1. Search for Electric Dipole Moment of Atom at RCNP

2. Nuclear Physics with Neutrino Beam at J-PARC

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RCNP
Search for permanent EDM

Time Reversal Symmetry ~ Violation ? ~ Test!

CPT ~ invariant in quantum field theory : No evidence of violation
✓T: Time Reversal ~ No evidence of violation
✓CP: violation was found ~ $K^0$, $B$ decay
✓CPT theorem + CP violation ⊥ T violation ?

Window to look at Beyond the Standard Model

(a) SUSY: Generates edm in virtual cloud.

(b) Standard Model: Edm cancels.
Challenge is set!

$\mathbf{d_e < 10^{-28}}$
**Enhancement effect for Atomic EDM**

\[
\frac{d_{\text{atom}}}{d_e} \sim Z^3 \alpha^2
\]

\[
H' = -d_e \sum_i \beta_i \sigma_i E_i
\]

\[
= \frac{d_e}{e} \left[ H_0 + \sum_i \sigma_i \cdot \nabla_i \right] + \frac{d_e}{e} \left[ \sum_i \sigma_i \cdot \nabla_i, \sum_{j<k} \frac{1}{2} B_{jk} \right] + d_e \sum_i (1 - \beta_i) \sigma_i \cdot E_i
\]

Relativistic effect

Heaviest Alkali Atom: Francium \(^{210}\text{Fr} \sim K=1150\)

- 1939 found
- Atomic number 87
- Average atomic weight 215
- Ionization Potential 4.08 eV
- **Radioactive** lifetime of \(^{210}\text{Fr} = 3.2\) min
- No stable isotopes ~ longest lifetime \(^{223}\text{Fr}: 22\) min.
Francium Production with Heavy Ion Fusion Reaction:

\[ {}^{197}\text{Au}(^{18}\text{O},xn)^{209-211}\text{Fr} \]
Electrostatic Lenses
Surface Ionizer
Ring Cyclotron
New Beam Line
Laser Trap
Required to construct
EDM Measurement and Sensitivity

\[ h \nu_{\uparrow\uparrow} = 2 \mu \cdot B + 2d \cdot E \]
\[ h \nu_{\uparrow\downarrow} = 2 \mu \cdot B - 2d \cdot E \]
\[ \Rightarrow h \Delta \nu = 4d \cdot E \]

Electric dipole moment : d

Sensitivity :
\[ \delta d = \frac{h}{2e} \cdot \frac{1}{K} \cdot \frac{1}{E} \cdot \frac{1}{\sqrt{N \cdot \tau \cdot T}} \]

\[ \begin{align*}
K & : \text{Enhancement factor} \quad \sim \text{Atom EDM} \quad = \text{Largest} \sim \text{Francium} \\
E & : \text{Electric Field} \quad \sim \text{Strong, } 100 \text{ kV/cm} \quad = \text{Laser trap in high vacuum} \\
N & : \text{Number of Particles} \quad \sim \text{Many particles !} \quad = \text{Ion Source + Ion guide} \\
\tau & : \text{Coherence Time (Stored time)} \quad \sim \text{Long !} \quad = \text{Laser trap} \\
T & : \text{Lifetime of Experimentalist} \quad \sim \text{Long !} 
\end{align*} \]
EDM measurement

\[ \delta d = \frac{h}{2e} \cdot \frac{1}{K} \cdot \frac{1}{E} \cdot \frac{1}{\sqrt{N \cdot \tau \cdot T}} \sim 10^{-28} \]

- Enhancement factor: \( K = 1150 \) for Fr
- \( E \sim 100\text{kV/cm} \)
- Coherence time: \( \tau \sim 1 \text{s} \)
- \( N \sim 6000 \) atoms @ 1 uA \( ^{18}\text{O} \) beam

Measurement time: \( T \sim 60 \) days needed

- If we have 10 days beam time / year \( \sim 6 \) years
- If we have 10 \( \Delta \) A …..

- Collection efficiency: trapping/cooling technique
- ECR ion source: High intensity
- Radiation protection
  - Low cost: AVF cyclotron only, RING cyclotron NOT used.
  - Not so much effect to beam time
    - no effect to main physics program at RCNP (high resolution, spin-isospin, cluster…)

![Francium Atomic Level Scheme](image)
### Present status

<table>
<thead>
<tr>
<th>Institute</th>
<th>Project</th>
<th>Elements</th>
<th>Trap</th>
<th>Status</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUNY</td>
<td></td>
<td>$^{210}\text{Fr}$</td>
<td>MOT</td>
<td>Atomic structure</td>
<td></td>
</tr>
<tr>
<td>KVI</td>
<td>TRIuP</td>
<td>Ra (p)</td>
<td>MOT/Penning</td>
<td>First beam</td>
<td></td>
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<tr>
<td>TRIUMF</td>
<td>TISOL</td>
<td></td>
<td>MOT</td>
<td></td>
<td></td>
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<tr>
<td>California / LBL</td>
<td></td>
<td>$^{205}\text{Tl}$ (e)</td>
<td>Atomic beam</td>
<td>Best limit</td>
<td></td>
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<tr>
<td>Kyoto</td>
<td></td>
<td>$^{171}\text{Yb}$ (p)</td>
<td>MOT</td>
<td></td>
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<tr>
<td>T.I.T.</td>
<td></td>
<td>Xe (p)</td>
<td></td>
<td></td>
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<tr>
<td>RCNP</td>
<td></td>
<td>$^{207-211}\text{Fr}$</td>
<td>MOT+Laser Trap</td>
<td>No plan…</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>EDM</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>Rb</td>
</tr>
<tr>
<td>Nucleus</td>
<td>$^{129}\text{Xe}$ $^1S_0$</td>
</tr>
</tbody>
</table>
AVF Cyclotron Upgrade Project at RCNP

EDM search with Laser Trap Apparatus

New Technique = Radioactive Atom Production with Accelerator + Laser Trap using
New machines constructed in AVF Upgraded Project in 2004/2005
Cost:
(Beam Line, Vacuum System, Surface Ionizer, Ion Guide, Laser Trap, Detector)
~ Total : 1 ~1.5 億円程度

Plan:
● Francium Production :
~ Feasibility Test Experiment : proposed at next B-PAC (Feb-21)
● Laser Trap : Design work in progress
~ Collaboration with Quantum Optics Group at Kyoto Univ.

When feasibility check is completed,
Propose to Experimental Project at B/P-PAC
Muon Yield at RCNP @ 400 MeV proton 1 uA

- QGD-Solenoid-QGDQQ  + $\sim 10^4$/s  - $\sim 5 \times 10^3$/s
- Solenoid capture + Muon cooling  + $\sim 10^9$/s  - $5 \times 10^8$/s
Nuclear Physics with Neutrino Beam

New Beam ~ Neutrino at J-PARC : $E_{\nu} \sim 1$ GeV

- Spin structure of nucleon : Hadron physics
  ~ Strange quark spin content $\otimes S$

- Spin response function : Nuclear physics
  ~ $\otimes, \bar{Q}$ propagation in the interior of the nucleus
Spin structure of the nucleon

Naive Parton Model:

\[ \Delta u_V + \Delta d_V = 1 \]

But

1988 EMC measured:

\[ \pm 0.123 \pm 0.013 \pm 0.019 \]

Spin Puzzle

From Inclusive Data:

- Valence quark ~ well known
- Sea quarks?

From Unpolarized Data:

- Light sea quark flavor asymmetry
- Gluons are important

\[ \frac{1}{2} = \frac{1}{2} (\Delta u_V + \Delta d_V + \Delta q_s) + \Delta G + L_q + L_g \]

\[ \Delta q_s = \Delta u_s + \Delta \bar{u} + \Delta d_s + \Delta \bar{d} + \Delta s + \Delta \bar{s} \]

Spin Content of Strange Quark

Full description of Jq & Jg

Orbital angular momentum
Quark Polarization from semi-inclusive measurement at HERMES

\[
A_I^h(x,z) = \frac{\int_f \frac{e_f^2 \cdot q_f(x) \cdot D_f^h(z)}{\bar{q}_f^2 \cdot q_f(x) \cdot D_f^h(z)} \, dq_f(x)}{q_f(x)}
\]

\[\checkmark \text{No indication for } \square s(x) < 0\]

\[\checkmark \square S : \text{first moment of } \square S(x)\]
\[\sim +0.03 \pm 0.03 \text{(stat.)} \pm 0.01 \text{(syst.)}\]

\[\square \text{consistent with 0, although negative from inclusive data}\]
\[ \int_{0}^{1} S(x) \, dx \]

Difficult to reach in DIS experiment

EMC + Baryon weak decays

\[ \Delta u \]
\[ \Delta s \]
\[ \Delta d \]

\[ \Delta S \text{ from Semi-inclusive} \sim 0 \text{.. Positive?} \]

flavor SU(3) symmetry assumed
How to measure: \[ S \] from Neutrino-Proton elastic scattering

\[
\frac{d\sigma}{dQ^2} = \frac{G_F^2 E^2_\nu}{2\pi Q^2} \left[ A \pm B W + C W^2 \right],
\]

\[ W = 4 \left( E_\nu / M_p - \tau \right), \quad \tau = Q^2 / 4M_p^2 \]

\[
A = \frac{1}{4} \left[ G_1^2 (1 + \tau) - \left( F_1^2 - \tau F_2^2 \right) (1 - \tau) + 4 \tau F_1 F_2 \right],
\]

\[
B = -\frac{1}{4} \left[ G_1 \left( F_1 + \tau F_2 \right) \right], \quad G_1(Q^2) = \frac{-0.631}{(1 + Q^2 / M_A^2)^2} + \frac{G_1^s(Q^2)}{2}
\]

\[
C = \frac{1}{16} \frac{M_p^2}{Q^2} \left[ G_1^2 + F_1^2 + \tau F_2^2 \right], \quad \frac{G_1^s(Q^2)}{Q^2 = 0} = \Delta S
\]

Axial form factor
Sensitivity for $\Delta s$ and Other Physics Impact

Conditions:
- Similar Detection Efficiency to E734:
  - 7.6% for neutrino-N elastic
  - 5.4% for anti-neutrino-N elastic
- with lower $Q^2$ cut-off: 0.1 GeV$^2$
  - Achievable with more uniform detector
- 25 times more statistics but pure proton only 1/6
  - Factor 2 reduction in statistical error
- Systematic control improvements to $\sim$5%
  - E734, 7.6% dominated by Beam Flux and Nuclear Effects
  - Possible to remove Nuclear Effects which could be larger in lower $Q^2$ region

Neutron EDM $\sim$ predicted using q-EDM and $Dq$

\[
d_n = \eta^E (\Delta u d_u^E + \Delta d d_d^E + \Delta s d_s^E) \\
\propto m_u \Delta u + m_d \Delta d + m_s \Delta s
\]
Coherent Pion Production

\[ A(\square, \square - \square +)A \]

- \( n, t \)
- \( \Delta \)
- Real \( \square^+ \)
- Virtual \( \square \)

- \( P,^3He \)
- (Virtual) Pion Scattering

- Residual interaction: \( \square + \square + g'(\text{short range}) \)

- Neutrino \sim Weak interaction
  - No distortion, absorption
  - test the \( \square, \square \) in the interior of nucleus
  - Adler’s theorem: \( M \sim T(\square(q) + N \square X) \)

- Hadron \sim Strong interaction
  - Distortion, absorption
  - peripheral reaction \sim nuclear surface

Sensitivity to NN short range component \( g' \)

- Sensitive to NN short range component \( g' \)

- \( g'_{00} = 0.33 \)
- \( g' = 0.4 \)
Effect to nuclear matter property

Short range correlation: \( g' \)
~ sensitive to critical density of pion condensation phase
~ determine the limit of from the CPP measurement
CPP experiment at RCNP

Proton Beam: $^{12}\text{C}(p, n \rightarrow)^{12}\text{C}$ at $E_p=400$ MeV
- Experiment ~ feasibility test in progress
- Detector development for $\pi$ detection
  ~ Gas Electron Multiplier (GEM)
- Hadron probe
  ✓ peripheral reaction
  ✓ $\pi^+$, $\pi^-$ propagation in surface

Excitation energy
Neutrino induced CPP

<table>
<thead>
<tr>
<th>Interaction Type</th>
<th>$\nu_\mu$ $10^{20}$ POT 1 ton</th>
<th>$\bar{\nu}_e$ $10^{20}$ POT 1 ton</th>
<th>$\nu_\mu + \bar{\nu}_e$ $10^{20}$ POT 1 ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC QE, $\nu_\mu n \rightarrow \mu^- p$</td>
<td>11,395</td>
<td>174</td>
<td>56</td>
</tr>
<tr>
<td>NC EL, $\nu_\mu N \rightarrow \nu_\mu N$</td>
<td>4,903</td>
<td>86</td>
<td>22</td>
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<tr>
<td>CC $\pi^+$, $\nu_\mu p \rightarrow \mu^- p \pi^+$</td>
<td>3,293</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>CC $\rho^0$, $\nu_\mu n \rightarrow \mu^- p \pi^0$</td>
<td>725</td>
<td>11</td>
<td>6</td>
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<tr>
<td>CC $\pi^0$, $\nu_\mu n \rightarrow \mu^- n \pi^0$</td>
<td>646</td>
<td>10</td>
<td>6</td>
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<tr>
<td>NC $\pi^0$, $\nu_\mu p \rightarrow \nu_\mu p \pi^0$</td>
<td>606</td>
<td>10</td>
<td>5</td>
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<tr>
<td>NC $\pi^0$, $\nu_\mu p \rightarrow \nu_\mu n \pi^0$</td>
<td>370</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>NC $\pi^0$, $\nu_\mu n \rightarrow \nu_\mu n \pi^0$</td>
<td>454</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>NC $\pi^0$, $\nu_\mu n \rightarrow \nu_\mu p \pi^+$</td>
<td>290</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>CC DIS, $\nu_\mu N \rightarrow \mu^- X$</td>
<td>176</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>NC DIS, $\nu_\mu N \rightarrow \nu_\mu p X$</td>
<td>64</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CC coh $\pi^+$, $\nu_\mu A \rightarrow \mu^- A \pi^+$</td>
<td>530</td>
<td>22</td>
<td>3</td>
</tr>
<tr>
<td>NC coh $\pi^0$, $\nu_\mu A \rightarrow \nu_\mu A \pi^0$</td>
<td>340</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>other</td>
<td>464</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>total</td>
<td>24,364</td>
<td>394</td>
<td>134</td>
</tr>
</tbody>
</table>

Table 3.1: Number of events expected at 50 m with a 25 m decay length for $1 \times 10^{20}$ POT per ton detector. These predictions do not include final state effects and assume 100% detection/reconstruction efficiency.
Neutrino Beam Line

Detector
~ BNL case

Liquid Sci.
With W.L.S

Target
● Proton
● Carbon

Around Near Detector
Cost and Timeline

- Impossible to locate the detector in the near detector hall
- New detector hall underground or ....
- Simulation study in progress to optimize the detector.

Cost ~ depend on the detector location
  ~ 穴掘り工事：10億円〜30億円？

✓ NeuFact04
✓ NP04
✓ Workshop at RCNP ~ Feb.-24/2005
Start to prepare Letter of Intent
Try to get budget.....

Working group: Kyoto, Tokyo Tech., KEK, RCNP,......
Summary

EDM search of Electron
- Time reversal symmetry violation, Beyond the standard model
- Open new research area with high precision measurement at RCNP
- Based on upgraded ECR ion source, AVF cyclotron, Beam line
- Accelerator Complex

Nuclear physics with Neutrino Beam
- New probe ~ Neutrino at J-PARC
  - Strange quark ~ Spin structure of nucleon
  - Interior of nucleus ~ Spin response function
- Natural extension of Spin-Isospin Physics at RCNP
- Nuclear physics facility (base) with Lepton-Photon beam
  - LEPS@SPring-8 + Neutrino + High energy electron beam from LC