Light Mass WIMP Searches with a Neutrino Experiment:
A Request for Further MiniBooNE Running

FNAL PAC Meeting
Oct 15, 2012
R. Van de Water
Outline

• The MiniBooNE request for further running.
• Summary of 10 years of neutrino/antineutrino running.
• Light mass WIMP production from protons beams.
• Enhanced WIMP sensitivity with beam off target running.
• MiniBooNE WIMP detection methods and sensitivities.
• Run issues, people power, etc.
• Summary and the request for further running.
The MiniBooNE Request

MiniBooNE requests running to collect a total of $2.0 \times 10^{20}$ POT in beam off target mode and with the 25m absorber deployed. This will allow a powerful search for light mass WIMPs in a parameter space that overlaps with muon $g - 2$ and cosmic relic density estimates. The experiment further requests that this beam be delivered in FY2013 and 2014 before the MicroBooNE experiment turns on.

- Search for low mass WIMP signals is compelling and explores uncharted territory.
- In the period before MicroBooNE turns on (~1 year), we put the idle Booster Neutrino Beamline (BNB) to good use that will produce publishable physics.
MiniBooNE Collaboration Currently Signed up for Beam Off Target Running

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Ten Years of Successful MiniBooNE Running and Results!

- Neutrino mode: 6.5E20 POT
- Antineutrino mode: 11.3E20 POT
- 10 oscillation papers
- 12 cross section and flux papers
- 1 detector and 1 supernova search paper
- 17 PhD thesis
- The experiment is well understood!
Is Further Neutrino/AntiNeutrino Running with no Changes Worthwhile?

• Neutrino Running: NO -- we are systematic limited, more running would not significantly improve the results.

• Antineutrino Running: Maybe – we are still statistics limited, but would take many years to double the data.

• We need a significant systematic change to add new information to the question of oscillations.
  – Submitted a LOI to add scintillator to the detector and run concurrently with MicroBooNE – next talk by Rex Tayloe
New Idea: WIMP Searches at MiniBooNE

• Can WIMP Dark Matter be light (sub-GeV)?
• Yes! What are the constraints on such a scenario? What does a model look like?
• Consequences of the model for other observations, e.g. muon g-2.
• If WIMPs are light, how can MiniBooNE produce and detect them.
  – Need lots of relativistic protons and large detector!
Dark Matter: Where to Look?

Nuclear Recoil too Weak

$\nu_{DM} \sim 10^{-3} c$

Find a Relativistic DM Beam

What about over here?

Standard Model

Light Mediator

Light Dark Matter

Underground Direct Detection Experiments

Lee-Weinberg Bound: SM mediator implies $m_{DM} \gtrsim \text{few GeV}$

(W, Z, ...)

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Minimal Dark Matter Vector Portal Model

Required for Low Mass WIMPs to achieve correct thermal relic abundance

\[ \mathcal{L}_{DM} = V_\mu \left( e \kappa J^\mu_{em} + e' J^\mu_\chi \right) + \mathcal{L}_{kin}(V, \chi) + \cdots \]

Model assumptions:
1. \( e = e' \) (perturbative regime)
2. \( K \) is small
3. \( M_V > 2M_\chi \)

Assuming thermal relic, if you know \( m_\chi, m_V, \kappa, e' \)
you know the present DM density
Experimental Consequences

- **Cosmology**
  - CMB: OK given p-wave annihilation
  - BBN: OK for $m_\chi \gtrsim 1$ MeV
  - Star Cooling: OK for $m_V \gtrsim 1 - 10$ MeV

- **Particle Physics**
  - Monophotons/Monojets: $pp/p\bar{p} \rightarrow \chi\chi + (\gamma, j)$
  - Dark Force searches: $e^+e^- \rightarrow \gamma V \rightarrow \gamma \ell^+\ell^-$
  - Rare Meson Decays: $K^\pm \rightarrow \pi^\pm V \rightarrow \pi^\pm + \text{inv.}, \ J/\psi \rightarrow V^* \rightarrow \text{inv.}$
  - MiniBooNE

\begin{footnotesize}
  Padmanabhan & Finkbeiner '05
  Jedamzik & Pospelov '09
  Shoemaker & Vecchi '11
  Fox et al.
  Bjorken et al. '09
  Batell et al. '09
  MAMI, APEX, BABAR
  E949
  CLEO
\end{footnotesize}
Model Consequences for Muon g-2

- Light kinetically mixed vector V that serves as a mediator in this model also contributes to the anomalous magnetic moment of SM fermions.
- This can explain the muon g-2 discrepancy.

The crosses represent the kinetic mixing $\kappa$ of the vector V with the photon.
Producing a Dark Matter Beam

Monte Carlo Simulation of WIMP Production at MiniBooNE:

- Use HARP-MiniBooNE Be target Sanford-Wang meson production model.
- Use MiniBooNE determined acceptance, fiducial, and energy cuts (35% efficiency).
- Calculate regions of $M_\chi$, $M_\nu$, $\kappa$, $\alpha'$ parameter space probed for 1, 10, and 1000 events.
MiniBooNE WIMP Sensitivities

- Number of WIMP events detected in MiniBooNE:
  - Dark Green: >1000
  - Green: 10-1000
  - Light Green: 1-10

- What sensitivity can MB actually achieve?

- $2M_x < M_v < M_\eta$

- Sensible choice of model parameters $M_{x'}$, $M_v$, $\kappa$, $\alpha'$.

- Light blue band is muon g-2 signal.

- Solid black line is where WIMP relic density matches observation.
Enhancing the WIMP Search

• The WIMP scattering signal looks like neutrino nucleon or neutrino electron elastic scattering. Thus, neutrino interactions are the biggest background to these searches.

• We employ a beam dump type method to significantly reduce charged meson decay, and hence the neutrino flux.
Beam Off Target Running

MB has the capability to steer the protons past the target and onto the 25m or 50m iron dump

- Target is 1 cm diameter
- Air gap between target and horn inner conductor is ~1 cm

- Beam spot position in beam off target mode (~1 mm spread)

• $\pi^0$ and $\eta$ produced by protons in the iron quickly decay producing WIMPs ($\chi$)
• Charged mesons are absorbed in the iron before decaying, which significantly reduces the neutrino flux (still some production from proton-Air interactions).
Neutrino Rate Reduction with Beam Off Target Running

- Estimated neutrino rate reduction:
  - 50m absorber one week beam off target run (~5.54e18 POT):
    \[
    \frac{\text{events/POT}}{\text{beam off target}}^\text{v mode} = 42 \pm 7 \quad \text{Data rate reduction}
    \]
  - 50m MC: \(\frac{\text{events/POT}}{\text{beam off target}}^\text{v mode} = 36 \quad \text{MC flux reduction}
  - 25m MC: \(\frac{\text{events/POT}}{\text{beam off target}}^\text{v mode} = 72 \]

Monte Carlo

\(v_\mu\) flux ratios

\[\text{ratio to std mu-mode flux} \]

Kinematics (\(\nu\) mode norm. to beam off)

Data: error bars
MC rel norm: line

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Estimating MiniBooNE WIMP Detection Sensitivities

- WIMPs ($\chi$) can interact in the oil scattering off nucleons and electrons.
  - WIMP events look like neutrino NC scattering off nucleons or electrons but possibly with different kinematics (momentum, angle, timing, etc).
- Can use different techniques to extract signal (there might be more)
  - Neutrino flux reduction (beam off target running)
  - Counting
  - Energy and/or angle fit
  - Timing fit
- Can also use combinations of the above four methods to increase signal over background
WIMP Nucleon Scattering

- MB has already published a detailed neutrino nucleus neutral current scattering result (Phys. Rev. D82, 092005 (2010)).
- Systematic error of 18.1%.
- Cosmic backgrounds not included but effects are small.

<table>
<thead>
<tr>
<th>POT</th>
<th>Beam Configuration</th>
<th>25m Absorber $\nu$-Background</th>
<th>25m Absorber 90% U.L.</th>
<th>50m Absorber $\nu$-Background</th>
<th>50m Absorber 90% U.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10.1 \times 10^{20}$</td>
<td>beam on target antinu</td>
<td></td>
<td></td>
<td>$60605$</td>
<td>$16294$</td>
</tr>
<tr>
<td>$6.5 \times 10^{20}$</td>
<td>beam on target nu</td>
<td>$1137$</td>
<td>$267$</td>
<td>$95531$</td>
<td>$22136$</td>
</tr>
<tr>
<td>$6.5 \times 10^{20}$</td>
<td>beam off target</td>
<td>$700$</td>
<td>$166$</td>
<td>$2275$</td>
<td>$531$</td>
</tr>
<tr>
<td>$4.0 \times 10^{20}$</td>
<td>beam off target</td>
<td></td>
<td></td>
<td>$1400$</td>
<td>$328$</td>
</tr>
<tr>
<td>$2.0 \times 10^{20}$</td>
<td>beam off target</td>
<td>$350$</td>
<td>$85$</td>
<td>$700$</td>
<td>$166$</td>
</tr>
<tr>
<td>$1.0 \times 10^{20}$</td>
<td>beam off target</td>
<td>$175$</td>
<td>$44$</td>
<td>$350$</td>
<td>$85$</td>
</tr>
</tbody>
</table>

- PAC request in blue: Estimated neutrino backgrounds and 90% C.L. upper limits
WIMP Electron Scattering

- WIMP-electron scattering is forward peak. With a forward angle cut, can reject 98% of neutrino induced backgrounds.
- Systematic error of 12%.

<table>
<thead>
<tr>
<th>POT</th>
<th>Beam Configuration</th>
<th>25m Absorber $\nu$-Background</th>
<th>25m Absorber 90% U.L.</th>
<th>50m Absorber $\nu$-Background</th>
<th>50m Absorber 90% U.L.</th>
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<tbody>
<tr>
<td>$10.1 \times 10^{20}$</td>
<td>beam on target antinu</td>
<td></td>
<td></td>
<td>31</td>
<td>8.6</td>
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<tr>
<td>$6.5 \times 10^{20}$</td>
<td>beam on target nu</td>
<td></td>
<td></td>
<td>41</td>
<td>10.3</td>
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<tr>
<td>$6.5 \times 10^{20}$</td>
<td>beam off target</td>
<td>0.45</td>
<td>2.75</td>
<td>0.90</td>
<td>3.20</td>
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<tr>
<td>$4.0 \times 10^{20}$</td>
<td>beam off target</td>
<td>0.30</td>
<td>2.60</td>
<td>0.60</td>
<td>2.90</td>
</tr>
<tr>
<td>$2.0 \times 10^{20}$</td>
<td>beam off target</td>
<td>0.15</td>
<td>2.45</td>
<td>0.30</td>
<td>2.60</td>
</tr>
<tr>
<td>$1.0 \times 10^{20}$</td>
<td>beam off target</td>
<td>0.08</td>
<td>2.38</td>
<td>0.15</td>
<td>2.45</td>
</tr>
</tbody>
</table>

- PAC request in blue: Estimated neutrino backgrounds and 90% C.L. upper limits
Energy Fit

• Improved sensitivity if the WIMP induced nucleon/electron momentum is significantly different than that of neutrinos.

• We are presently working on these MC estimates and fits using the current neutrino and antineutrino data sets.
  – WIMP event generator needs to be folded into the MiniBooNE MC.
  – Nucleon/electron kinematics depend on $M_\chi$, $M_\nu$, $\kappa$, $\alpha'$.

Example WIMP-Nucleon Scattering

6.5E20 POT neutrino mode
WIMP Time of Flight

- Neutrinos produced in p-Air interactions traveling at c and in phase with beam RF structure
- π^0 and η produced by protons quickly decay producing WIMPs

<table>
<thead>
<tr>
<th>Timing cut (nsec)</th>
<th>Background Reduction (%)</th>
<th>WIMP Velocity</th>
<th>WIMP Mass (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>90</td>
<td>0.9984</td>
<td>85</td>
</tr>
<tr>
<td>4.6</td>
<td>99</td>
<td>0.9974</td>
<td>108</td>
</tr>
<tr>
<td>5.9</td>
<td>99.9</td>
<td>0.9967</td>
<td>122</td>
</tr>
</tbody>
</table>

- Absolute beam – detector event timing known to about 1.8 nsec.
- Timing can significantly reject neutrino induced backgrounds for M_x > 50 MeV.
90% C.L. Sensitivities for WIMP-Nucleon Scattering:
2E20 POT Beam off Target and 25/50m Absorber Run

- Estimate 90% C.L. upper limits includes timing information.
- Can cover a significant part of the muon g-2 signal region.
90% C.L. Sensitivities for WIMP-Electron Scattering: 2E20 POT Beam off Target and 25/50m Absorber Run

- Estimate 90% C.L. upper limits includes $\cos\theta_{\text{beam}}$ and timing info.
- Can cover a significant part of the muon g-2 signal region.
Estimated WIMP Signal Significance: 2E20 POT Beam off Target and 25m Absorber Run

- Signal, backgrounds and significance for various $M_x$ and $\sigma$ points in the g-2 band.
- g-2 band mostly covered at $>5\sigma$

<table>
<thead>
<tr>
<th>Pt.</th>
<th>Scattering Channel</th>
<th>Beam Mode (2.0 x 10^{20} POT)</th>
<th>WIMP mass (MeV)/cross section (cm^2)</th>
<th>Signal</th>
<th>Background and Errors</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nucleon</td>
<td>25m</td>
<td>10/4 x 10^{-37}</td>
<td>1859</td>
<td>350±66</td>
<td>&lt; 10^{-10}</td>
</tr>
<tr>
<td>2</td>
<td>Nucleon</td>
<td>25m</td>
<td>30/3 x 10^{-36}</td>
<td>1453</td>
<td>350±66</td>
<td>&lt; 10^{-10}</td>
</tr>
<tr>
<td>3</td>
<td>Nucleon</td>
<td>25m</td>
<td>50/8 x 10^{-36}</td>
<td>1326</td>
<td>203±40</td>
<td>&lt; 10^{-10}</td>
</tr>
<tr>
<td>4</td>
<td>Nucleon</td>
<td>25m</td>
<td>100/3 x 10^{-35}</td>
<td>1186</td>
<td>9.2±3.4</td>
<td>&lt; 10^{-10}</td>
</tr>
<tr>
<td>1</td>
<td>Electron</td>
<td>25m</td>
<td>10/4 x 10^{-37}</td>
<td>13.2</td>
<td>0.15</td>
<td>&lt; 10^{-10}</td>
</tr>
<tr>
<td>2</td>
<td>Electron</td>
<td>25m</td>
<td>30/3 x 10^{-36}</td>
<td>7.7</td>
<td>0.15</td>
<td>~ 10^{-9}</td>
</tr>
<tr>
<td>3</td>
<td>Electron</td>
<td>25m</td>
<td>50/8 x 10^{-36}</td>
<td>4.8</td>
<td>0.09</td>
<td>~ 10^{-6}</td>
</tr>
<tr>
<td>4</td>
<td>Electron</td>
<td>25m</td>
<td>100/3 x 10^{-35}</td>
<td>1.4</td>
<td>0.004</td>
<td>~ 10^{-3}</td>
</tr>
</tbody>
</table>

Pt. 3 is overlap of g-2 and relic density

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Preference is to Run Beam off Target in 25m Absorber Mode

• Pros:
  – Increases the neutrino flux reduction by a factor of two!
    • Improved sensitivities and signal significance.
    • Insurance against less POT delivery.
  – The 25m iron blocks are solid with no cracks. The 50m dump has cracks, if the beam is positioned on the cracks we would not know it and could alter flux reduction profile.
  – 25m dump has imbedded muon monitors for tracking proton direction angles.

• Cons:
  – Cost $80k and 2.5 weeks to deploy. Also, need to bring absorber back up if MicroBooNE runs in 50m mode.
Run Stability and Logistics

• MB running has been stable for 10 years:
  - Neutrino/POT stability
  - Should continue stable running for the next few years. Will keep the beamline tuned up for MicroBooNE.
  - There are sufficient beamline (3rd horn and target) and detector spares. Some upgrades being done (see backup slides).
  - The infrastructure costs of further running are relatively small. FTE’s required to run almost the same as in shutdown.
People Power

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Collaborators</th>
<th>New postdocs and students</th>
<th>Hired Full Tme Shifter</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>54</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2008</td>
<td>54</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2009</td>
<td>54</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2010</td>
<td>42</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2011</td>
<td>42</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2012</td>
<td>42</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2013</td>
<td>28</td>
<td>unknown</td>
<td>1</td>
</tr>
<tr>
<td>2014</td>
<td>28</td>
<td>unknown</td>
<td>1</td>
</tr>
</tbody>
</table>

- Are there enough people to run the experiment? -- YES
  - All past beamline and detector experts are signed up for the run.
  - With 28 collaborators and a hired owl shifter, will require about 2.5 shifts per month per collaborator. The collaboration is okay with this.
  - We can run shifts remotely which reduces the shift duty burden.
  - There are enough analysis experts on hand to perform the analysis.
  - If approved to run we will be looking for new students who would be interested in a PhD on the proposed physics.
Bonus Physics: NOvA Off Axis Neutrino Rate Measurement.

- If the detector is up and running, we will trigger on NuMI events.
- Can perform an off axis rate measurement similar to what we did for MINOS (Phys. Rev. Lett. 102, 211801 (2009)).

- Off axis rate checks will be even more useful for NOvA.
  - NOvA is 14 mrad and MB 110 mrad off axis.
  - Both NOvA and MB are CH$_2$ targets
Summary

• The beam off target run we are proposing is a demonstration of the feasibility and sensitivity of low mass WIMP searches at accelerators using proton beam dumps.
  – We are asking for a short ~12 month run to collect 2E20 POT in beam off target mode to significantly enhance WIMP searches.
  – We prefer the 25m absorber to be deployed.
  – There are sufficient hardware and people resources to ensure the run and analysis is successful.

• This run will result in at least 1-2 papers that will produce relevant WIMP limits (or possibly signals).
  – MiniBooNE sensitivities explores new regions of WIMP parameter space that are consistent with relic density estimates.
  – MiniBooNE explores a region that is a possible explanation for the muon g-2 anomaly. We could play a role in the interpretation of the upcoming muon g-2 run at FNAL.
  – Our theory team is looking into other production and interaction modes.

• If successful, this could motivate future proposals for dedicated beam dump experiments using existing FNAL accelerators, or with Project X.
The MiniBooNE Request

MiniBooNE requests running to collect a total of $2.0 \times 10^{20}$ POT in beam off target mode and with the 25m absorber deployed. This will allow a powerful search for light mass WIMPs in a parameter space that overlaps with muon $g - 2$ and cosmic relic density estimates. The experiment further requests that this beam be delivered in FY2013 and 2014 before the MicroBooNE experiment turns on.

- We have already made the investment in the detector and the beamline, let's capitalize on that investment to explore this unique physics opportunity relevant to the dark matter sector and possibly muon g-2.
BackUp Slides
Ten Years of MiniBooNE Running: Oscillation Results

- Combined $\nu_e$ and $\bar{\nu}_e$ Event Excess from 200-1250 MeV = 240.3±34.5±52.6 (3.8$\sigma$)
Ten Years of MiniBooNE Running: Cross Section Results

- We have measured cross section for 90% of $\nu$ interactions in MB. The detector is well understood!
- Additional $\overline{\nu}$ results to be reported this fall.
- These results have motivate much new and needed theoretical work on neutrino nucleus scattering.
Traditional underground direct detection experiments run out of sensitivity below \(~1\) GeV.
Beam Off Target Running Issues

- Target is 1 cm diameter
- Air gap between target and horn inner conductor is ~1 cm

- Successfully ran beam off target on 50 m dump for 1 week in March, 2012.
  - Rad safety reviewed beam dump safety documents and gave the okay.
  - Autotune can keep beam off target with ~1mm spread.
  - No radiation alarms or beamline monitoring anomalies.
  - No risk to the horn from spray as donut collimator would prevent extremely off target beam from hitting the horn.
- For a 12 month run we would turn off the horn, reducing fatigue/stress.
Assumptions on 90% C.L. Upper Limits

• Include statistical and systematic errors on background estimates.
• In the limit of small signal \((N_s)\) and large backgrounds \((N_b)\), 90% upper limits is
  \[ -1.28\sqrt{N_b + (\text{SysErr} \times N_b)^2} \]
• In the limit of zero signal and small backgrounds, the Poisson 90% upper limit is
  \[ -2.3 \text{ events} \]
Absolute Timing of Detector Events Compared to RWM

- MiniBooNE 1-sigma absolute event timing relative to the beam is ~1.8 nsec in neutrino mode (worse in antineutrino mode).
- To achieve 99% rejection of events going at the speed of light, require a $2.58 \times 1.8$ nsec = 4.6 nsec timing cut.
  - This results in a 50% efficiency hit to the signal.

RF buckets

Event Time – Beam Time (all corrections) - nsec

Out of time (late) events
Mass Threshold for 4.6nsec Time Cut

• Based on WIMP kinetic energy distribution, we can assume 
  ~1.5 GeV wimp momentum, then $M_t = 108$ MeV.
  – Above this mass we can reject neutrino backgrounds by 99%.
  – Coupled with beam off target running, we can achieve 90% limits at the few event level.
  – Using more sophisticated analysis can set limits as a function of WIMP mass for realistic momentum distribution.
Upgrades to Beam Positioning

- With new dual low mass multiwires, will be able to reliably point the proton beam at the detector to within 0.5 mrad, or about 25 cm spatial resolution.
RWM Timing Upgrades

• Installing new fiber timing circuit between target RWM and the detector electronics.
  – Will result in more stable operation and improved timing.

• We are working with AD to install a wave form analyzer to digitize the RWM RF structure and stored via ACNET.
  – This will provide detailed RF timing structure from pulse to pulse.

With old RWM we have to make various quality cuts to remove tails. This created some timing bias which we are trying to understand and quantify. Effect worse in antinu mode.