(VERY?) LOW ENERGY BETA-BEAMS

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• What is it?

• Where could it be?

• What for?
Low energy Beta-beams


THE PROPOSAL

To exploit the beta-beam concept to produce intense and pure low energy neutrino beams.

PHYSICS POTENTIAL

- Neutrino properties, like the $\nu$ magnetic moment.
- Neutrino-nucleus interaction studies.
- ...

A BETA-BEAM FACILITY FOR LOW ENERGY NEUTRINOS.
Many laboratories will produce intense exotic ion beams in the future.

### Possible sites for low energy $\beta$-beams

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Intensities</th>
<th>$\gamma$</th>
<th>Storage Ring</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>GANIL</td>
<td>$10^{12}$ ,$\nu$/s</td>
<td>1</td>
<td>×</td>
<td>$4\pi$</td>
</tr>
<tr>
<td>GSI</td>
<td>$10^{9}$ ,$\nu$/s</td>
<td>1-10</td>
<td>√</td>
<td>$4\pi$ and Close detector</td>
</tr>
<tr>
<td>CERN</td>
<td>$10^{12-14}$ ,$\nu$/s</td>
<td>1-100</td>
<td>√</td>
<td></td>
</tr>
</tbody>
</table>
Neutrino-nucleus interactions

NUCLEAR PHYSICS

Supernovae, Nucleosynthesis

Neutrino experiments

STANDARD MODEL and BEYOND

A TOPIC OF CURRENT GREAT INTEREST.
Understanding Nucleosynthesis

The site where the heavy elements are synthetized is not known.

Supernova type II explosions: 99% of the energy is emitted as neutrinos.

Calculations of abundances.

ν-NUCLEUS INTERACTIONS ARE NEEDED.
Neutrinos probe nuclei over a wide energy range.

Experimental data are very scarce (deuteron and iron, carbon). Theoretical predictions are absolutely necessary.

The interpolation between these two regimes as well as the extrapolation from stable to exotic nuclei are needed!
Constraints and Challenges

From other weak processes:
Very low momentum transfer (a few MeVs)
Low momentum transfer (about 100 MeV)

From model-independent sum-rules, for some states.

BUT...
Neutrinos can transfer a lot of energy to a nucleus.

\[ \nu_\mu + ^{12}_\text{C} \rightarrow ^{12}_\text{N} + \mu^- \]

GETTING PRECISE PREDICTIONS IS A CHALLENGING TASK.
Neutrino-nucleus measurements

...or at one of the laboratories that will produce intense radioactive beams in the future (need of ion acceleration to GeV energy and of a storage ring).


Two options studied:
- Large ring
- Small Ring

Length of the straight sections
Total length

Beta-beam baseline at CERN
ν-Nucleus Interaction Rates


Interesting interaction rates can be obtained.

The unique feature that the ν-energy can be easily varied.

<table>
<thead>
<tr>
<th>Mass (tons)</th>
<th>Small Ring</th>
<th>Large Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e + \text{D}$</td>
<td>35</td>
<td>25779</td>
</tr>
<tr>
<td>$\bar{\nu}_e + ^{16}\text{O}$</td>
<td>952</td>
<td>82645</td>
</tr>
<tr>
<td>$\nu_e + ^{208}\text{Pb}$</td>
<td>360</td>
<td>103707</td>
</tr>
</tbody>
</table>

Events per year for $\gamma=14$

Small Ring: $d = 150$ m, $L= 450$ m Large Ring: $d = 2.5$ km, $L= 7.5$ km

Interesting interaction rates can be obtained.
The contribution of forbidden states to the total cross section increases for increasing impinging neutrino energy.

No experimental information is available.

Learn about forbidden states.

Neutrinos as a Probe for Nuclear Structure Studies.


\[ \nu_e + ^{208}\text{Pb} \rightarrow ^{208}\text{Bi} + e^- \]
v: Majorana or Dirac particles?

How do we search for the v-nature?

Majorana or Dirac particles?

ν ≠ ν

ν = \bar{ν}

2β(2ν): 2n → 2p + 2e^- + 2\bar{ν}_e

Within the Standard Model (V-A theory)
Observed in various nuclei.

2β(0ν): 2n → 2p + 2e-

Lepton-violating process
Beyond the Standard Model
(e.g. exchange of massive Majorana neutrinos)
Never observed.
The experimental search

The theoretical situation

- Theoretical predictions on the half-lives exhibit important variations for the same candidate emitter.
- Several processes have been considered to constrain the nuclear matrix elements, in particular beta-decay, muon capture, $2\beta(2\nu)$, charge-exchange reactions.
The $2\beta(0\nu)$ half-life

$2\beta(0\nu): 2n \rightarrow 2p + 2e^-$

Because of the massive Majorana neutrino propagator, many nuclear states between the initial (final) nucleus and the intermediate one can be excited.

MANY STATES ARE INVOLVED.
2β(0ν): Link to ν-nucleus

C. Volpe, article in preparation.

The forbidden Fermi and Gamow-Teller states involved are the same as those excited in neutrinoless double-beta decay due, e.g. to a massive neutrino exchange.

These studies could give a supplementary constrain to 2β(0ν) decay predictions.
Low energy Beta-beams


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- Neutrino-nucleus interaction studies.
- ...

A beta-beam facility for low energy neutrinos.
Conclusions and Perspectives

**Low energy Beta-beams**

- A facility producing low energy neutrinos.
- **CERN appears as a unique site, but there could be other possibilities.**
- A rich physics program can be performed.
- **The feasibility study:**
  A close look at the feasibility of the small storage ring?

*More to come...*
IT’S A UNIQUE OPPORTUNITY
The $\nu$-Magnetic Moment: Prospects

PRESENT DIRECT LIMIT:
\[ \mu_\nu < 1.0 \times 10^{-10} \mu_B. \]

\[ \nu_e \rightarrow e \quad \text{with} \quad Q_\beta = 4. \text{MeV} \]

\[ \nu_e - e \text{ events with low-energy beta-beams (} 10^{15} \nu/s \text{) and a} \]
\[ 4\pi \text{ low threshold detector.} \]

THE LIMIT CAN BE IMPROVED BY ONE ORDER of MAGNITUDE.

Beta-beam baseline at CERN

...or at one of the laboratories that will produce intense radioactive beams in the future (need of ion acceleration to GeV energy and of a storage ring).

TWO POSSIBLE SCENARIOS.

Prospects with low energy beta-beams


\[
\mu \nu \text{ introduces a } 1/T \text{-like divergence.}
\]

\[
\begin{align*}
Q_\beta &= 4 \, \text{MeV} \\
\mu \nu &= 0
\end{align*}
\]

\[
\begin{align*}
v_e - e \text{ events with } 10^{15} \nu/\text{s from } ^6\text{He} \\
\text{and a } 4\pi \text{ low threshold detector.}
\end{align*}
\]

AN IMPROVEMENT BY ONE ORDER of MAGNITUDE.
Present limits and strategies

PRESENT DIRECT LIMITS:  \( \mu_\nu < 1.0 \times 10^{-10} \mu_B \) (95% C.L.)
from reactor experiments (MUNU, Kuo-Sheng, Rovno, …)

INDIRECT LIMITS:  \( \mu_\nu < 10^{-10} - 10^{-12} \mu_B \)  model-dependent!
from astrophysical considerations (star cooling, SN1987A, …)

To improve direct limits one needs:

- **SOURCE**
  - well known \( \nu \)-fluxes
  - high \( \nu \)-intensities

- **DETECTORS**
  - low-threshold detectors

**STRATEGIES**

- reactors
- static sources
- beta-beams

The neutrino magnetic moment

A large $\nu$ magnetic moment points to new physics.

This neutrino property has important implications in astrophysics, e.g. for core-collapse Supernovae.

Since $m_\nu \neq 0$, at the one-loop level:

$$\mu_\nu = 3.2 \times 10^{-19} \left( m_\nu / 1 \text{ eV} \right) \mu_B$$

How can one measure $\mu_\nu$?

The presence of a magnetic moment introduces in the $\nu_e$-$e$ cross section, a $1/T$-like divergence, where $T$ is the electron recoil energy.
A comparison with conventional beams

McLaughlin, nucl-th/0404002.

Neutrino flux from the decay of muons

\[ \nu_e + ^{208}\text{Pb} \rightarrow ^{208}\text{Bi} + e^- + 2n \]

Neutrino Flux (s\(^{-1}\) MeV\(^{-1}\) cm\(^{-2}\))

Complementary information can be obtained.