



The Health Effects of ^{210}Po Polonium Exposure

The Death of Alexander
Litvinenko

The Health Effects of ^{210}Po Exposure

The Death of Alexander Litvinenko



- Born Aug 30, 1962, Voronezh, Soviet Union
- Former Lieutenant in the Russian Federation's Federal Security Service
- 2000 Sought political asylum in the U.K.
- 2002 writes "Blowing up Russia; Terror from Within"
- Oct 19, 2006 accuses Putin of murdering Anna Politkovskaya, a Kremlin critic and journalist

The Health Effects of ^{210}Po Exposure

Chronology of Events

- Nov. 1, 2006 at 5 pm Litvinenko meets former KGB agents Andrei Lugovoi, Dmitry Kovtun, Vyacheslav Sokolenko at the Pine Bar of the Millennium Hotel in London. He drinks a cup of tea. Falls ill later that evening.
- Nov. 3rd brought to Barnet General Hospital
- Nov. 11th becomes seriously ill, tells BBC he was poisoned
- Nov. 17th moved to University College Hospital

The Health Effects of ^{210}Po Exposure

Chronology of Events

- Nov. 19th reports emerge that Litvinenko was poisoned with thallium
- Nov. 20th moved to intensive care unit
- Nov. 22nd hospital announces that his condition has worsened substantially
- Nov. 23rd: 9:21 pm Litvinenko dies
- Nov. 24th HPA announces that cause of death attributed to ^{210}Po poisoning

The Health Effects of ^{210}Po Exposure

The Death of Alexander Litvinenko

- Background
- Chemical, Physical, Biologic Properties
- Acute Radiation Syndromes
- Internal Effects
- Potential Treatments
- Secondary Effect Carcinogenesis
- Why Polonium?

The Health Effects of ^{210}Po Exposure

Background

- 1st element discovered by Curies in 1898
- Extremely rare naturally occurring
 - 100 μg per ton of Uranium ore
- Silver gray metal
- 25 Isotopes, all radioactive
 - Only 3 with any significant half life
- Commercial use as static eliminators
- Produced in a reactor from Bismuth 209
 - 100 grams produced world wide each year

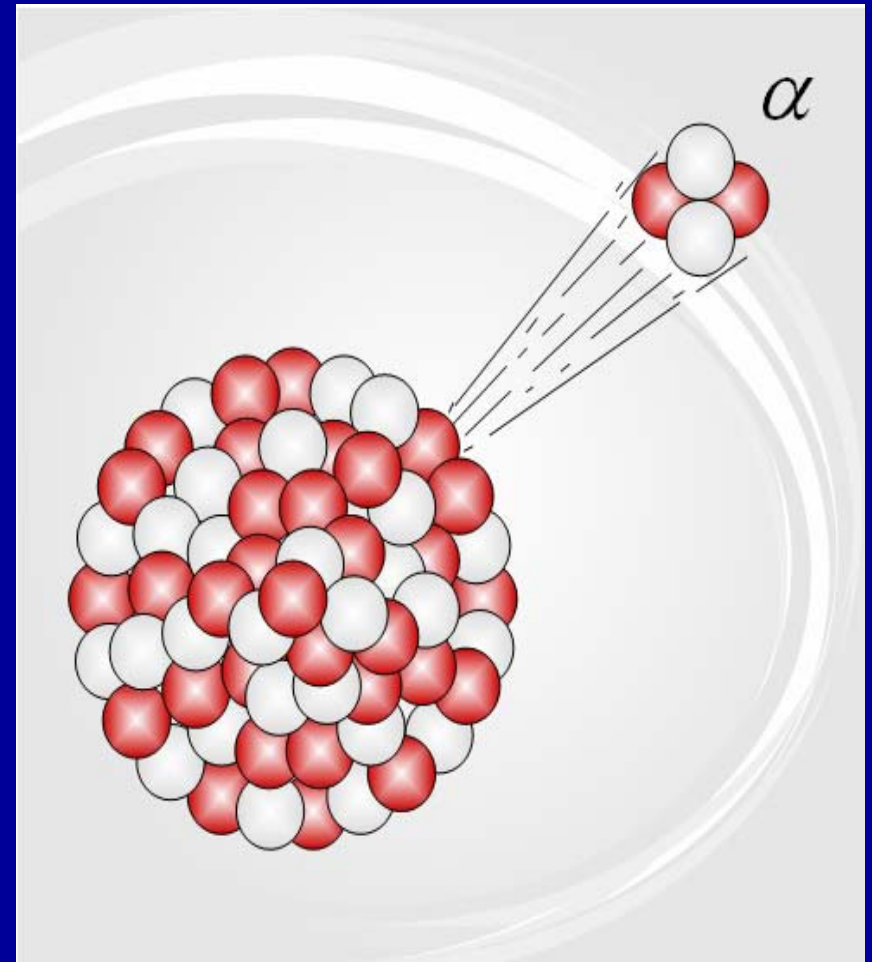
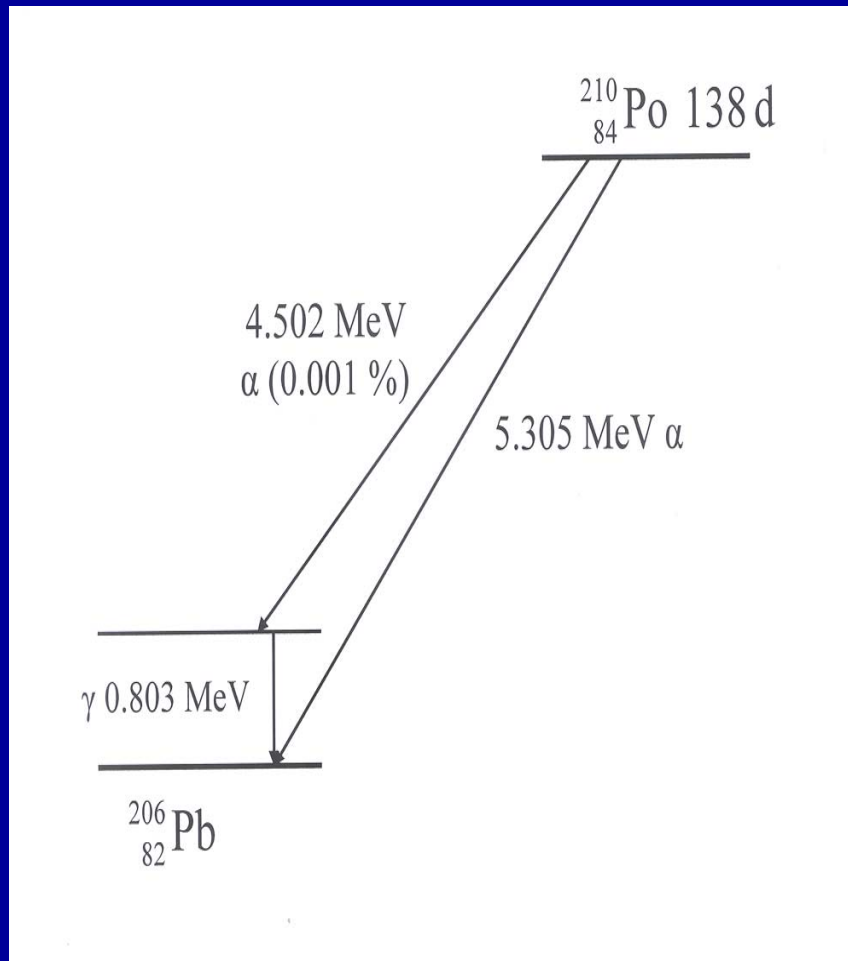
Los Alamos National Laboratory Chemistry Division

Periodic Table of the Elements

1A 1 H hydrogen 1.008																	8A 2 He helium 4.003						
3 Li lithium 6.941	2A 4 Be beryllium 9.012																	3A 5 B boron 10.81	4A 6 C carbon 12.01	5A 7 N nitrogen 14.01	6A 8 O oxygen 16.00	7A 9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31	3B	4B	5B	6B	7B	8B				11B	12B	13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.07	17 Cl chlorine 35.45	18 Ar argon 39.95					
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.88	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.39	31 Ga gallium 69.72	32 Ge germanium 72.58	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.80						
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.94	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3						
55 Cs cesium 132.9	56 Ba barium 137.3	57 La* lanthanum 138.9	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 190.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.5	81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 208.9	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 (260)	106 Sg seaborgium (263)	107 Bh bohrium (262)	108 Hs hassium (265)	109 Mt meitnerium (266)	110 Ds darmstadtium (271)	111 Uuu (272)	112 Uub (277)	114 Uuq (296)		116 Uuh (298)		118 Uuo (?)							
Lanthanide Series*		58 Ce cerium 140.1	59 Pr praseodymium 140.9	60 Nd neodymium 144.2	61 Pm promethium (147)	62 Sm samarium (150.4)	63 Eu europium 152.0	64 Gd gadolinium 157.3	65 Tb terbium 158.9	66 Dy dysprosium 162.5	67 Ho holmium 164.9	68 Er erbium 167.3	69 Tm thulium 168.9	70 Yb ytterbium 173.0	71 Lu lutetium 175.0								
Actinide Series~		90 Th thorium 232.0	91 Pa protactinium (231)	92 U uranium (238)	93 Np neptunium (237)	94 Pu plutonium (242)	95 Am americium (243)	96 Cm curium (247)	97 Bk berkelium (247)	98 Cf californium (249)	99 Es einsteinium (254)	100 Fm fermium (253)	101 Md mendelevium (256)	102 No nobelium (254)	103 Lr lawrencium (257)								

element names in **blue** are liquids at room temperature
 element names in **red** are gases at room temperature
 element names in **black** are solids at room temperature

Polonium 210 Decay Scheme



The Health Effects of ^{210}Po Exposure

Background

Isotope	Half-Life	Specific Activity (TBq/g)	Decay Mode	Alpha (α) Energy (MeV)
Polonium-208	2.9 yr	21.8	α	5.1
Polonium-209	103 yr	0.63	α	4.9
Polonium-210	138 days	166	α	5.3

g = gram, and MeV = million electron volts;

The Health Effects of ^{210}Po Polonium Exposure

Chemical Properties

- **Soluble in acidic environment**
 - **The Polonium was likely dissolved in solution and poured into his tea**
 - **Acidic gastric environment probably improved solubility and absorption**
- **Electron configuration and properties similar to Selenium and Tellurium**
- **Binds most favorably to molecules with sulfhydryl groups**

The Health Effects of ^{210}Po Exposure

Physical Properties

- Relatively low melting point
- Aerosolizes at 100°C
 - 45% aerosolized at 55°C
 - Significant aerosolization at room temp
- Tendency to “creep”
 - Contaminates local environment
- Radioactive - α particle decay to ^{208}Pb
 - 138 day physical half life

The Health Effects of ^{210}Po Polonium Exposure

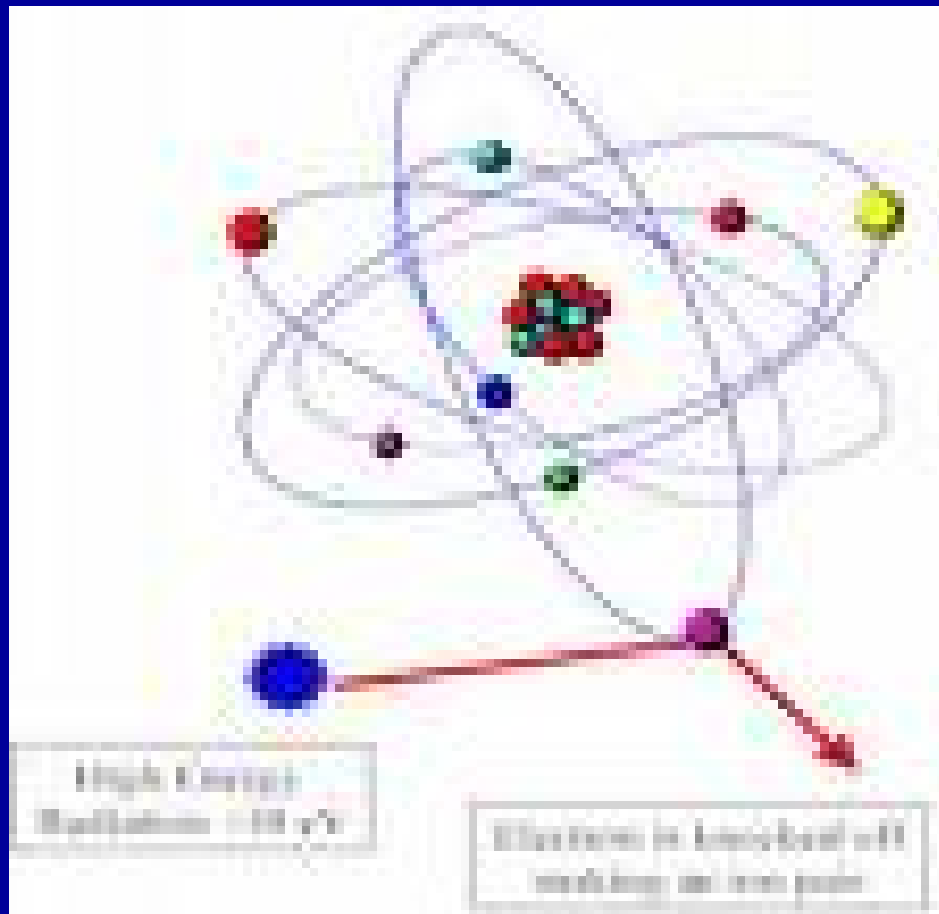
Ionizing Radiation

- **Gamma Rays**
- **X-rays**
- **Particles**
 - **Alpha particles**
 - **Beta particles**
 - **Neutrons**



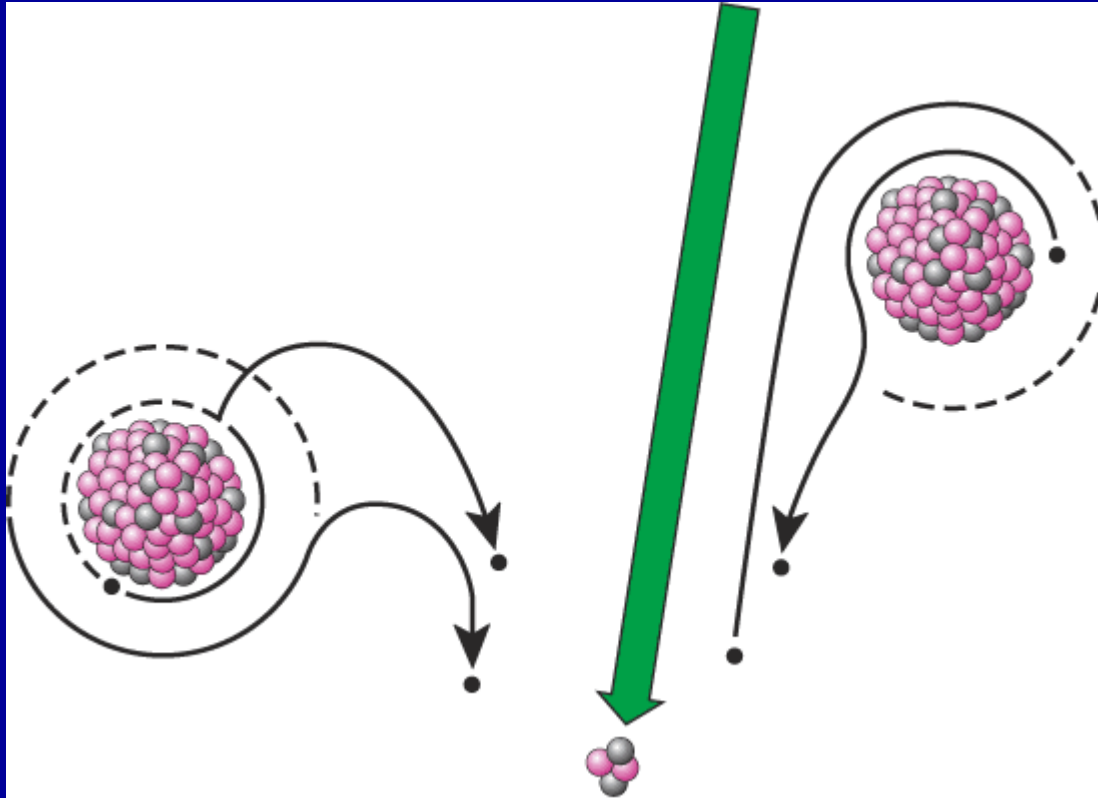
The Health Effects of ^{210}Po Polonium Exposure

Ionizing Radiation



The Health Effects of ^{210}Po Exposure

Ionizing Radiation



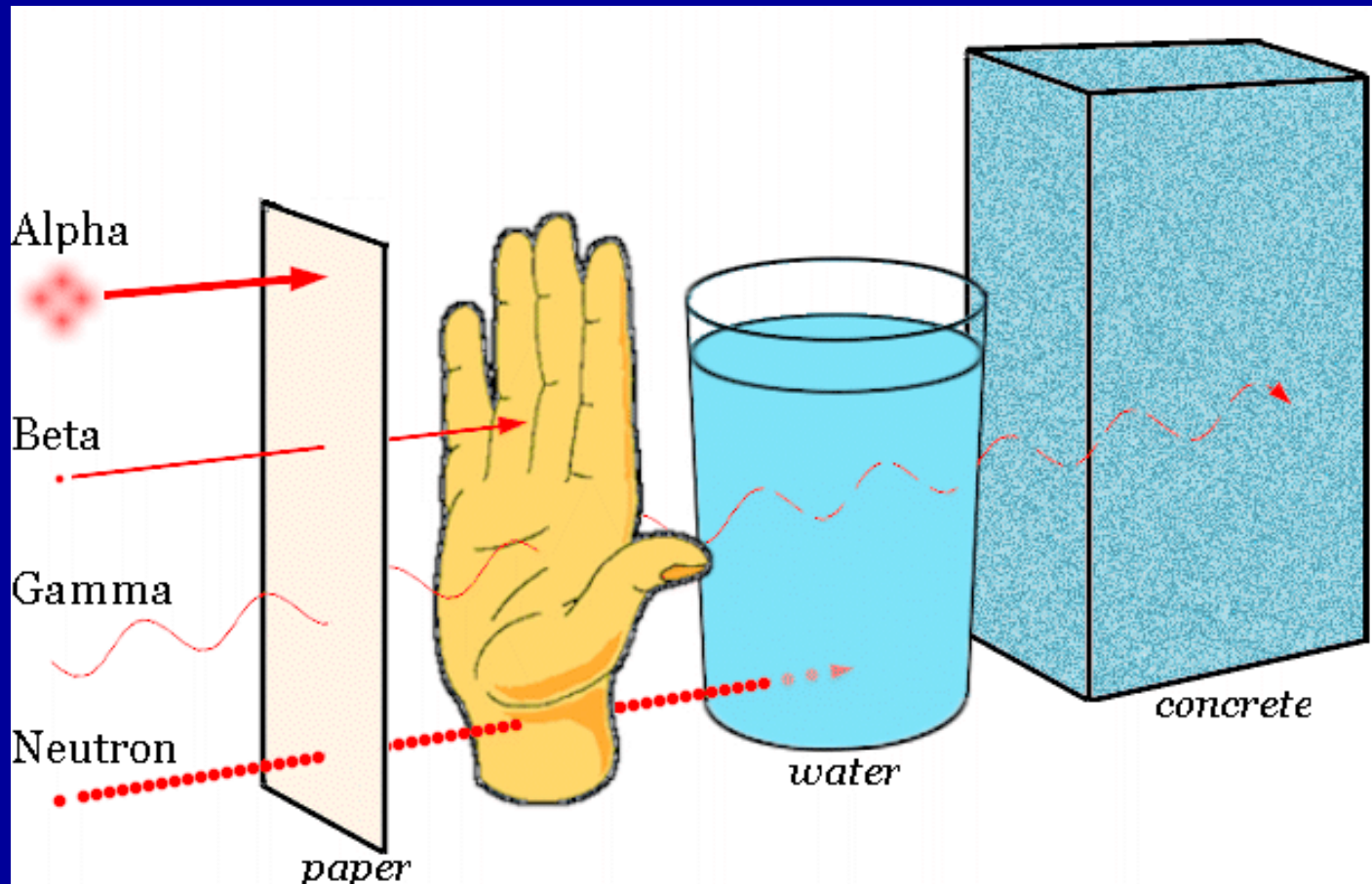
The Physical Properties of ^{210}Po

Radioactive Properties

- **Almost pure α emitter, 5.297 MeV**
 - **Mass number 4, Charge +2**
 - **Short range, 2-3 cm in air**
 - **Low penetrating power**
 - **Skin or sheet of paper can stop penetration**
 - **Damage only if internalized**
- **γ wave only 1/100,000 disintegrations**
- **Generates high heat internally**
 - **1 gm can spontaneously reach 500°C**

The Health Effects of ^{210}Po Exposure

Ionizing Radiation



The Physical Properties of ^{210}Po

Radioactive Properties

- **Extremely high specific activity (Bq/s)**
 - **166 TBq/g (10^{12}) trillion**
 - **By comparison 1gm has same radioactivity as 5 kg of Radium**
 - **1 μg delivers 50 Sieverts (5000 rads) whole body dose if absorbed – grain of salt**
 - **10 μg estimated to have killed Litvinenko, more than 200 X the median lethal dose**
- **1 trillion times more toxic than cyanide**

The Health Effects of ^{210}Po Polonium Exposure

Biologic Properties

- High LET α particle radiation
- Directly ionizing heavy charged particle
 - Disrupts cell structures, fragments nuclei, damages DNA with double strand breaks and causes cell death
 - Damage is in large part **IRREVERSIBLE** and **IRREPARABLE**
- Biologic 1/2 life is 50 days
- Effective 1/2 life is 36.7 days (P + B)

The Health Effects of ^{210}Po Exposure

Biologic Properties

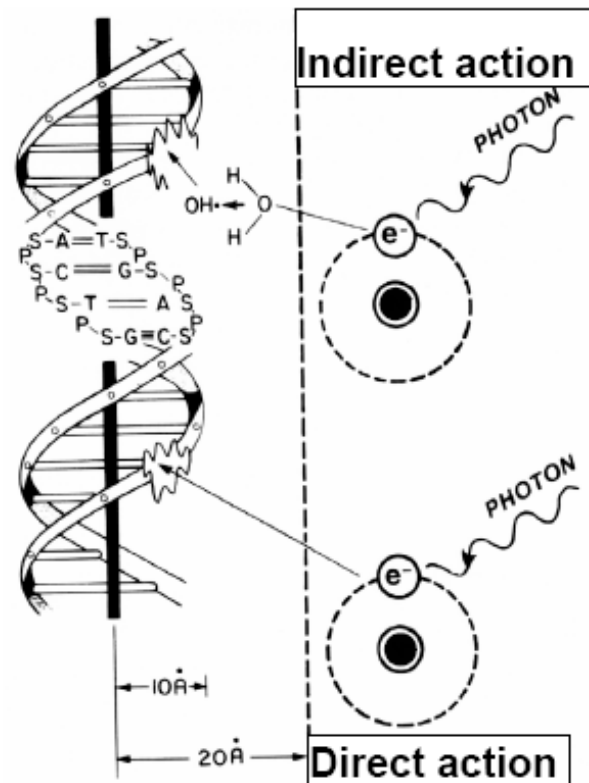
Direct and indirect action of radiation

Indirect action:

secondary e^- interacts with another molecule, e.g. H_2O
generation of radicals which produce the damage to the DNA,
dominant process for radiations with low LET: X-, γ -rays.

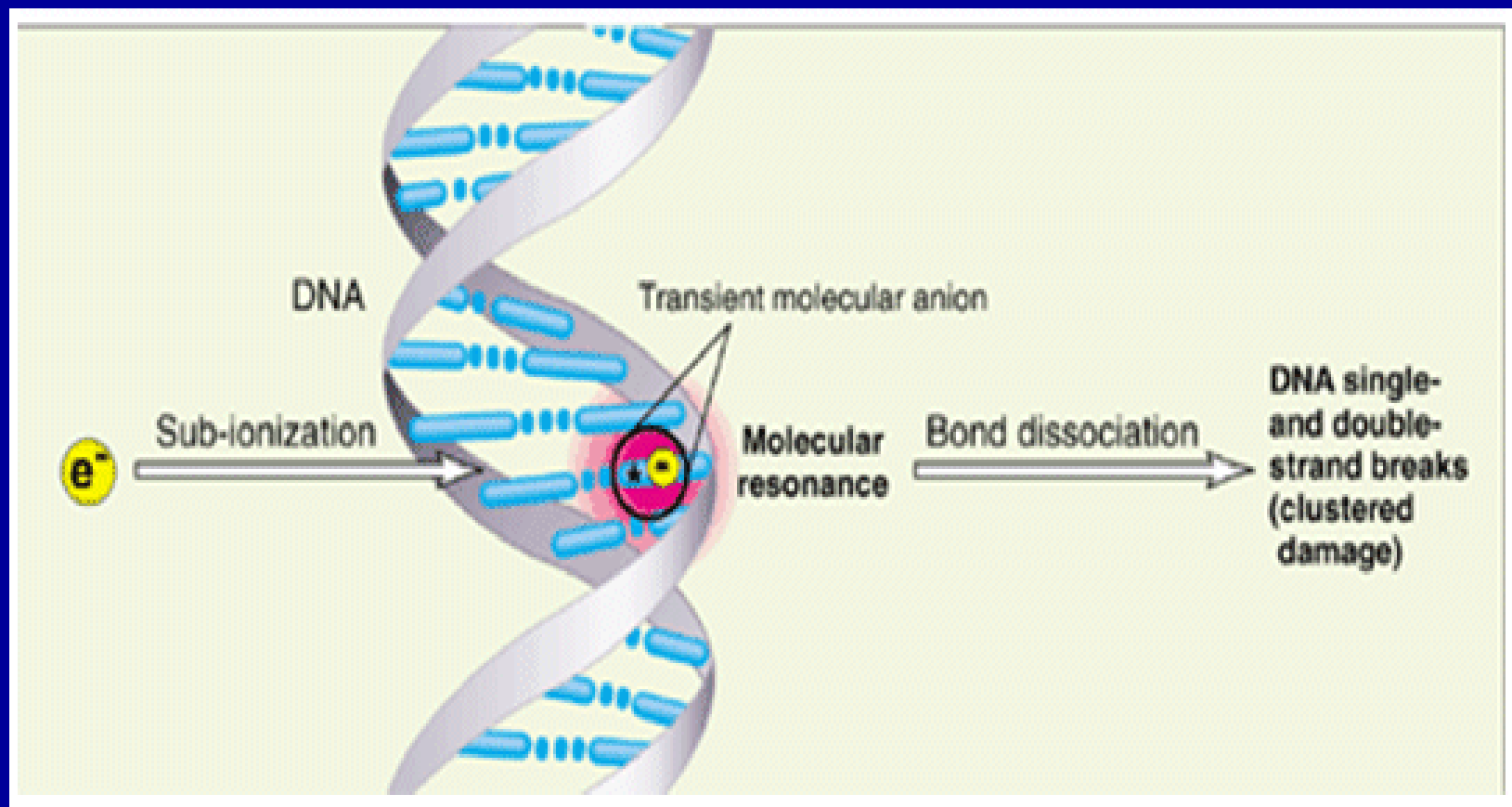
Direct action:

secondary e^- resulting from absorption of a photon interacts directly with the DNA,
dominant process for radiations with high LET: neutrons, α -particles, heavy ions



The Health Effects of ^{210}Po Exposure

Biologic Properties



The Health Effects of ^{210}Po Exposure

Biologic Properties



The Biologic Properties of ^{210}Po α Particle High LET Radiation

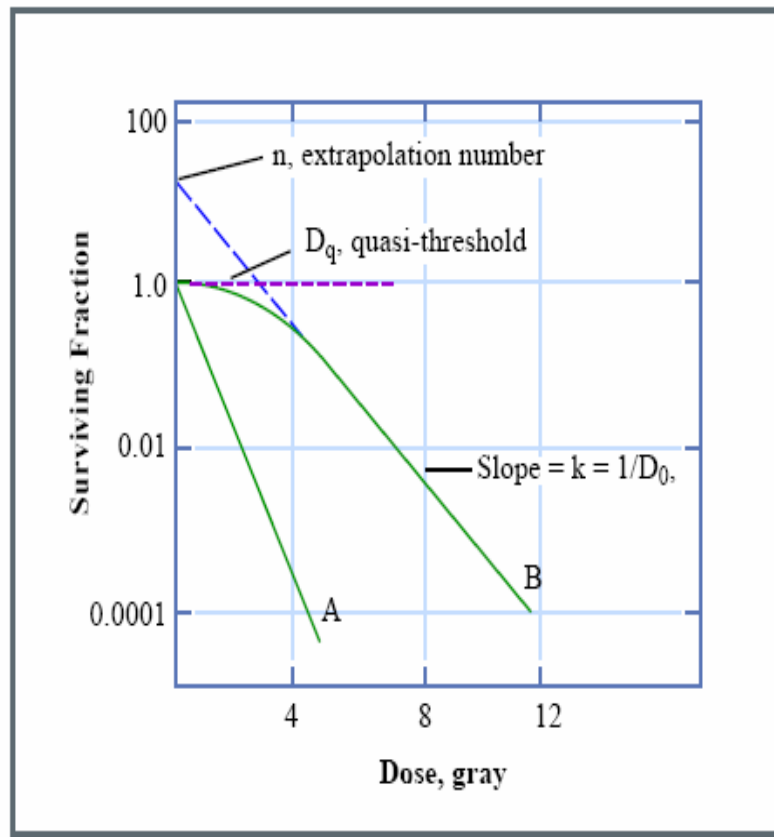
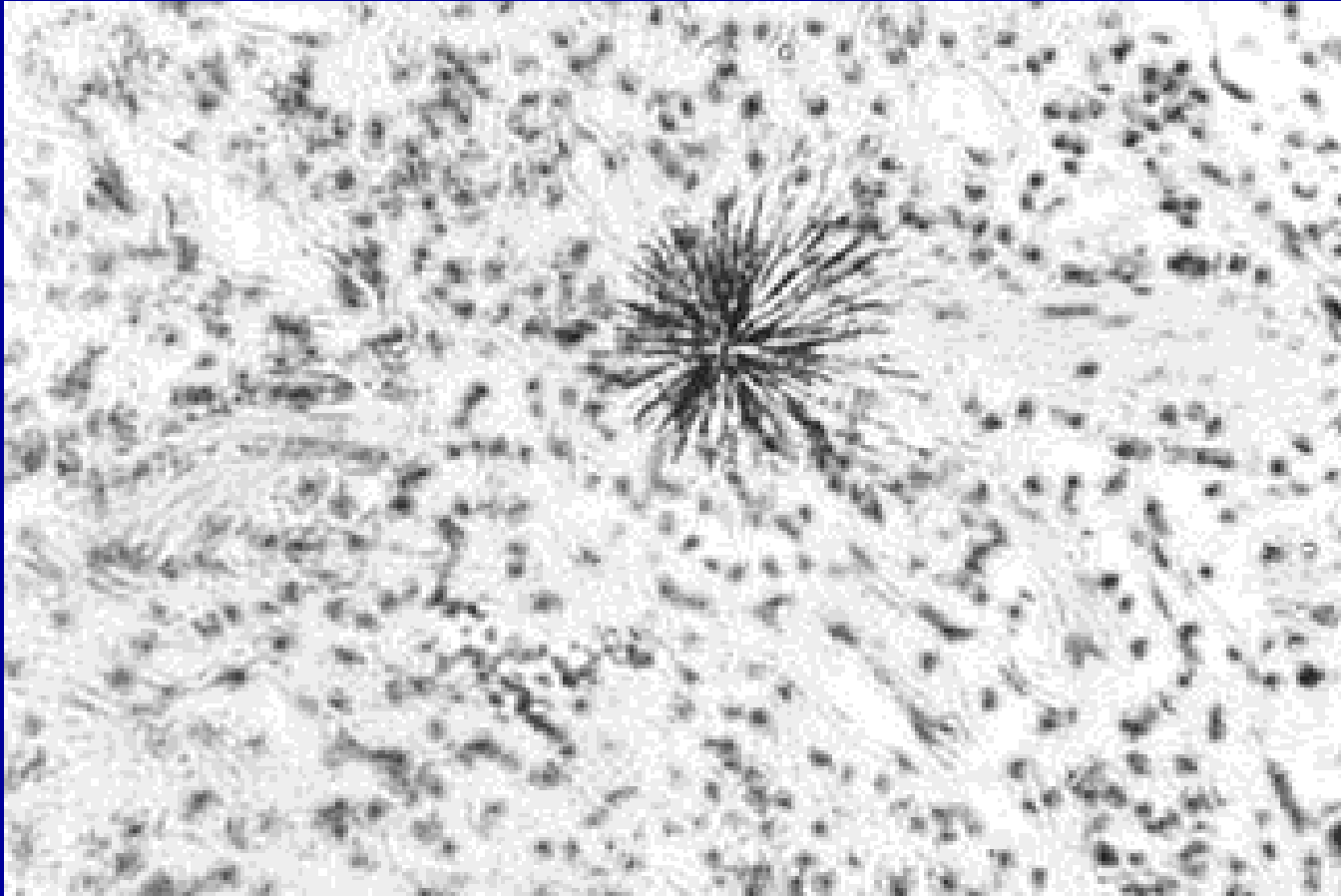


Figure by MIT OCW.

- No shoulder indicating no repair
- Steeper indicating more kill per dose of radiation
- 20 times more lethal than photons
- 1Gy (100 rads) = 20 Sieverts (2000 rads)

The Health Effects of ^{210}Po Polonium Exposure

Biologic Properties



Alpha track ionization from 1 micron Plutonium particle in lung, Mag 500X

The Health Effects of ^{210}Po Polonium Exposure

Biologic Properties



The Health Effects of ^{210}Po Exposure

Acute Radiation Syndromes

- **Dose Dependent**
 - Onset of symptoms, type of symptoms, severity of symptoms, time to lethal effect
- **Time Dependent**
- **External vs Internal Exposure**
 - **Often easier to estimate external dose**
 - **Internal Radionuclide becomes incorporated into tissues of affected individual**
 - **Difficult to decontaminate**
 - **Becomes systemic and delivers whole body dose**

The Health Effects of ^{210}Po Polonium Exposure

Acute Radiation Syndromes

- **Prodromal Syndrome**
 - Vary with time of onset, severity and duration
 - Dose close to LD_{50} causes anorexia, nausea, vomiting and easy fatigability
 - Immediate, diarrhea, fever, hypotension associated with supralethal exposure
- **Cerebrovascular Syndrome**
 - Whole body exposure of 10,000 rads
 - Characterized by edema, convulsion, coma
 - Death within 30 – 50 hours

The Health Effects of ^{210}Po Polonium Exposure

Acute Radiation Syndromes

- **Gastrointestinal Syndrome**
 - Whole body exposure of 1000 rads
 - Depopulation of the epithelial lining
 - Death in about 9 days from infection, volume loss
- **The Hematopoietic Syndrome**
 - Whole body exposure of 300-800 rads
 - Sterilization of blood forming elements
 - Death in 3 weeks or more
 - LD_{50} about 300 to 400 rads

The Health Effects of ^{210}Po Exposure

Acute Exposure Levels and Symptoms

- 0.2 - 0.5 Sv No noticeable symptoms
- 0.5 – 1 Sv Mild sickness with headaches increased risk of infection
- 1 -2 Sv Mild to mod nausea, possible vomiting 3 - 6 hours after. 10 – 14 day latent period then fatigue. Depressed immune system
- 2 – 3 Sv Moderate poisoning. $\text{LD}_{35/30}$ Nausea common, vomiting at 2.8 Sv. Symptom onset 1- 6 hours. 50% loss of body hair at 3 Sv. Fatigue, significant drop in WBC, infection

The Health Effects of ^{210}Po Exposure

Acute Exposure Levels and Symptoms

- 3 – 4 Sv Severe poisoning, $\text{LD}_{50/30}$, Above symptoms plus bleeding from mouth, under skin, kidneys after latent phase
- 4 – 6 Sv Acute poisoning, $\text{LD}_{60/30}$, Symptoms 1-2 hours after exposure and last for 2 days. Latent period 7 – 14 days. Death from infection, bleeding.
- 6 -10 Sv $\text{LD}_{100/14}$, Bone marrow almost completely destroyed. Symptoms 15 – 30 minutes after exposure. 5 – 10 day latent phase. Death from infection, bleeding. Occasional survivor.

The Health Effects of ^{210}Po Exposure

Acute Exposure Levels and Symptoms

- 10 – 50 Sv, $\text{LD}_{100/7}$, Symptoms 5 to 30 minutes after exposure. Powerful fatigue and immediate nausea. Latent “walking ghost” phase. Then massive diarrhea, delirium, circulatory collapse.
- >50 Sv Death in 2 – 3 days

The Biologic Properties of ^{210}Po Polonium

Target Organs

- **Only dangerous if internalized**
 - **Ingested, inhaled, injected, or open wound**
- **Ingested Route (GI portal of entry)**
 - **50-90% excreted in feces**
 - **Remaining fraction enters blood stream**
 - **45% concentrated in the spleen, kidney, liver**
 - **10% makes it to the bone marrow**
 - **The rest to soft tissues, mucous lining, nodes**
 - **Mirrors whole body external exposure because of significant systemic component**

The Health Effects of ^{210}Po Exposure

What happens after ingestion

- Dose to GI tract delivered rapidly
 - Sensitive mucosal lining affected 1st causing food poisoning like symptoms with nausea, vomiting, diarrhea
- Binds avidly to hemoglobin resulting in high concentration in the blood
- Systemic dose accumulates slowly but becomes significantly larger than GI
 - Latent period occurs during this accumulation

The Health Effects of ^{210}Po Exposure

What happens after ingestion

- **Maximum total exposure is 43 times the first day dose**
 - **Most accumulated in first 30 days**
 - **Accumulation thereafter is still significant**
- **Minimal lethal dose for 80 kg person is 4 mCi, about $0.89\mu\text{g}$ (10^{-6}g). An almost invisible speck of matter.**

The Health Effects of ^{210}Po Exposure

Ingestion of Minimal Lethal Dose

- No initial illness, 1st day dose .16 Sv
- No effect 1st week, mild symptoms next
- Serious illness not expected for month
 - Dangerous levels of damage accumulates
- Exposure rises to over 7 Sv in next two months
- Death in 2 – 3 months due to hematopoietic syndrome
 - Lethal dose required is higher than single acute exposure of external radiation

The Health Effects of ^{210}Po Exposure

Ingestion of a Supralethal Dose

- Assumed to have received at least 10 times the lethal dose, $10\mu\text{g}$ or 50mCi .
 - GI tract receives disproportionate dose for 1st few days at 1.6 Sv/day , total 4 Sv causing nausea and diarrhea within hours
 - Systemic dose continues to accumulate in GI tract, $>7\text{ Sv}$ destroying the lining and causing the gastrointestinal syndrome
 - Total accumulated dose at death about 35 Sv resulting in cardiovascular collapse

The Health Effects of ^{210}Po Exposure

Treatment

■ Chelators

- **BAL (British Anti-Lewisite) 2,3-dimercaptopropanol**
 - Lipid soluble molecule used for treatment of heavy metal poisoning
 - Developed for WWI and WW2
 - Painful intramuscular injections
 - Low therapeutic safety index due to side effects
- **DDTC (diethyldithiocarbamate) derivatives**
 - 1997 study in rats extended survival over 100 days

The Health Effects of ^{210}Po Exposure

Treatment Limitations

- Studies using chelating agents performed under optimal controlled situations with agents given within hours of contamination
 - **Not realistic in the real world however:**
 - Delay in getting to the hospital
 - Delay in diagnosis, sx's mimic food poisoning etc.
 - Delay in identifying the radioactive material
 - The longer the delay between contamination and treatment the more dose delivered
 - Effects are Irreversible and Irreparable
 - Newer agents not tried on humans as yet

The Health Effects of ^{210}Po Exposure

Practical Management

- Keep exposure in differential diagnosis
- Estimate exposure based excreted dose in urine
- Supportive Care
 - Antibiotics
 - Aggressive fluid management
 - Transfusions, bone marrow transplants
- Keep fingers crossed

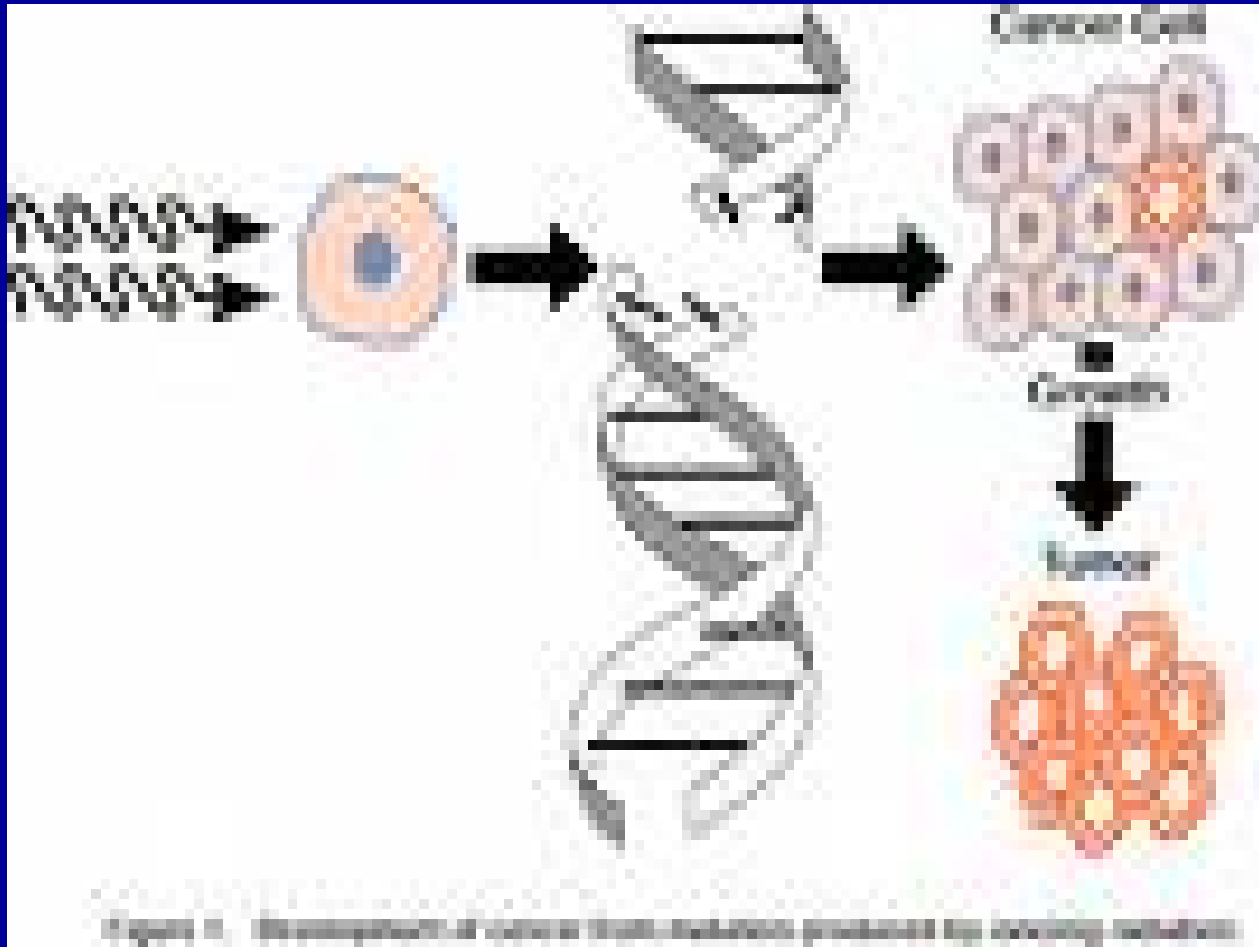
The Health Effects of ^{210}Po Exposure

Carcinogenesis

- Occurs from mutations or activation of oncogenes
- Radiation carcinogenesis is a Stochastic effect, no threshold
- Long latent period
 - Leukemia 5 years or more
 - Solid tumors 20 years or more
- Risk higher for high LET radiation
- Total cancer risk estimate $100/10^4/\text{Sv}$ or $1/10^5/\text{mSv}$ according to (UNSCEAR)

The Health Effects of ^{210}Po Exposure

Biologic Properties



The Health Effects of ^{210}Po Exposure

Incidental Exposure

- **Category 1**
 - **592 people, <30 mBq per day in urine**
 - Background is 5-15 m/Bq per day of ^{210}Po
 - Below reporting level, unlikely exposed
- **Category 2**
 - **85 people, >30 mBq, but dose < 1 mSv**
 - Probable contact, no public or individual health risk
- **Category 3a**
 - **35 people, > 1mSv but < 6 mSv**
 - Probable contact, no public or individual health risk

The Health Effects of ^{210}Po Exposure

Incidental Exposure

- **Category 3b**
 - **17 people with $> 6\text{mSv}$ exposure**
 - Not enough to cause any short term illness
 - Increased risk in long term illness is very small
 - Risk of malignancy is $1/100,000/\text{mSv}$
 - So would expect to see maybe 6 additional cancers per 100,000 people exposed

The Health Effects of ^{210}Po Exposure

Radiation Dose Comparisons

ITEM	DOSE (Gy)	DOSE (Rad)	DOSE EQUIVALENT (mSv)
Flying roundtrip from NY to Ca	0.00006	0.006	0.06
Chest X-ray	0.00006	0.006	0.06
One-View Abdominal X-ray	0.001	0.1	1
Avg. Annual Background Radiation Dose	0.0036	0.36	3.6
Abdominal CT scan	0.01	1	10
NRC Occupational Worker Annual Limit	0.05	5	50
Acute Dose Causing Decreased WBC	1	100	1000
LD50/30, Lethal dose to 50% of exposed individuals	4.5	450	4500

The Health Effects of ^{210}Po Polonium Exposure

Why Polonium?

- Essentially a pure α emitter
 - Easy to shield and carry undetected
- High Specific Activity (Very Radioactive)
 - Small amount needed for lethal effect
- High LET radiation
 - Damage is irreparable and irreversible. Likely to have intended effect.
- Not easily detected externally in those exposed
- Initial symptoms mimic other maladies
 - Diagnosis ^{210}Po not likely in initial differential
 - Never used as poison before this
- Limited medical treatment available
- Political Statement
 - Let other traitors know they are not out of reach

The Health Effects of ^{210}Po Exposure

The Death of Alexander Litvinenko



- Died Nov. 23rd, 2006
9:21 pm, age 43
 - 22 days after ingestion
- Nov. 24th dictated deathbed statement published
- Nov. 24th, HPA announces Litvinenko died from ^{210}Po poisoning