Applications of the high-Current IsoDAR Cyclotron from Neutrino Physics to Beyond

Loyd Waites

On behalf of the IsoDAR collaboration
Neutrino Oscillations

\[ |U_{PMNS}| = \begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} \sim \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.36 & 0.56 & 0.71 \\ 0.42 & 0.60 & 0.68 \end{pmatrix} \]

\[ |\nu_e\rangle \rightarrow |\nu_{1,2,3}\rangle \rightarrow |\nu_\mu\rangle \]
Neutrino Oscillations

\[ |U_{PMNS}| = \left( \begin{array}{ccc} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu1}| & |U_{\mu2}| & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{array} \right) \]

\[ P_{\nu_{\alpha} \rightarrow \nu_{\beta}} = \delta_{\alpha\beta} - 4 \sum_{j>i} U_{\alpha i} U_{\beta i} U_{\alpha j}^* U_{\beta j}^* \sin^2 \left( 1.27 \Delta m_{ij}^2 \frac{L}{E} \right) \]
Neutrino Oscillations

\[ |U_{PMNS}| = \begin{pmatrix}
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\end{pmatrix} \]

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The Royal Swedish Academy of Sciences has decided to award the

2015 NOBEL PRIZE IN PHYSICS

to:

Takaaki Kajita and Arthur B. McDonald

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Nobelprize.org

The Official Web Site of the Nobel Prize
Oscillation Anomalies (ν_μ → ν_e appearance)

**LSND Anomaly**

~3σ \( \bar{\nu}_e \) excess in \( \bar{\nu}_\mu \) beam

**MiniBooNE low energy excess**

4.7σ \( \nu_e \) excess in \( \bar{\nu}_\mu \) beam
Oscillation Anomalies (νₑ → νₑ disappearance)

The Gallium Anomalies

~2.3 - 3σ deficit observed in measured νₑ interaction rate

\[ {^{71}\text{Ga}} + \nu_e \rightarrow {^{71}\text{Ge}} + e^- \]

R = N_{exp} / N_{cal} ≈ 0.84 ± 0.05

GALLEX Cr1 Cr2 SAGE Ar

Reactor Anomaly

~3σ deficit observed in measured \( \bar{\nu}_e \) interaction rate

\[ R = 0.928 ± 0.024 \]
STERILE NEUTRINOS
Oscillation Anomalies (\(\nu_e \rightarrow \nu_e\) disappearance)

The Gallium Anomalies

\(~2.3 - 3\sigma\) deficit observed in measured \(\nu_e\) interaction rate

\[7^1\text{Ga} + \nu_e \rightarrow 7^1\text{Ge} + e^-\]

\[R = \frac{N_{\text{exp}}}{N_{\text{cal}}}, \quad R = 0.84 \pm 0.05\]

Reactor Anomaly

\(~3\sigma\) deficit observed in measured \(\bar{\nu}_e\) interaction rate

\[R = \frac{N_{\text{exp}}}{N_{\text{cal}}}, \quad R = 0.928 \pm 0.024\]
5 MeV bump

- Reactor Flux not well understood
- Anti-electron neutrino channel must be investigated using a well understood source
Enter: IsoDAR

- “Neutrino light bulb”
- Isotropic anti-electron neutrino source
- Close proximity to detector
* Built in an underground mine
Innovation

- Intense neutrino source requires intense proton source
- 10 mA beam current
  - 10X higher than commercial
- Built underground, at a reasonable cost
A New Cyclotron Design
Cyclotrons

\[ V(t) = V_{\text{max}} \cdot \cos(\omega_{RF} \cdot t - \Phi_S) \]

\[ \omega_{RF} = \frac{qB}{\gamma m_0} \]
Three Breakthroughs to Higher Currents:
Use of $\text{H}_2^+$

**Problem**
- High beam intensity + slow beam velocity
  - Space charge $\Rightarrow$ emittance growth
- High impact of space charge in the low energy region

**Solution**
- $\text{H}_2^+$: Two units of charge for one in the low energy region
- Remove electron by stripping $\Rightarrow$ two protons
MIST-1 Ion Source

- Filament-driven, Multicusp Ion source
- Designed to maximize $\text{H}_2^+$ with very low emittance
Experimental results

- Currently Commissioning at 25% power
- 80% pure $H_2^+$
- High quality beam emittance: 0.05 $\pi$-mm-mrad (RMS, norm.)
- Currently working to increase power
Vortex Motion
Vortex Motion
Vortex Motion
With Space Charge

Without Space Charge

Horizontal (mm)  Longitudinal (mm)  Horizontal (mm)  Longitudinal (mm)
RFQ injection

- Replaces large LEBT
- Bunching allows for higher phase acceptance
- Significantly higher transmission
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System Overview:
RFQ

- Electric Quadrupole (Split Coaxial)
  - Alternating voltage on vanes at RF
  - Vanes modulated for longitudinal effects
- Effects:
  - Acceleration
  - Bunching
  - Focusing
Use of Machine Learning

- Machine learning techniques to Model Accelerator System
  - Neural Networks
  - Polynomial Chaos Expansion
- Computational Speed Up
  - Sensitivity studies
  - Design Optimization
RFQ input parameters

- Neural Net able to reproduce RFQGen simulation at sub-percent level in
- Training data generated via RFQGen
  - Input of a series of varying input Twiss parameters
  - Output of Twiss parameters and transmission
New Technology

- 3 Breakthroughs allow ground-breaking current and power
  - *note, PSI cyclotron, although 2.7 mA, is not compact
- Capable of applications beyond the scope of particle physics

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<thead>
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<th>Parameter</th>
<th>IsoDAR</th>
<th>IBA C-30</th>
<th>IBA C-70</th>
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<td>Maximum energy (MeV/amu)</td>
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New Targets, New Applications
Target Limitations

600 kW beam vs. 60 kW Target
Target Management

- Use of electron strippers to divide beam
- Can be done repeatedly
Example: $^{225}\text{Ac}$

- Therapeutic alpha emitter (9.9 day half-life)
- Parent of chain to emit 4 X $\alpha$ ending with stable $^{209}\text{Bi}$
- 50 $\mu$m radius of effect

- BLIP and LANSCE at 100 $\mu$A would increase the world supply by 60 times (2012)
- IsoDAR production rate at 200mCi/hr
Example: $^{68}$Ge/$^{68}$Ga Generator

- $^{68}$Ge parent isotope (270 day half-life)
  - Decays to $^{68}$Ga positron emitter (68 minute half-life)
- $^{99}$Mo 66 hour half-life
  - $^{99m}$Tc daughter 6 hour half-life
- 50 curies of $^{68}$Ga parent /week
- Could eliminate need for rapid supply chain
Accelerating New Ions

- With minor tuning changes, can accelerate particles with the same charge/mass ratio
  - He\(^{++}\), C\(^{6+}\),
  - There are commercially available ion sources for this (2.4 mA of alphas and 50 μA of C\(^{6+}\))
  - New Reactions
Conclusions

The requirements of an ambitious particle physics experiment have driven the development of new cyclotron technology. This development can grow beyond the scope of neutrino physics, and shift paradigms in the medical isotope community.

IsoDAR not only has the opportunity to change physics, but also has the opportunity to change lives.
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The requirements of an ambitious particle physics experiment have driven the development of new cyclotron technology. This development can grow beyond the scope of neutrino physics, and shift paradigms in the medical isotope community.

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References:

- Slide 40: Krtochwil JNM 2016 and 2017
- Slide 41: [https://www.pantechnik.com/ecr-ion-sources/](https://www.pantechnik.com/ecr-ion-sources/)
Backups