“Neutron-rich nuclides”

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Most neutron-rich nuclides

$N/Z = \infty \quad ^1n$ not a nuclide but a nucleon

$N/Z = 3 \quad ^8\text{He}$

$^\text{11}\text{Li}: \ N/Z = 2.67$
Most neutron-rich nuclides

$N-Z = 61$: $^{293}\text{Lv},^{289}\text{Fl},^{285}\text{Cn},^{281}\text{Ds},^{277}\text{Hs}$
Including unbound nuclides

$^7\text{H}: \frac{N}{Z} = 6$

$^1\text{H}$

$^2\text{H}$

$^3\text{H}$

$^4\text{He}$

$^5\text{Li}$

$^6\text{Li}$

$^7\text{Li}$

$^8\text{Li}$

$^9\text{Li}$

$^{10}\text{Li}$

$^{11}\text{Li}$

$^{12}\text{Li}$

$^{13}\text{Be}$

$^{14}\text{Be}$

$^{15}\text{Be}$

$^{16}\text{Be}$

$^{17}\text{O}$

$^{18}\text{O}$

$^{19}\text{O}$

$^{20}\text{O}$

$^{21}\text{O}$

$^{22}\text{Ne}$

$^{23}\text{Na}$

$^{24}\text{Mg}$

$^{21}\text{Na}$

$^{20}\text{Na}$

$^{19}\text{Ne}$

$^{18}\text{F}$

$^{17}\text{F}$

$^{16}\text{F}$

$^{17}\text{O}$

$^{18}\text{O}$

$^{19}\text{O}$

$^{20}\text{O}$

$^{21}\text{O}$

$^{22}\text{Ne}$

$^{23}\text{Na}$

$^{24}\text{Mg}$

$\Gamma \sim 5\text{ MeV} \quad T_{1/2} = 9 \cdot 10^{-23}\text{s}$

A.A. Korsheninnikov et al., PRL 90 (2003) 082501
A.A. Korsheninnikov et al., PLB 326 (1994) 31
Neutron emitting nuclei

Dripline!
The neutron-rich limit is only known up to oxygen.

Neutron-bound: \( T_{1/2} > \text{ms} \)
Neutron-unbound: \( T_{1/2} < 10^{-20} \text{ s} \)
Observation of New Neutron-Rich Isotopes by Fragmentation of 205-MeV/Nucleon $^{40}$Ar Ions

T. J. M. Symons, Y. P. Viyogi, (a) G. D. Westfall, P. Doll, (b) D. E. Greiner, H. Faraggi, (c) P. J. Lindstrom, and D. K. Scott
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

and

H. J. Crawford and C. McParland
Space Sciences Laboratory, University of California, Berkeley, California 94720
(Received 1 November 1978)

Fragments were detected in a zero-degree magnetic spectrometer and identified in a ΔE-E silicon detector telescope.
Projectile fission at relativistic velocities: a novel and powerful source of neutron-rich isotopes well suited for in-flight isotopic separation


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Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

M. Bernas et al., PLB 331 (1994) 19
Quest for $^{40}\text{Mg}$

H. Sakurai et al., PLB 448 (1999) 180
M. Notani et al., PLB 542 (2002) 49
S.M. Lukyanov et al., JPG 28 (2002) L41
First Observation of $^{40}\text{Mg}$

$^{40}\text{Mg}$ production:

1 in $10^{17}$ $^{48}\text{Ca}$ beam particles!
Dripline Extends Further than Believed

Starting with $^{42}\text{Al}$ the $p_{3/2}$ shell is filled, indicating that $^{45}\text{Al}$ is bound; and even $^{47}\text{Al}$ could be bound ($p_{1/2}$)
Identification of 45 New Neutron-Rich Isotopes Produced by In-Flight Fission of a $^{238}$U Beam at 345 MeV/nucleon


New isotopes

- Present work
- RIKEN(2007)

Stable Known Unknown (KTUY)

r-process path
Using the high-resolution performance of the fragment separator FRS at GSI we have discovered 60 new neutron-rich isotopes...
Production cross sections from $^{82}$Se fragmentation as indications of shell effects in neutron-rich isotopes close to the drip-line

O. B. Tarasov,1,* M. Portillo,2 D. J. Morrissey,1,3 A. M. Anthor,2 L. Bandura,2 T. Baumann,1 D. Bazin,1 J. S. Berryman,1 B. A. Brown,1,4 G. Chubarian,5 N. Fukuda,6 A. Gade,1,4 T. N. Ginter,1 M. Hausmann,2 N. Inabe,6 T. Kubo,6 J. Pereira,1 B. M. Sherrill,1,4 A. Stolz,4 C. Sumithrarachchi,1 M. Thoennessen,1,4 and D. Weisshar1

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(Dated: February 5, 2013)
RIBF and BigRIPS: 2011-2014

More than 70 new isotopes!
Reaching the neutron dripline
Add protons to the $0d_{5/2} \cdot \nu 0d_{3/2} - \pi 0d_{5/2}$ interaction changes the $N=16$ shell gap.
Invariant mass spectroscopy

Example: \( ^{26}\text{O}: \, ^{9}\text{Be}(^{27}\text{F},^{26}\text{O})X \)

\[ E_{\text{decay}} = \sqrt{m_f^2 + m_n^2 + 2[E_f E_n - p_f p_n \cos(\Theta_{\text{open}})]} - m_f - m_n \]
Populating $^{26}\text{O}$ in one-proton removal reactions from $^{27}\text{F}$
Reconstructing $^{26}$O

Identifying real two-neutron events

Causality cuts:
• $\Delta v = 7 \text{ cm/ns}$
• $\Delta d = 25 \text{ cm}$

$E_{\text{rel}} = 150^{+50}_{-150} \text{ keV}$

Spectroscopy of neutron-rich oxygen isotopes

Z. Elekes et al., PRL 98 (2007) 102502
A. Schiller et al., PRL 99 (2007) 112501
C.R. Hoffman et al., PLB 672 (2009) 17
C.R. Hoffman et al., PRC83 (2011) 031303
K. Tshoo et al., PRL 109 (2012) 022501
C.R. Hoffman et al., PRL 100 (2008) 152501
C. Caesar et al., arXiv:1209.0156
E. Lunderberg et al., PRL 108 (2012) 0142503
C. Caesar et al., arXiv:1209.0156

\[ \begin{align*}
0^+ & \quad 3/2^+ 4.0 \text{ MeV} \\
& \quad 5/2^+ 2.8(1) \text{ MeV} \quad (4^+) \quad \sim 7.5 \text{ MeV} \\
& \quad 1^+ \quad \sim 7.3 \text{ MeV} \\
& \quad 2^+ \quad \sim 5.2 \text{ MeV} \\
& \quad \sim 4.7 \text{ MeV} \\
& \quad 1/2^+ \\
& \quad 22\text{O} \\
& \quad 23\text{O} \\
& \quad 24\text{O} \\
& \quad 25\text{O} \quad 3/2^+ \quad \sim 0.75 \text{ MeV} \\
& \quad \leq 0.1 \text{ MeV} \\
& \quad 26\text{O} \quad 0^+ \\
\end{align*} \]
Results confirmed by R$^3$B-LAND

Lifetime limit: $\tau < 5.7$ ns

$E_d = 100$ keV $\leftrightarrow T_{1/2} \approx 10^{-11}$ ps
$E_d = 600$ keV $\leftrightarrow T_{1/2} \approx 10^{-16}$ ps

 Lifetime measurement

Improved lifetime limit: $\tau < 5.6$ ps

Lifetime: $\tau = 4.5^{+1.1}_{-1.5} \, \text{(stat)} \pm 3 \, \text{(syst)}$ ps

82\%C.L. for possible finite two-neutron radioactivity lifetime

New lifetime calculations


“realistic theoretical limits”

$E_T < 1$ keV
Limits of beam intensity ($^{26}\text{F}$ to $^{25}\text{O}$)

GSI

$\sim$15 counts/200 keV

C. Caesar et al., arXiv:1209:0156v2

MSU

$\sim$80 counts/100 keV

Recent results from RIBF on $^{25}$O

>1100 counts/50 keV

Factor of ~25 intensity increase compared to MSU

Beyond the dripline in the *pf*-shell

- The single particle energies within the $f_{7/2}^+$ orbit change very little with increasing neutron number
- The separation energies stay almost constant
- Potential for several neutron unbound isotopes with low decay energy
The FRDM predicts $^{38}\text{Ne}$ and $^{44}\text{Mg}$ to be direct four neutron emitters.

They are bound with respect to 1-, 2-, and 3-neutron emission but unbound with respect to 4-neutron emission.
Known isotopes

![Graph showing the increase in known isotopes over time. The graph includes lines for Total, (Near)Stable, Proton-Rich, Neutron-Rich, and Heavy Elements. The x-axis represents the year, ranging from 1890 to 2010, and the y-axis represents the number of nuclides, ranging from 0 to 3000. The graph illustrates a significant increase in the number of known isotopes over time, particularly in the later years.]
Five-year running average
How many more nuclides are there?

7000 bound nuclide should exist (Erler et al., Nature 486 (2012) 509)
How can new nuclides be discovered?
Summary and outlook

- About 1300 neutron-rich isotopes have been discovered, most recently by projectile fragmentation and projectile fission.
- There are still a few thousand of neutron-rich isotopes left to be discovered.
- In order to reach the (super)heavy neutron-rich nuclei deep inelastic reactions or fusion reactions with radioactive beams are necessary.
- The neutron dripline is not the limit. Spectroscopic information for nuclides beyond the dripline can be extracted from neutron coincidence measurements.