Donostia International Physics Center

Lecture 2

Xenon

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Donostia International Physics Center

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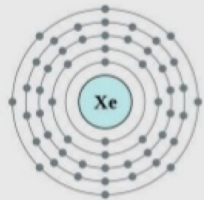
Xe Xe XENON Xe Xe Xe Xe

What is Xenon & its Physical Properties?

Xenon is a colourless, heavy and odourless noble gas; located in the periodic table in period five and group eight. Xenon occurs in the Earth's atmosphere in trace amounts and is generally unreactive. The boiling point of Xenon is 108.13°C (-162.5°F) and a melting point of -111.8°C . The atomic number for Xenon is 54 and its atomic weight is 131.293. Its electron configuration is 2,8,18,18,8.



The Discovery of Xenon

Scottish chemist William Ramsay and English Chemist Morris Travers discovered Xenon on the 12th of July, 1898. Both chemists found Xenon in the residue left over from evaporating components of liquid air. Xenon is a Greek word meaning "Foreign", "Strange" and "Guest".

Xe Xe XENON Xe Xe Xe Xe

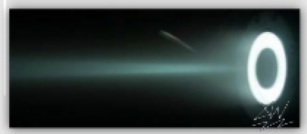
Chemical Properties

Xenon is a unreactive gas that is regarded as completely inert until Neil Barlett, in 1962 reported the synthesis of Xenon **Haxafluoroplatinate**. In a gas filled tube xenon emits blue light when excited by electrical discharge.

Uses

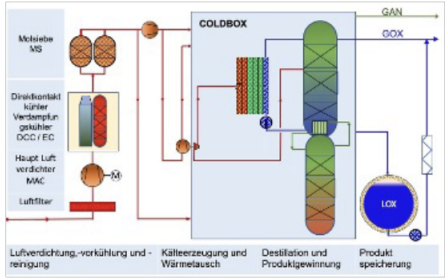
Xenon is used in:

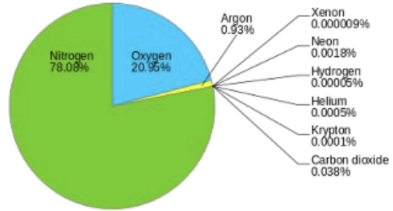
- photographic flash lamps
- Stroboscopic lamps
- High-intensitive arc-lamps for motion picture projection
- High-pressure arc lamps to product ultraviolet light (solar simulators).
- Xenon 'blue' headlights and fog lights are used on some vehicles and are said to be less tiring on the eyes. They illuminate road signs and markings better than conventional lights.



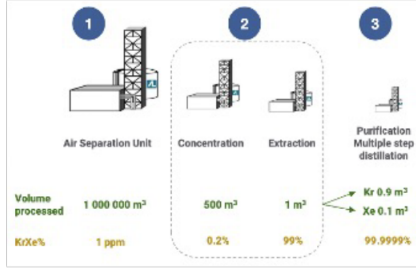
Xenon Production

➔ xenon is a by-product of air liquification predominantly for steel production





➔ cryogenic distillation: liquify & boil-off



LOX: increased fraction of Xe, Kr, ...

➔ second round of distillation

➔ further xenon-krypton enhanced 'crude'

➔ further distilled to seperate Xe and Kr

➔ another distillation for highest purity Xe (6.0 or higher)

Nomenclature: $5.0 = 10^{-5} = 99.999$ purity

Xenon Production Bottlenecks

There exist O(500) (sizable) air liquification plants all over the world

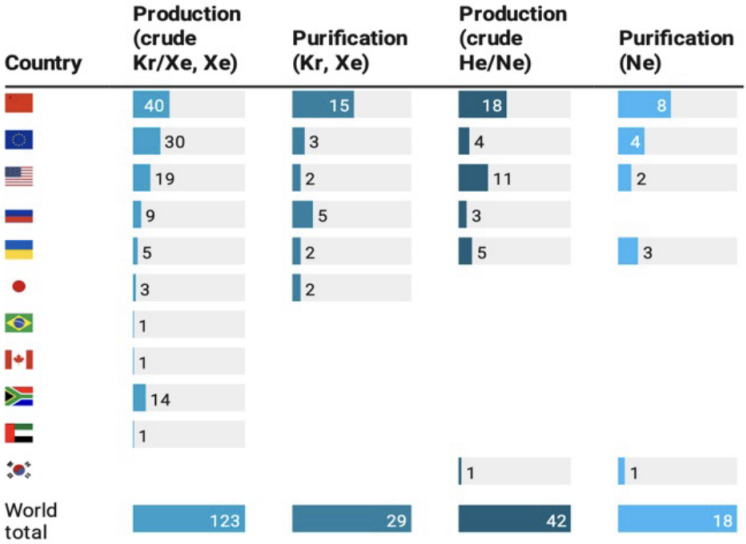
Only a small fraction (~1/5) is equipped to produce rare gases
- traditionally high fraction in the former Soviet Union = Russia, Ukraine,...
- China growing rapidly...

Crude Xe/Kr production and Xe/Kr purification often in different countries

Adding Xe/Kr production requires to specially equip ASU's:
- financially not worth while to modify existing plants (cost/efficiency)
- financial threshold: O(80M€)
- newly built ASU's or added upon replacement of existing ASU's
  - if prices are expected high enough for long enough ⟷ return of invest

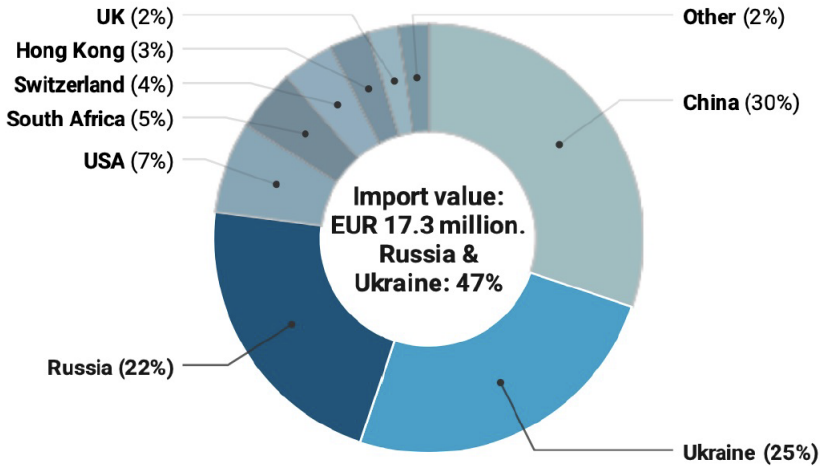
Overall world-wide xenon production (before Ukraine war):
~ linearly growing. Now ca. 65 t / year; growth ca. 2t/year
~ ca. 90% are fixed term contracts with industry → small spot market few t/year

Xenon Production by Country



Xenon from Russia and Ukraine

EU import value of rare gases[16] by origin, in 2021



Source: Eurostat Comext (2022).

It's the economy stupid

- Xe/Kr is a by-product of steel production – otherwise extremely expensive
  ←→ connected to the steel market ←→ overall economic development
- Who pays for Kr/Xe separation
  ←→ Kr and Xe markets: demand ←→ uses
- The Krypton market:
  Insulation windows ←→ energy costs for heating
  lighting ←→ transition to LED's
  propellant for thrusters ←→ Xe price
- Typical Xe price range: 5-20$ /liter ←→ threshold for investing into new ASU's
- Past price excursions due to unexpected events:
  - Iridium satellite plans
  - plasma displays
  - now: Ukraine war...

A Volatile Market

Recent developments during due to Ukraine war:

- a large fraction of the Ukrainian production is missing
- embargo policies ←→ Russian suppliers

Consequences:

➔ very volatile market

➔ consumers moving to alternative solutions:

- e.g. Starlink ➔ argon (lifetime of thrusters ←→ cost of replacement)
- ...

➔ in addition: general market trends

➔ prices went very high even beyond 1000$/liter

Changes:

A) gas companies think about new ASU's in other countries

- time scales?
- is on-going...

B) embargo by-passing: xenon from Kasachstan? ...more from China?, ...

➔ prices have significantly dropped, even $10/L , market still volatile...

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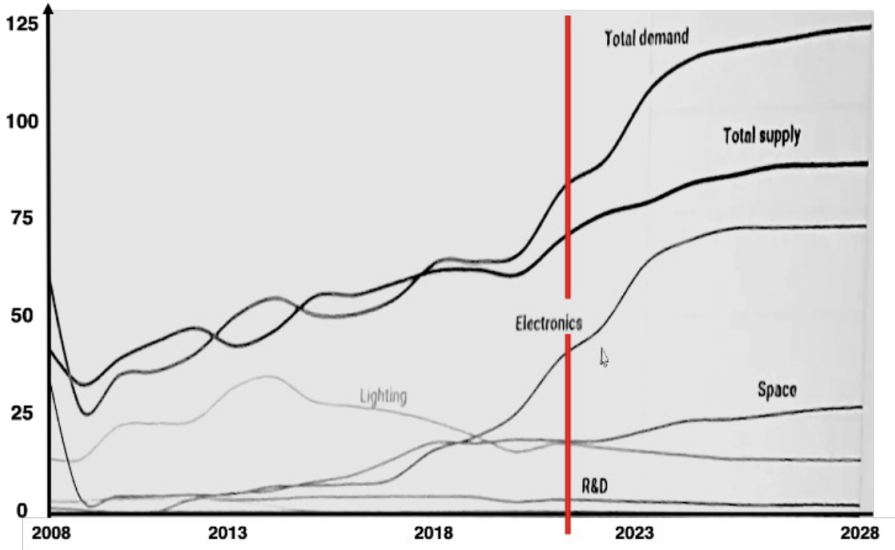
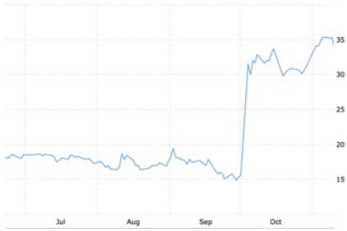
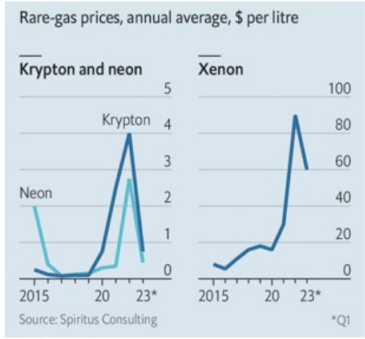
Supply versus Demand



Xenon Price

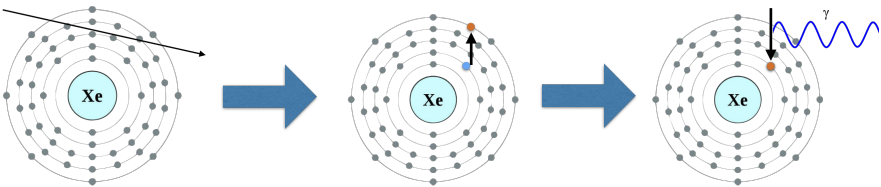

40
35
30
25
20
15
10
5
2015
2016
2017
2018
2019
2020
2021
2022


35
30
25
20
15
Jul
Aug
Sep
Oct


Rare-gas prices, annual average, $ per litre
Krypton and neon
Xenon
Krypton
Neon
5
4
3
2
1
0
100
80
60
40
20
0
2015
20
23*
2015
20
23*
Source: Spiritus Consulting
*Q1
The Economist

Ionisation and scintillation in Xe

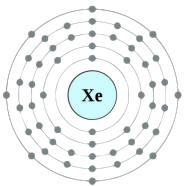
Energy (charged particle interacting with the gas)

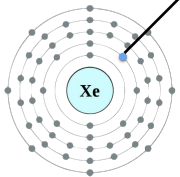


$$Xe^* + Xe + Xe \rightarrow Xe_2^* + Xe,$$
$$Xe_2^* \rightarrow 2Xe + h\nu$$

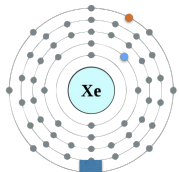
Ionisation and scintillation in Xe

Energy (charged particle interacting with the gas)

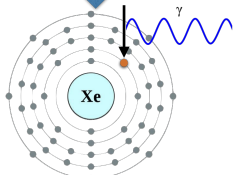




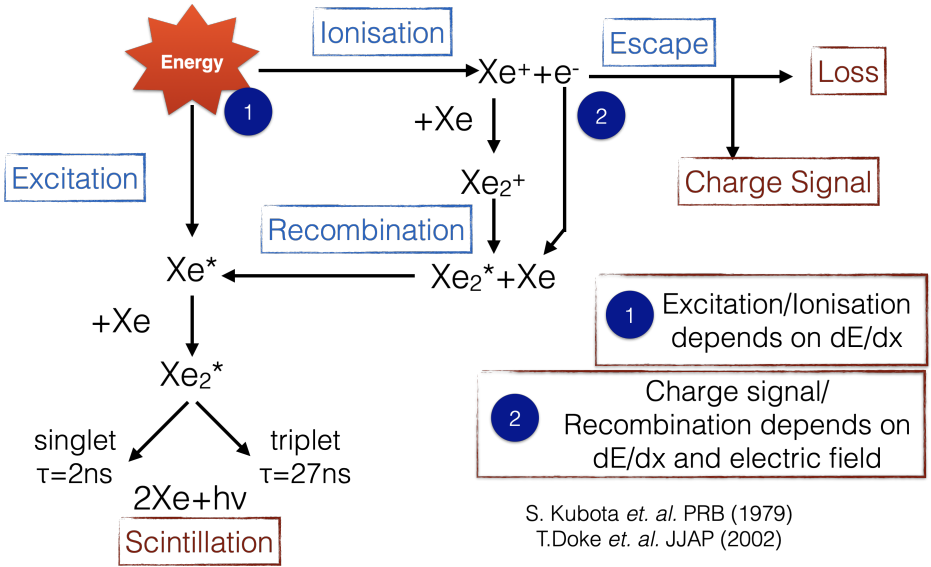
If electron escapes, charge signal or information loss



$$Xe^{+} + Xe \rightarrow Xe_2^{+},$$
$$Xe_2^{+} + e^{-} \rightarrow Xe^{**} + Xe$$
$$Xe^{**} \rightarrow Xe^{*} + heat$$
$$Xe^{*} + Xe + Xe \rightarrow Xe_2^{*} + Xe,$$
$$Xe_2^{*} \rightarrow 2Xe + h\nu$$

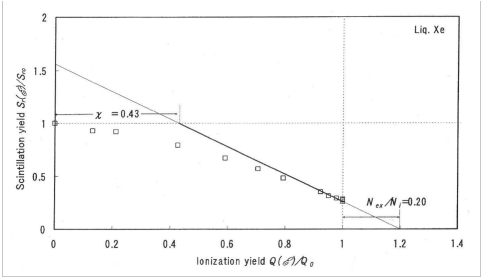


Ionisation and scintillation in Xe



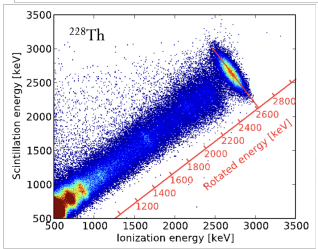
S. Kubota *et. al.* PRB (1979)
T.Doke *et. al.* JJAP (2002)

Anticorrelation between ionisation and scintillation in Xe

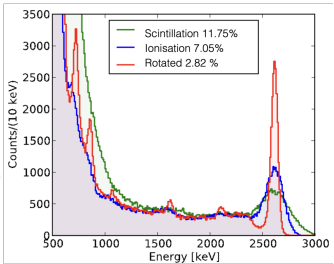


Perfect anti-correlation
of the charge and light signal

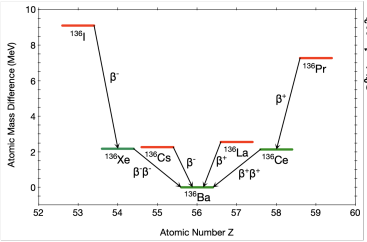
Doke, T. et al., 2002, Jpn. J. Appl. Phys

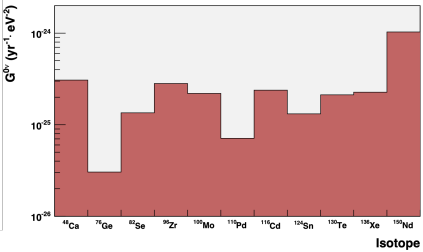


LXe experiments
use this anti-correlation to
get a better energy
measurement

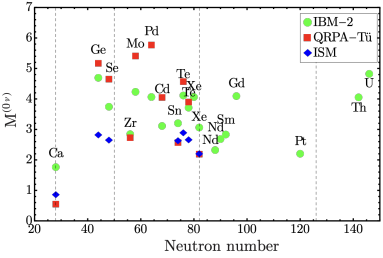


^{136}Xe is a good isotope for $\beta\beta0\nu$ searches



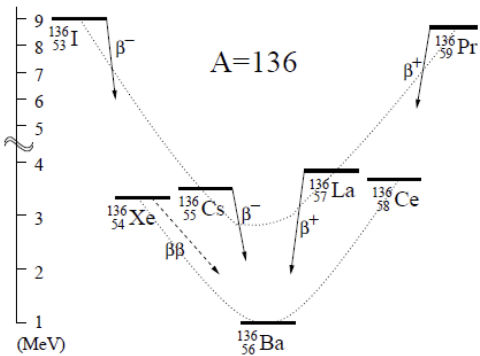


Relative atomic mass	135.907219(8) [24]
Q value $^{136}\mathrm{Xe} \to {}^{136}\mathrm{Ba}$	2457.83(37) keV [25]
	2458.7(6) keV [26]
	2458.1(3) keV (average)
$G^{0\nu}$ (10^{-15} year^{-1})	14.58 [27]
	14.54 [28]
$0\nu\beta\beta$ decay NME	2.19 (ISM) [29]
	3.05 (IBM-2) [30]
	2.46 (QRPA) [31]
	2.91 (QRPA) [32]
	4.12 (EDF) [33]
	4.32 (EDF) [34]



^{136}Xe is a good isotope for $\beta\beta0\nu$ searches

- Xenon is a good candidate for bb0n search
  - Q-value larger than energy of gammas from most natural radionuclides
  - Relatively easy to enrich in Xe-136 isotope
    - (no chemistry, centrifuge eff ~ dm=4.7 a.m.u.)
  - No need to grow high-purity crystals, continuous purification is possible (and relatively easy for a noble gas), more easily scalable
  - No long-lived cosmogenically activated isotopes
  - Final state (Ba-136 ion) can, in principle, be tagged, greatly reducing backgrounds



Exercise 1

- How much money would you need to buy the raw material for your ultimate $\beta\beta0\nu$ experiment in 2017? And in 2023? Assume you will need O(100) tons of Xe.