A Breakthrough in Isotope Separation and its Application to Ca-48

Mark G. Raizen
The University of Texas at Austin
Isotope Separation

Calutron

Ernest O. Lawrence, Berkeley, CA, 1930
Calutron: 20th century workhorse

Applicable to almost all stable isotopes (over 250)

Primary US facility (Y-12 at ORNL) shut down in 1998
Modern Calutron (ca. 1950)
Worldwide Supply Crisis of Enriched Isotopes

Only large Calutron facilities in operation… in Russia

Urgent Need for New Methods!
Lack of Domestic Isotope Production Since 1990’s

“The US isotope program presently has no working facilities for the separation of a broad range of stable and long-lived isotopes. Each year it is depleting its unique stockpile of isotopes to the point where some are no longer available.”

- 2009 U.S. Nuclear Science Advisory Committee Report, page 7
Trace Sciences International
Production of Stable Isotopes

Modes of Production

H  He
Li  Be
Na  Mg
K  Ca  Sc  Ti  V  Cr  Mn  Fe  Co  Ni  Cu  Zn  Ga  Ge  As  Se  Br  Kr
Rb  Sr  Y  Zr  Nb  Mo  Tc  Ru  Rh  Pd  Ag  Cd  In  Sn  Sb  Te  I  Xe
Cs  Ba  *  Hf  Ta  W  Re  Os  Ir  Pt  Au  Hg  Tl  Pb  Bi  Po  At  Rn
Fr  Ra  **

*Lanthanides  La  Ce  Pr  Nd  Pm  Sm  Eu  Gd  Tb  Dy  Ho  Er  Tm  Yb  Lu
**Actinides  Ac  Th  Pa  U  Np  Pu  Am  Cm  Bk  Cf  Es  Fm  Md  No  Lr

Calutron  Centrifuge (Bulk Production)  Photochemical
Atomic Vapor Laser Isotope Separation (AVLIS)

Resonant ionization with pulsed lasers (~three visible photons)

Isotope shift to select desired isotope

Problems:

Requires very high power lasers (multi-kW)
Only applied to U, discontinued
New Technologies?

VECSEL
High-power solid-state lasers

Fiber Amplifiers

Fabry-Perot build-up cavities
Advanced LIGO, 1 MW cw power
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Can we use lasers more efficiently?
Alternative to Laser Cooling of Neutral Atoms

Two-step approach:

1. Atomic Coilgun

2. One-way wall cooling (Maxwell’s Demon)

M. G. Raizen, Science 324, 1403 (2009)

Supported by the W. M. Keck Foundation
A New Method for Efficient Isotope Separation

Magnetically-Activated and Guided Isotope Separation

MAGIS

Replacement for Calutron
Figures of Merit

Isotopic purity

Scalability to required quantities

Efficiency
Optical Pumping

Alfred Kastler
Nobel Prize 1966

Lumino-refrigeration
Optical Pumping

Initial Distribution

Optical Pumping

Final Distribution
MAGIS

A) View looking down onto the guiding plane

B) Oblique 3D view
Computer Simulation of MAGIS
Highly Depleted Li (HDLi)

Natural lithium: 92.41% Li-7, 7.59% Li-6

Nuclear reactors require Li-7 at 99.95% or better
Highly Depleted Li (HDLi)

Natural lithium: 92.41% Li-7, 7.59% Li-6

Nuclear reactors require Li-7 at 99.95% or better

Predicted performance of MAGIS:

Isotopic purity > 99.95%
Scalability to many kg/year
Efficiency of few photons/atom
Experiment results:

Purity > 99.95%
Scalability, Efficiency as predicted.
Li-6 depletion (RGA)
Li-6 depletion vs. temperature

![Graph showing Li-6 depletion factor vs. temperature.](image)
MAGIS Can Separate Over 130 Isotopes of Over 30 Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Stable Isotopes</th>
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<tbody>
<tr>
<td>1 Li</td>
<td>6,7</td>
</tr>
<tr>
<td>2 Mg</td>
<td>24,25,26</td>
</tr>
<tr>
<td>3 Ar</td>
<td>36,38,40</td>
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<tr>
<td>4 K</td>
<td>39,40,41</td>
</tr>
<tr>
<td>5 Ca</td>
<td>40,42,43,44,46,48</td>
</tr>
<tr>
<td>6 Cr</td>
<td>50,52,53,54</td>
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<tr>
<td>7 Fe</td>
<td>54,56,57,58</td>
</tr>
<tr>
<td>8 Ni</td>
<td>58,60,61,62,64</td>
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<tr>
<td>9 Cu</td>
<td>63,65</td>
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<tr>
<td>10 Zn</td>
<td>64,66,67,68,70</td>
</tr>
<tr>
<td>11 Ga</td>
<td>69,70</td>
</tr>
<tr>
<td>12 Kr</td>
<td>78,80,82,83,84,86</td>
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<tr>
<td>13 Rb</td>
<td>85,87</td>
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<tr>
<td>14 Sr</td>
<td>84,86,87,88</td>
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<tr>
<td>15 Mo</td>
<td>92,94,95,96,97,98,100</td>
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<tr>
<td>16 Ag</td>
<td>107,109</td>
</tr>
<tr>
<td>18 In</td>
<td>113,115</td>
</tr>
<tr>
<td>19 Xe</td>
<td>124,126,128,129,130,131,132,134,136</td>
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<tr>
<td>20 Ba</td>
<td>130,132,134,135,136,137,138</td>
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<tr>
<td>21 Nd</td>
<td>142,143,144,145,146,148,150</td>
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<tr>
<td>22 Gd</td>
<td>152,154,155,156,157,158,160</td>
</tr>
<tr>
<td>23 Dy</td>
<td>156,158,160,161,162,163,164</td>
</tr>
<tr>
<td>24 Er</td>
<td>162,164,166,167,168,170</td>
</tr>
<tr>
<td>25 Yb</td>
<td>168,170,171,172,173,174,176</td>
</tr>
<tr>
<td>26 Hg</td>
<td>196,198,199,200,201,202,204</td>
</tr>
<tr>
<td>27 Tl</td>
<td>203,205</td>
</tr>
<tr>
<td>28 Sn</td>
<td>114,115,116,117,118,119,120</td>
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<tr>
<td>29 Si</td>
<td>28,29,30</td>
</tr>
<tr>
<td>30 Ge</td>
<td>70,72,73,74</td>
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<tr>
<td>31 Pb</td>
<td>204,206,207,208</td>
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- See NSAC Report page 67 re MAGIS; see pages 66 re stable isotopes produced only outside US
Where do we go from here?
The Pointsman Foundation

A not-for-profit research organization, The Pointsman Foundation will use the efficiency of MAGIS technology to greatly reduce the costs of separated isotopes and make life-saving therapies and diagnostics more readily available to the global medical community.
Can MAGIS work magic for separating stable isotopes?

Atomic beams, optical pumping, and magnet geometry are the crux of a fledgling method that may help meet the demand for pure isotopes.

Mark Raizen didn’t set out to separate isotopes. But a few years ago the University of Texas at Austin physicist realized that the methods he was using to cool atoms to near absolute zero could be adapted to enrich isotopes, and he had a hunch his approach—magnetically activated and guided isotope separation (MAGIS)—could help satisfy the growing demand for isotopes.

Fundamental research, medicine, energy, and other markets are finding new and growing applications for isotopically enriched materials, both stable and radioactive. “Many isotopes have been expensive and rare. They’re like an untapped natural resource,” says Raizen. It’s not unusual for enriched stable isotopes to cost $50,000 per gram, he notes.
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Ca-48

Calutron element

Low natural abundance: 0.187%

Current cost:  ~ $150,000 per gram
Calutron Production of Ca-48

Desired quantity: 10 kg
Calutron Production of Ca-48

Required feedstock: 100,000 tons

USS John C. Stennis
MAGIS ideally suited to Ca-48
MAGIS ideally suited to Ca-48

Zero magnetic moment in ground state

$^{1S_0}$
MAGIS ideally suited to Ca-48

Low temperature oven with controllable beam divergence

Effusive oven design with microcapillary array output

Weld group, UCSB
MAGIS Production of Ca-48

Desired quantity: 10 kg
MAGIS Production of Ca-48

Required Feedstock: ~15 tons

Still need some engineering!
MAGIS ideally suited to Ca-48

Non-toxic element
MAGIS ideally suited to Ca-48

Optical pumping to metastable state
Optical Pumping to Metastable State
Laser Technology

Two lasers required to populate $^3P_2$ state:

657.2 nm (direct diode laser + tapered amplifier)

612.2 nm (doubled VECSEL at 1224.4 nm)

Efficiency: 1 W lasers can produce
~10 kg of Ca-48 per year!
Production of Ca-48 by the Pointsman Foundation

Estimated cost: ~ $5,000 per gram (after ~$3.5 million development cost)

Seeking partnerships!
The Pointsman Foundation

www.pointsman.org