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EXPERIMENTAL USE OF NEUTRINOS FROM ISABELLE BEAM DUMPS

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INTRODUCTION

The purpose of this paper is to emphasize the technical feasibility and possible applicability of using ISABELLE beam dumps as powerful sources for directed high energy neutrino bursts. In the present machine design two dump systems are applied to absorb the extracted fast beams.¹ These systems are normally activated when a machine working period terminates or when the beams in the rings become somewhat anomalous. Disregarding the latter, emergency extractions, the expected normal beam extraction rate is 1 to 2 per day, when about $(6.3 \text{ to } 7.5) \times 10^{14}$ protons are hitting the external targets during a pulse length of $\sim 50 \mu\text{sec}$. These protons are considered so far to be useless.

The present interest in having neutrino beams at high energy and measurable intensity at very large (so to say, global) distances, however, suggests a natural application of these apparently useless protons: converting them into neutrinos. In other words, the proton dumps can serve as neutrino bursters. This does not mean that the ISABELLE neutrino bursters would compete with the dedicated neutrino beams of various laboratories such as FNAL. However, since they would provide 2 to 4 neutrino bursts per day during the whole lifetime of the machine (without disturbing the ISABELLE normal research program), these neutrino bursts might have importance for research activities that require years of continuous running of massive neutrino detectors.

It is anticipated that among these activities the following would be included: (1) the study of coherent neutrino regeneration, (2) calibration and permanent testing of cosmic-ray and astrophysical neutrino detectors, (3) research on the practical applicability of neutrinos in telecommunication, and (4) certain astro- and geophysical applications.

1. ISABELLE DUMPS AS NEUTRINO BURSTERS

Although the proposition to use the ISABELLE dumps as intensive neutrino sources is apparently independent of the problem of slow beam ejection, it is practically inherently related to it.* A method proposed by S. Myers³ for slow ejection of normal beams seems to solve this problem, and we use it to illustrate a viable method of neutrino burst generation: A beam at the end of a run can be ejected from the ring in pulses in which the number of

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protons can be maximized on the target without overheating it. Considering ejection in pulses containing $\sim 2 \times 10^{13}$ protons and using a sweeping time³ $t_s = 43.8$ sec, complete ejection will occur during 23 to 27 min in 32 to 38 pulses.

In accordance with the present machine design the downward directed protons would hit a target system. The muon decay pipe, of course, would have to be aimed also below horizon.*

The expected neutrino energy spectrum with or without a horn system would be about the same as for the FNAL neutrino facility⁴ (Fig. 1). The yield for 10^{13} incident protons would be $\sim 10^{10}$ ν peaked at $E_{\nu} \sim 15$ GeV, as at the FNAL. The total expected ν_{μ} field of a complete ejection is therefore $(6 \text{ to } 7) \times 10^{11}$ ν_{μ} .

Fig. 1. Neutrino broad-band spectrum for horn, quadrupole, and bare target beam at FNAL.

So far there is no specific machine-connected requirement concerning the location around the rings of the slow extraction systems. The location would be determined by the requirements appropriate to the physics task. However, to maximize the reaction rate to be investigated, it is reasonable to direct the neutrino beams from both rings of ISABELLE to the same detector location. In certain situations one can anticipate, of course,

* Deflecting the protons downward through large angles involves an expensive beam transport. The flux estimates are based on this system. Another alternative would be to deflect the secondaries with a large-aperture magnet after the target and an appropriate focusing device. This might be a more economical design, but no details have been worked out or evaluated.

different sign and type selection of neutrinos or direction of the neutrino beams toward different detector locations.

2. APPLICABILITY OF ISABELLE NEUTRINO BEAMS

To illustrate the applicability of the neutrino beams provided by ISABELLE, consider now the possibilities listed in the Introduction. This will indicate some more specific requirements for the ISABELLE slow extraction system.

a. Coherent Neutrino Regeneration

Recently Wolfenstein pointed out⁶ that, if neutrinos are propagating in matter, neutrino oscillation can occur. This phenomenon is analogous to K_S regeneration from a K_L beam passing through matter. The effect is caused by the coherent forward scattering provided the neutral current has an off-diagonal connecting different neutrino types, i.e., if the neutral current can change neutrinos from one type to another. (The effect represents a violation of separate lepton number conservation.)

In contrast to vacuum oscillations^{6,7} the neutrinos are not required to have mass. Thus, to distinguish it from vacuum oscillation, we call the effect coherent neutrino regeneration.

The transformation probability for $\nu_\mu \rightleftharpoons \nu_a$ regeneration (ν_a can be any new type of neutrino) is given by

$$P(\nu_\mu \rightleftharpoons \nu_a) = \frac{1}{2}[1 - \cos(2\pi x/\ell_a)] \quad , \quad (1)$$

where x is the distance from the neutrino source and ℓ_a is the oscillation length. The probability is energy independent since

$$\frac{1}{\ell_a} \propto \left| \frac{d\sigma/dq^2(0)}{2\pi} \right|^{\frac{1}{2}} \quad (2)$$

and it is well known that the forward neutrino elastic scattering is independent of energy. For terrestrial rock ($\rho = 4 \text{ g/cm}^3$) and assuming maximum nondiagonal neutral current

$$\frac{2\pi}{\ell_a} \approx \left| 10^{-8} \text{ cm}^{-1} (g_p + g_n + g_e) \right| \quad , \quad (3)$$

where the quantities g_p , g_n , and g_e must be determined from neutral current scattering experiments or can be taken from theory. The Weinberg-Salam theory gives $(g_p + g_n + g_e) \equiv L_{WS} = -0.5$.

The continuous curve in Fig. 2 shows the transition probability as a function of x . The maximum where a ν_μ -beam is completely transformed (i.e., disappears) is at a distance of about the Earth's radius, $x_m \approx R_0$.

If electron neutrinos (ν_e) are involved, the transformation probability $P(\nu_\mu \rightleftharpoons \nu_e)$ is somewhat different because there is a

contribution to the coherent scattering from the charged current as well. For this case, with maximal nondiagonal terms the transformation probability is

$$P(\nu_\mu \rightarrow \nu_e) = \frac{1}{2}[1 - \cos(2\pi x/l_e)] \quad , \quad (4)$$

where $2\pi/l_e \approx 0.71 \times 10^{-8} \text{ cm}^{-1}$. Observe that both the transition amplitude and the oscillation length are smaller than in the previous case.

The broken line in Fig. 2 shows the dependence on the distance x . The location of the maximum (i.e., where a ν_μ -beam decreases to half its intensity) is at $x_m \approx 0.7R_0$.

Using most other reasonable gauge-models, as Wolfenstein points out, one still arrives at oscillation due to flavor changing neutral currents.

Fig. 2. Neutrino transformation probability as a function of rock thickness. Parameters: $\sin^2 \alpha = 1.0$; $\rho_p \approx \rho_n \approx \rho_e = 2$; $g_p + g_n + g_e \equiv L_{WS} = -0.5$. See ref. 5.

Figure 3 shows the declination angles (α) at which a ν_μ -beam should be oriented below the horizontal into the earth to obtain a given intensity decrease at beam path x .

These values were obtained by using Fig. 4, which shows general relationships between declination angle (α), effective beam path in rock (x), and sagitta (Δ) vs geodetical distance (L).

For neutrino detection, in the first phase of experimentation, a relatively simple measurement is anticipated. In an appropriately massive target detector we would measure the rate of the reactions

$$\nu_\mu + n \rightarrow \mu^- + \text{hadrons} \quad , \quad (5)$$

which are in coincidence with the gate pulses of ISABELLE. This

Fig. 3. ν -beam declination angles for measuring coherent neutrino regeneration.

Fig. 4. General relationship between declination angle (α), effective beam path in rock (x), and sagitta (Δ) vs geometrical distance (L).

would then be compared with the rate predicted from the known ν_μ flux at the source and the ν_μ -beam divergence.

Large, moduled, water Cerenkov arrangements can be used for the measurements, and the direction of the impinging ν_μ 's can be relatively easily determined from the muon Cerenkov radiation.* The module length (k) is determined basically by the light transmission properties of the water. We anticipate $k \sim 20$ to 30 m. Since the timing and direction of the muons are known (muons come from "below"), the background from downward traveling cosmic-ray muons is diminished.

Just for illustration, we give in Fig. 5 the characteristic radius (R) and volume (V) of such a detector for a ν_μ -beam with a divergence angle of 0.2 mrad as a function of the effective distance in rock, x. Figure 6 shows the expected specific rates (SR) and total rates (TR) in the detector vs the effective distance in rock, x. The rates are determined by using the cross section formula for reaction (5) as

$$\sigma_{\nu_\mu} \approx (0.58 \times 10^{-38}) E_\nu \text{ cm}^2, \quad (6)$$

where the neutrino energy was taken to be $E_\nu = 15$ GeV. At the maximum of the $\nu_\mu \rightarrow \nu_e$ transition a representative set of values is $x = 4.44 \times 10^3$ km, $R = 444$ m, $V = 3.67 \times 10^8$ m³, $SR = 1.25 \times 10^{-3}$ int/m³ per 6×10^{14} protons, $TR = 4.58 \times 10^5$ int per 6×10^{14} protons. In these rates the coherent regeneration effects are not taken into account.

Although the detection of coherent neutrino regeneration is extremely interesting,** at present it is hard to imagine that dedicated detectors would be built just for this purpose. Instead, we consider application of the planned large-scale intercontinental cosmic or astrophysical neutrino stations, which use the water Cerenkov detectors described above and are deep enough in the ocean or in rock to avoid serious background. The search for coherent neutrino regeneration using ISABELLE neutrinos might be easily incorporated into such a research program.

b. Calibration and Permanent Checking of Cosmic and Astrophysical Neutrino Detectors

We think the use of the ISABELLE steady neutrino beams for calibration and permanent checking of the above mentioned detectors would be of particular importance. These beams are especially

* Muons produced by $E_\nu \sim 15$ GeV neutrinos will travel ~ 50 m in water. The flux of emitted Cerenkov photons is independent of the muon energy and equal to $n_\gamma \sim 200/2\pi r$ photons/cm² in the visible region (4000 to 8000 Å) at a distance r (cm) from the μ trajectory. The angle of the Cerenkov cone is $\sim 41^\circ$.

** The measurement would also give information about the vacuum oscillation.⁷

Fig. 5. Characteristic radius (R) and volume (V) of water Cerenkov detector for a ν_μ -beam with divergence angle 0.2 mrad vs effective distance in rock, x.

Fig. 6. Specific rate (SR) and total rate (TR) of reaction $\nu_\mu + n \rightarrow \mu^- + \text{hadrons}$ in a water Cerenkov detector of volume V vs effective distance in rock, x. Parameters: $\sigma(\nu_\mu \rightarrow n) = (0.58 \times 10^{-33}) \epsilon_\nu \text{ cm}^2$; $\epsilon_\nu = 15 \text{ GeV}$; ν_μ -beam divergence angle $\approx 0.2 \text{ mrad}$.

well suited for this purpose since the pulse structure would imitate neutrino emission from extraterrestrial sources mainly from collapsing stars (time scale: μsec to msec).

The planned water Cerenkov stations within the USA are listed below:

	Volume (m^3)
PPG Limestone Mine, Barberton, OH ⁸	2.0×10^3
Homestake Gold Mine, Lead, SD ⁸	2.0×10^3 (7.5×10^2 operating)
Deep Underwater Muon and Neutrino Detection (DUMAND), Hawaii ⁹	1.0×10^9

The DUMAND project in the Pacific is of the right size to be considered as a possible detector for the ISABELLE neutrino bursts from both rings.

c. Practical Applicability of Neutrinos in Telecommunication

Recently proposals^{10,11} have been made to develop technology for using neutrinos in global communication and orientation. This seems to be important during wartime when all normal radio (or sonar) communications with submarines are virtually blacked out. The practical applicability of these proposals requires long-lasting experimentation, in which we think the ISABELLE beamed neutrino bursts would be useful. In this connection we should like to point out also the importance of studying coherent neutrino regeneration, which represents a certain kind of "fading" effect in telecommunication language.

d. Certain Astro- and Geophysical Applications

Besides the above mentioned applications, interesting dividends can be expected from any long-range terrestrial neutrino experiment. For example, correlation of the time at the distance detector with the rf structure of the accelerator pulse could have significant consequences in long-base-line radio astronomy and (as we mentioned) in terrestrial neutrino astronomy. Certain geophysical applications can be anticipated also, since the only possible means of investigating the internal structure of the earth, besides seismic waves, are neutrinos.

3. CONCLUSION

The possibility of using ISABELLE as a powerful neutrino-producing source greatly extends its importance and the number of its users. The envisioned neutrino experiments would provide unique information both for elementary particle physics and for astrophysics.

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The neutrinos produced could be used for the following activities:

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