Laser Isotope separation

Keiichi YOKOYAMA

Kansai Photon Science Institute & Quantum Beam Science Center,
Japan Atomic Energy Agency
Isotopes

- Atoms with the same chemical character but different masses
  \[ ^{235}\text{U}, \, ^{238}\text{U}, \ldots \]

- Strongly related with nuclear reactions
  
  Fission, nuclear spallation, neutron capture

- Abundant in spent nuclear fuel
  
  \( \text{U, Pu, MA, FP} \)

- Both radioactive and non-radioactive isotopes exist
  
  \[ ^{137}\text{Cs}, \, ^{135}\text{Cs}, \, ^{133}\text{Cs} \]

- Isotope separation: to separate different isotopes in mixture
Why isotope separation demanded?

- To qualify neutron balance in transmutation

Some nuclides need isotope separation before their transmutation.

- To collect valuable rare metals from spent nuclear fuels without radioactivity

\[ ^{106}\text{Pd}, ^{107}\text{Pd} \]
Principal difficulty in the isotope separation

- Request for extremely high selectivity

Separation factors for cesium separation and uranium enrichment

Cesium separation

<table>
<thead>
<tr>
<th>Cs in spent fuel</th>
<th>Cs-135</th>
<th>Cs-133</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>99%</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

\[
\alpha \approx \frac{x}{1-x} \frac{y}{1-y}
\]

Separation factor \(\alpha \approx 9800\)!

Uranium enrichment

<table>
<thead>
<tr>
<th>Natural U</th>
<th>Enriched U</th>
<th>Depleted U</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7%</td>
<td>3-5%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

Require three-orders of magnitude higher SF

→ A paradigm shift is desired.
Why so small separation factor?

- No chemical method different from element separation
- Only mass-difference usable
- Very small mass difference in LLFP $^{135}$Cs, $^{133}$Cs
- Separation factor and cascade number in known methods

<table>
<thead>
<tr>
<th></th>
<th>Gas diffusion</th>
<th>Gas centrifuge</th>
<th>Molecular laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separation factor</td>
<td>1.003</td>
<td>1.4</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Cascade number</td>
<td>1000</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

- Laser method with as many cascade as gas diffusion method?
  → We proposed “quantum-diffusion method”.

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Quantum diffusion, how innovative

- From the classical mechanics to the quantum
- Surprisingly high isotope selectivity

- Relying on two hot topics in mathematics
  → “Quantum walk” and “Anderson localization”
How to realize quantum diffusion

- Repeatedly irradiate THz-wave laser pulse to diatomic molecules
  → Quantum diffusion realizes in the angular momentum space of molecular rotation


Quantum diffusion enables “isotope-selective heating”!? 

- Corresponding to a laser method with a large-scale cascade as large as the gas diffusion method
Numerical simulation

- Pronounced isotope selectivity in the CsI molecule

L. Matsuoka et al., GLOBAL2011, 392063

- By further pulse shaping, perfect separation possible

- Predicting a separation factor of 8000 for CsI @ 1000K
Experimental demonstration

- Demonstrated with an ordinary laser in place of the THz laser


Irradiating a pulse train whose interval is tuned to the rotational period of $^{14}\text{N}_2$

- THz-wave laser is under development for the true demonstration
Prospect to realization and key techniques

**Strong point**
- Molecular laser method without ultracold gaseous feed
  (Such a process has already been industrialized.)

**Techniques to be developed**
- Recovery scheme
- High-power THz-wave laser
- Precise manipulation of THz-wave pulses
Framework of the project and current activity

- @JAEA Kansai Photon Science Institute (Kizu, Kyoto)
- THz-wave laser (Nagashima, Ochi, Maruyama, Tsubouchi, Kono, Kiriyama, Okada, Kosuge)
- Demonstration (Matsuoka, Hashimoto, Yoshida) • Recovery (Ichihara, Kurosaki, Kobayashi)
Road map

Light elements
LiCl, KCl, ...

Heavy elements
CsI, Rbl

Recovery tech.
Improve throughput

2017
Demo. of select. heat
2014
<0.6THz, 10µJ
High power THz generation

2020
Demo. at high T
2017
<0.6THz, 100µJ
High power THz generation

2025
Engineering res.
2030
Pilot plant

2013
1µm, 1ps, 10mJ, kHz
Driver laser
2015
1µm, 1ps, 100mJ
Driver laser

2020
Pulse shaping
<0.6THz, 100µJ
THz optics

2025
Intense THz generation
2030
<0.6THz, 10mJ, 10Hz

2014
Photon frontier network (MEXT)

2017
1µm, 1ps, 10J, 10Hz
Intense driver laser
Microwave technology
Synchrotron technology
- We proposed a new isotope-selection scheme using quantum diffusion to override the difficulty in the isotope separation of heavy elements.

- Some fundamental studies are running at KPSI to realize quantum diffusion method.

Advocation of zero release of nuclear waste will drive germination of new science and technology.