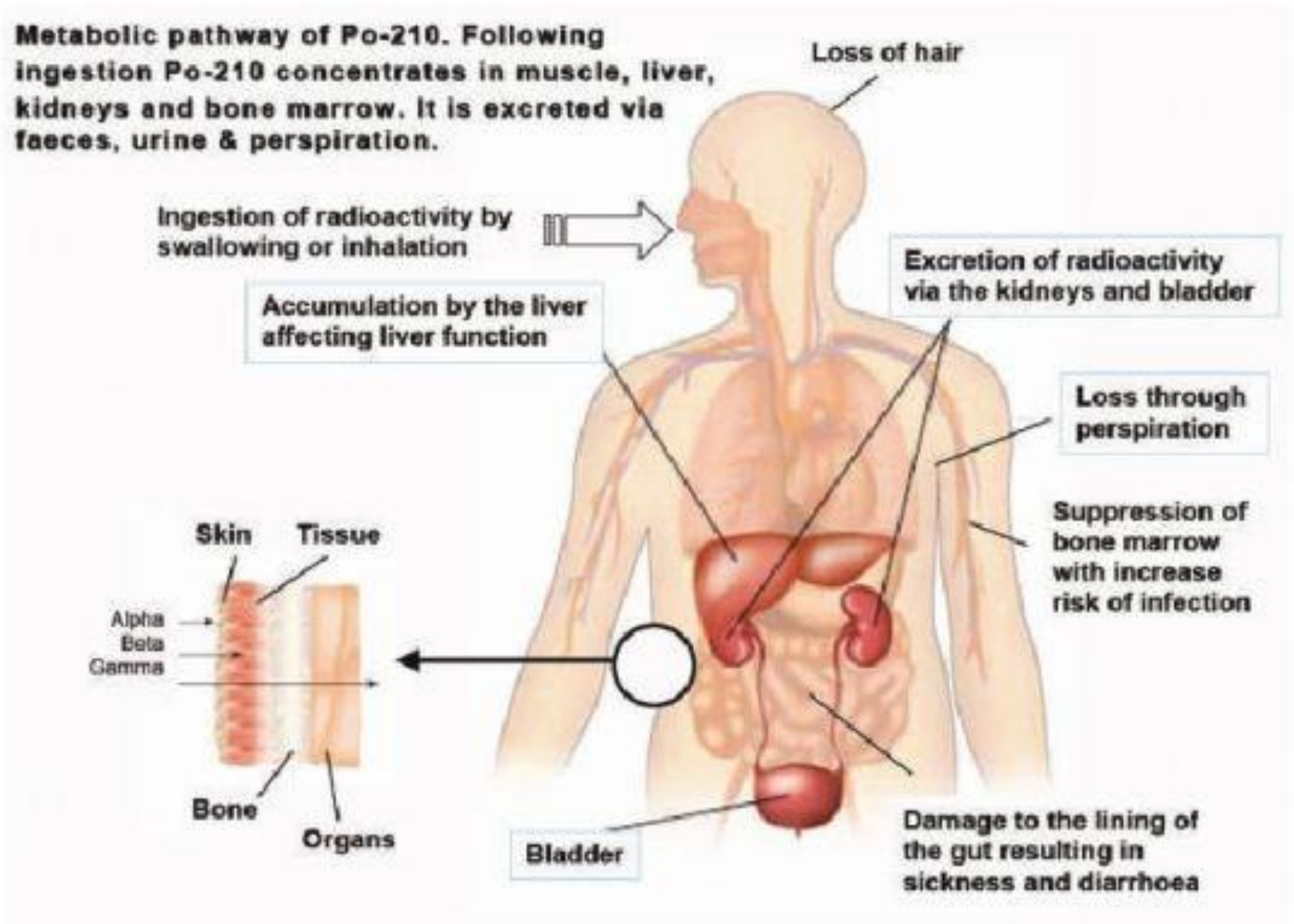



https://commons.wikimedia.org/wiki/File:Polonium_210.png

# $^{210}$Po used as a poison

- Weight for weight Po-210 is a million times more toxic than hydrogen cyanide.
- **The maximum allowable body burden for ingested polonium is only seven picograms which gives a maximum allowable body burden for ingested polonium of 1100 Bq**.
- The amount of material required to produce a lethal dose would only be 0.12 micrograms.
- The alpha radiation has enough energy to tear apart the DNA killing or causing them to mutate into tumor-producing forms although **the radiation penetrate about 60 µm through biological tissue- equivalent to the wall cell thickness**.

# The effect of Polonium poisoning




http://warincontext.org/2012/07/04/the-effects-of-polonium-poisoning/

# Detection of Po-210

- Polonium-210 inside someone's body is not detectable with standard radiation survey instruments used outside that person's body.
- Testing the individual's urine or feces for alpha radiation would be the method of detection.

- The radioactive substance sometimes called the "**Perfect Poison**."

# Summary
# Po-210 : the perfect poison

- Polonium is an immensely powerful poison. Its presence in the body is also very hard for doctors to identify unless they are looking specifically for it.
- Part of the difficulty in detecting polonium poisoning is that its outward symptoms resemble poisoning with much less powerful substances. **Among the earliest symptoms are hair loss, which is also a standard symptom of poisoning by thallium, an element in rat poison.**
- This ability of polonium to conceal its presence by appearing to be another, simpler, poison enables it to fool investigators into looking for other culprits than the real assassin.

# HOW POLONIUM-210 KILLED LITVINENKO

The ex-spy's final days were an agonizing process of cellular damage throughout the body