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HUNTER: A Facility for a Trapped Atom Sterile Neutrino Search and Other Studies

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The **HUNTER** project (**H**eavy **U**nseen **N**eutrinos from **T**otal **E**nergy-momentum **R**econstruction) brings together HEP, AMO, and NP techniques to build a versatile facility for measurements on trapped radioactive atoms. HUNTER will first be used to mount a unique search for beyond-Standard-Model sterile neutrinos having masses in the 20-300 keV range, based on total energy-momentum reconstruction of ^{131}Cs electron capture decays[1]. We will perform event-by-event reconstruction of the decays, detecting the recoil ^{131}Xe, the atomic x-ray, and one or more Auger electrons and seeking a separated nonzero missing-mass peak from massive sterile neutrinos[2–4]. HUNTER is an example of the power of AMO science techniques to enable demanding tests of the most fundamental laws of nature. The initial HUNTER equipment is funded by $1.2M we have received from the W.M. Keck Foundation (plus substantial institutional contributions).

The motivation for sterile neutrino searches generally, and HUNTER in particular, starts with neutrino oscillations and the inferred exceedingly small but nonzero neutrino masses. However, "it is not possible to construct a renormalizable mass term for the neutrinos with the fermionic content and gauge symmetry of the Standard Model"[5]. Thus neutrino oscillations represent the most unambiguous current evidence for physics beyond the Standard Model.

Many modelers work with theories giving sterile neutrinos in this mass range[6]. For certain choices of parameters (the "νMSM"[7]), theories having two heavy sterile neutrinos with masses at or below the electroweak scale, plus one in the keV-mass range, can be consistent with all existing experimental constraints, while solving an impressive list of physics problems. Diagonalizing the mixed Majorana- and Dirac-mass matrix can generate a spectrum of mass eigenstates with small masses for the active neutrinos as implied by the oscillation data, and additional heavy and light (keV-scale) eigenstates. The heavy sterile neutrinos of these theories can also generate the baryon asymmetry of the Universe through leptogenesis[8].

Finally, a keV-mass sterile neutrino would also be a candidate[9] for the Warm Dark Matter suggested by large scale structure calculations and observations[10]. Such neutrinos can be produced in the early universe by vacuum oscillations[9] or MSW-type resonant oscillations[11] of the active neutrinos. However, the actual number produced can vary dramatically depending on the (unknown) reheating temperature after inflation[12].

Under standard cosmological assumptions, keV sterile neutrino dark matter is in tension with astrophysical observations which have not convincingly shown the monoenergetic x-rays expected from the decay $\nu_s \rightarrow \nu_e + \gamma$[13–15], suggesting an exceedingly small coupling between the sterile and active neutrinos. This conflict can however be evaded by a combination of low reheating temperature and nonstandard particle physics content[16]. On the other hand, a *large* coupling would also lead to no observed x-ray lines: any sterile neutrinos produced in the Big Bang would have decayed away by now. In any case, the HUNTER experiment is agnostic as to sterile neutrino models and dark matter content.

Present laboratory limits on the sterile-active neutrino coupling ($\sin^2\theta$) in the mass range explored by HUNTER range from $\sim 10^{-4}$ to $\sim 10^{-2}$. Our initial proposed configuration will surpass these limits, and an upgrade path exists to extend the sensitivity by many orders of magnitude, allowing HUNTER to eventually probe lower neutrino masses and much smaller $\sin^2\theta$ values.

The HUNTER apparatus is centered around a high-occupancy Magneto-Optical Trap (MOT). For the ^{131}Cs sterile neutrino search, a collimated beam of neutral ^{131}Cs atoms is efficiently produced from a solid source in an orthotropic oven[17]. The beam is first loaded into a subsidiary 2-D MOT, then transferred to the main 3-D MOT where it is trapped and laser-cooled to sub-milliKelvin temperature. The MOT uses versatile external-cavity diode lasers with automated, very-high-resolution frequency and intensity controls, which can later be adapted to trap other species of interest.

^{131}Cs was selected for the sterile neutrino search since it decays 100% by electron capture (EC) with a 9.7 day halflife. EC decays allow total energy-momentum (and thus neutrino mass) reconstruction without the need for high resolution measurement of relativistic beta particles. ^{131}Cs is commercially available at very reasonable cost as a brachytherapy source. It also decays directly to a stable daughter, emitting no radiation more penetrating than a 35 keV x-ray. This allows the experiment to be run in a University lab without beamtime and scheduling constraints. Later coupling of the apparatus to accelerator-produced radioactive beams of other isotopes would be possible.

The main MOT is viewed by large-acceptance, high-resolution electrostatic spectrometers ("Reaction Ion Microscope") to detect the recoil ions and Auger electrons from EC decays in the trap. The ion spectrometer collects recoil ions with 100% geometrical efficiency and directs them onto a position-sensitive MCP detector, with vector momenta measured by time-of-flight (TOF) and hit position. The spectrometer is "double focusing," i.e., resolution is insensitive to transverse and longitudinal MOT source cloud size. The design is based on an extensive program of electrostatic simulations and achieves momentum resolution of about 0.1%, limited by the spatial resolution and size of commercially available MCP's. Simulations show that up to an order of magnitude higher ion resolution can be achieved by re-tuning in the same apparatus, at the expense of geometrical efficiency. This would improve the mass reconstruction resolution, extending the statistical power of peak-searching for a given event sample and reducing the minimum detectible sterile neutrino mass.

A similar spectrometer in the opposite hemisphere detects the Auger electrons from ^{131}Cs decay. The resolution requirement for the Auger electrons is not as severe as that for the ions, since the ion momentum is much larger. A uniform longitudinal magnetic field of 8 Gauss confines the electron trajectories.

The MOT is also viewed by a position-sensitive scintillator array to measure vector momentum of the atomic x-rays. 2 mm thick YAP tiles are viewed by photomultipliers, covering 12% of 4π. Aside from contributing to the total energy-momentum reconstruction, the fast signal from the YAP provides the TOF start for both charged particle spectrometers. A later upgrade of the PMT readout to SiPMs would further enhance the x-ray vector momentum resolution and consequently the neutrino mass resolution.

We have also extensively simulated the physics backgrounds and random triggers in the experiment, including their reconstruction. Physics backgrounds that have been considered include: scattering of recoil ions or Auger electrons within the laser-trapped source; radiative K-capture, giving an additional undetected photon; electrons knocked from surfaces by coincident x-rays from source atoms, mimicking Augers; residual gas scatters by Auger electrons during flight to detectors; emission of a photon instead of an Auger electron; cosmic ray muons; and radioactivity in walls and component materials. Of these, by far the dominant effect turns out to be scattering of the outgoing ^{131}Xe^{+} ion by the ^{131}Cs atoms[18] as the ion exits the trapped atom cloud. Next (though much smaller) is radiative K-capture[19–22], and the rest are negligible.

HUNTER has the potential to discover changes to the basic particle content of the Standard Model, which would have wide implications in science. A variety of other experiments with the apparatus are also possible. Polarizing the source atoms by optically pumping the MOT would allow the spin asymmetry of electron capture to be measured, which is more sensitive than the beta asymmetry[23] to tensor weak interaction terms[24] from spin-zero leptoquark exchange[25]. The cold, dense ^{131}Cs cloud could also be used for an atomic parity violation measurement complementary to the anapole measurement in stable ^{133}Cs[26]. The apparatus could also be used for measurements of atomic scattering properties relevant to BEC realization with Cs isotopes. Such a BEC has been discussed in connection with possible realization of a gamma ray laser[27,28].

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