Japan Proton Accelerator Research Complex (J-PARC)
—Status of J-PARC and Tokai-to-Kamioka Neutrino Project—

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Abstract

Japan Proton Accelerator Research Complex (J-PARC) is a high intensity proton accelerator facility which is under construction in Japan. The 50-GeV proton synchrotron in J-PARC provides 0.75 MW beam. The accelerator construction will complete in 2008. In 2003, a new long baseline neutrino oscillation experiment using J-PARC has been approved and the facility construction started in 2004. In the experiment ν_μ beam is produced by the 50-GeV beam and detected by Super-Kamiokande located at 295 km from J-PARC. The experiment will start in 2009 and will improve sensitivity on ν_e appearance search by more than one order of magnitude in 5 years of running.

1 Introduction

Recently, high intensity proton accelerators have been attracting much attention as a key component to extend horizon of knowledge in many fields of science. One of the strong driving force for such high intensity machines is long baseline neutrino experiment, and the other is material and life science with neutron beam. In Fig. 1, world's proton accelerators are summarized. Most of the existing proton machines range around 100 kW beam power. Next

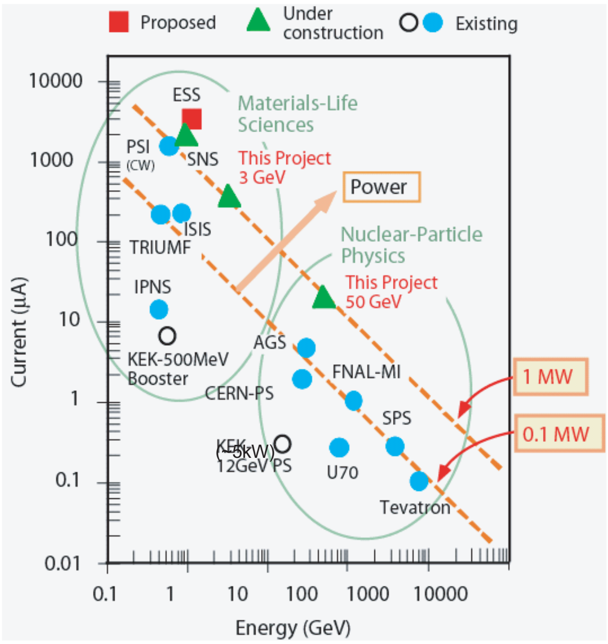

Figure 1: World's proton accelerators.

generation machines of high intensity frontier aim at MW power.

Japan Proton Accelerator Research Complex (J-PARC) is one of future MW proton facilities [1]. The construction started in 2001 and will complete in 2008. Unique feature of J-PARC is multi purposes; three goals of science are covered, namely (1) Material & life science, (2) Nuclear & Particle Physics, and (3) R&D toward nuclear transmutation. One of the major goal of J-PARC is a long baseline neutrino oscillation experiment from J-PARC to Kamioka. The neutrino experiment has been approved in 2003 and the construction started in April 2004.

In this report, J-PARC and the neutrino experiment are introduced.

2 Japan Proton Accelerator Research Complex (J-PARC)

J-PARC is a proton accelerator complex which is now under construction in JAERI (Japan Atomic Energy Research Institute) Tokai site, Tokai village, Ibaraki prefecture in Japan. JAERI-Tokai site is located at about 60 km N.E. of KEK (Fig. 2).

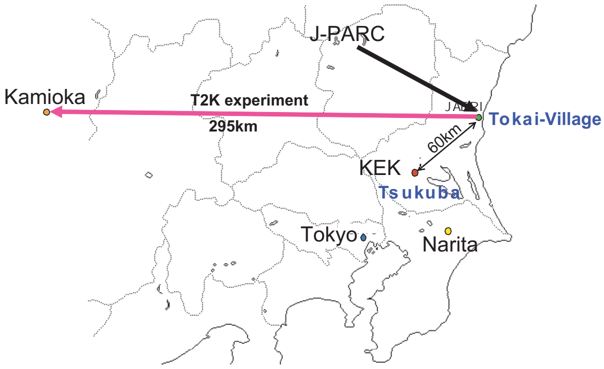

Figure 2: Location of J-PARC in Japan

J-PARC consists of a LINAC, the 3 GeV rapid cycling synchrotron (3GeV-RCS) and the 50 GeV proton synchrotron (50GeV-PS) [2]. The LINAC is used

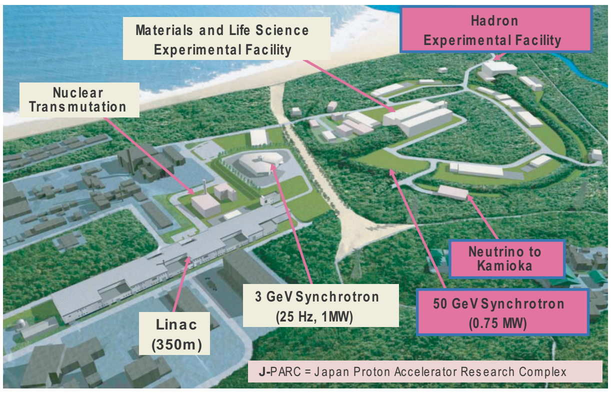

Figure 3: Bird's-eye image of J-PARC.

for injection to 3GeV-RCS. Design energy of the LINAC is 400 MeV. When the nuclear transmutation facility is build in the future, which has not been approved yet, the LINAC will be upgraded to 600 MeV with superconducting RF cavities. The 3-GeV RCS produces 1 MW average beam power with 25-Hz repetition. The beam extracted from the ring is transfered to Material and Life Science Experimental Facility (MLF) and is irradiated on a spallation neutron target to produce intense neutron beam. The 50GeV-PS accelerates 3.3×10^{14} protons to 50 GeV every 3.53 s and its beam power reaches 0.75 MW. The beam in 50-GeV PS is slow-extracted to hadron experimental facility and fast-extracted to neutrino facility. The slow extraction beam is used for various nuclear and particle physics experiments such and hyper-nuclear physics and Kaon rare decay experiments.

The performance of the accelerators in J-PARC mentioned above is the design specifications. Due to budgetary limitations, the LINAC energy will be 181 MeV and "50-GeV"-PS energy will be 40 GeV in normal operation just after the completion. The design performance will be restored later. In order not to reduce beam power from 50-GeV PS even with these degraded accelerator performances, possibility of doubling harmonic numbers in 50-GeV PS is being studied.

The construction of the accelerator complex, MLF, and hadron facility was started in 2001 and will be completed in 2008.

3 Tokai-to-Kamioka (T2K) neutrino experiment

3.1 Overview

The T2K (Tokai-to-Kamioka) experiment is a next generation LBL neutrino oscillation experiment in which ν_μ beam is produced using the 50 GeV proton synchrotron in J-PARC and sent to Super-Kamiokande (SK) with 295 km flight distance (Fig. 4) [3]. At the first phase of the project, the power of the 50-

Figure 4: Overview of T2K experiment.

GeV PS is 0.75 MW and SK will be used as a far detector. In the future, PS upgrade up to 4 MW and 1-Mt "Hyper-Kamiokande" [4] are envisaged. The main goals of the first phase are discovery of ν_e appearance and the precision measurements of oscillation parameters in ν_μ disappearance.

Special features of T2K beam line are (1) the first use of SC combined function magnets in the primary proton beam line, and (2) the first application of "off-axis" (OA) beam [5]. The use of the combined function magnets enabled to reduce cost while keeping large acceptance of the beam line. The OA beam can produce low energy high intensity ν_μ beam with adjustable sharp peak in the energy spectrum. The position of the peak will be tuned at energy of oscillation maximum to maximize the sensitivity.

The neutrino beam line was approved in December 2003 and the construction is started in April 2004 and will finish in March 2009.

3.2 Neutrino facility in J-PARC

The layout of the neutrino facility in J-PARC is illustrated in Fig. 5.

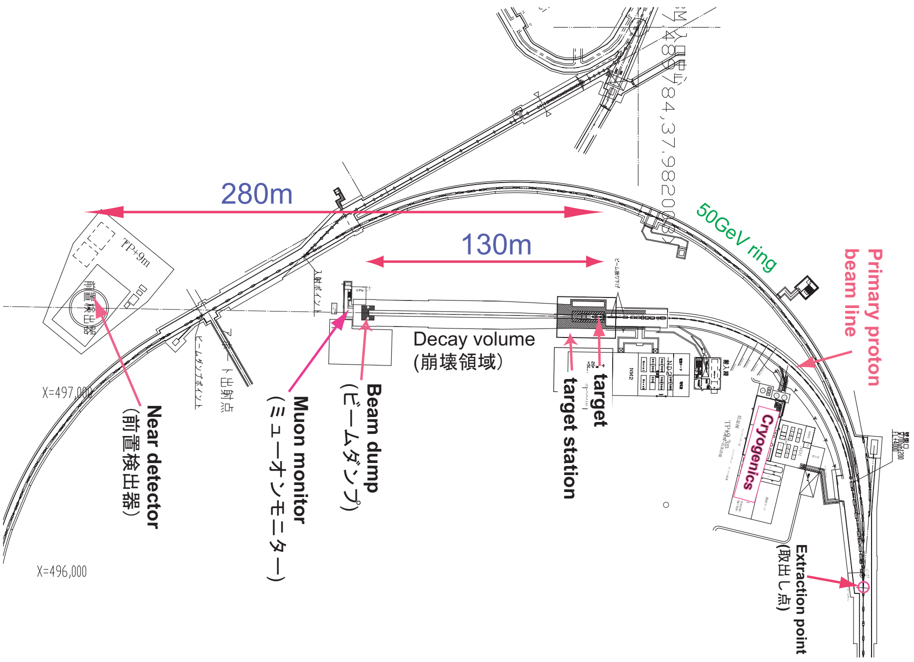

Figure 5: The layout of neutrino beam line.

The proton beam is extracted from 50-GeV PS in single turn by series of kicker magnets (fast extraction). A spill consists of 8 bunches each with 58-ns full width and separated 598 ns, resulting $\sim$4.2 μs total spill length. The primary beam line to transport the proton beam to a production target consists of preparation, arc, and final focusing section (Fig. 6). The preparation section

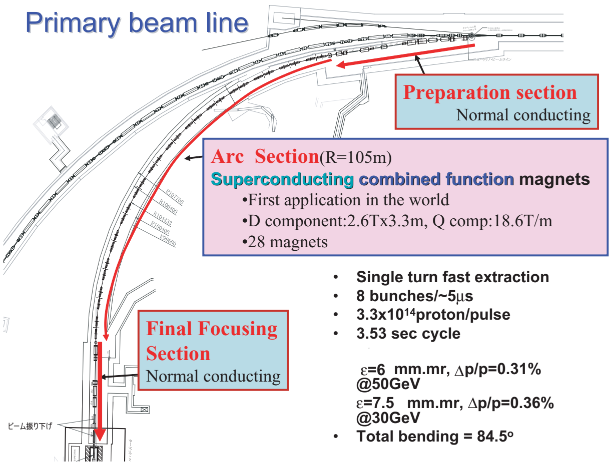

Figure 6: Primary beam line.

consists of series of normal conducting magnets and collimators. The arc section is composed of 28 combined function superconducting magnets and bends the proton beam about 80° toward SK with 28 magnets. The final focusing section, using normal conducting magnet, shapes the beam from the arc section to be suitable for the production target.

The production target is made of graphite of 3-cm diameter and 90-cm long (corresponding to 2 interaction length). About 80% of incoming protons interact in the target. The target is followed by three electromagnetic horns which focus generated pions to forward direction. They are driven by pulsed current of 320 kA at peak synchronized with the proton beam. The decay volume (DV) is a free space down stream of the horn where pions decay in flight into ν_μs and muons. The length between the target and the end of the decay volume is about 130 m. DV is filled with helium gas to reduce pion absorption. The decay pipe is designed to accommodate the beam of $2 \sim 3°$ off-axis angle. The beam dump is placed at the end of DV and stops hadrons such as remaining protons and secondary mesons. The dump consists of graphite blocks of about 2 m thickness, 1.35-m thick Copper and 1.35-m thick Iron. The Muon monitor is placed just after the beam dump to detect muons. High energy muons of > 5 GeV penetrate the beam dump and reach the muon monitor. The muon monitor provides pulse by pulse information on the intensity and profile of the beam. At 280 m from the production target, neutrino detectors will be placed in order to measure neutrino beam properties. Two independent detector systems on the proton beam axis and off-axis (pointing to SK) are currently planned. The main purposes of the on-axis detector is to monitor the neutrino beam direction, intensity while the off-axis detector aims to measure energy spectrum, contamination of electron neutrino and neutrino interactions with similar energy spectrum to SK.

The expected ν_μ spectrum at SK without oscillation is plotted in Fig. 7. The ν_e to ν_μ flux ratio is as small as 0.2% at the peak energy of ν_μ spectrum. Expected numbers of interactions at SK with 2° off-axis is about 3000 for CC interactions in fiducial volume of 22.5 kt in 1 year.

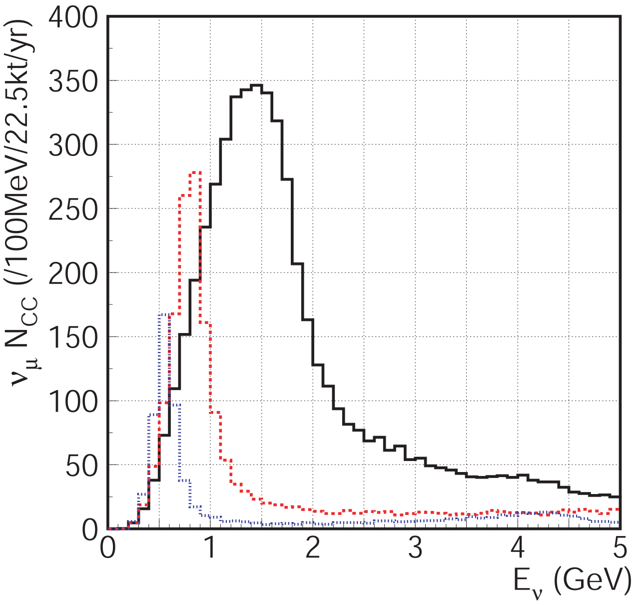

Figure 7: Expected spectrum of CC interactions at SK. The solid (black), dashed (red) and dotted (blue) histograms are OA1.5°, OA2° and OA3°, respectively.

3.3 Sensitivities

3.3.1 ν_μ disappearance

The precision measurement of oscillation parameters θ_{23} and Δm^2_{23} is done by precisely measuring the spectrum distortion in ν_μ disappearance mode.

In SK, fully contained events with single μ-like ring are selected to enhance the ν_μ CCqe events. In Fig. 8, expected distributions of reconstructed E_ν are shown for both without and with oscillation. Significant deficit in peak region is seen

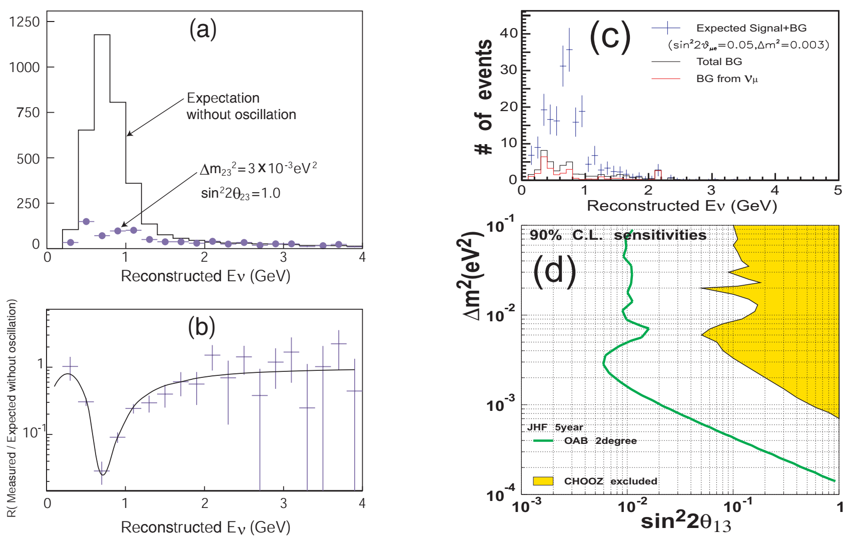

Figure 8: (a) Reconstructed muon neutrino energy spectrum in the case of $(\Delta m^2_{23}, \sin^2 2\theta_{23}) = (3\times10^{-3}\text{eV}^2, 1.0)$, compared with the null-oscillation case, (b) ratio of the measurement-to-expectation in the case of without oscillation (OAB 2°, 5-year measurements). (c) Reconstructed neutrino energy spectrum for FC 1R e-like events for 5 years of operation with OAB 2°. (d) Expected 90% sensitivity contour on (Δm^2 ,$\sin^2 2\theta_{13}$) compared with the CHOOZ exclusion plot.

even without subtraction of background from non-qe events. The expected precision of the oscillation parameters are 1% for $\sin^2 2\theta_{23}$ and $\lesssim 10^{-4}$ eV^2 for Δm^2_{23}.

3.3.2 ν_e appearance

The signature of ν_e appearance in ν_μ beam is a single electromagnetic shower from ν_e CC interaction. Major sources of the background are beam ν_e contamination and ν_μ NC π^0 production. Combination of narrow spectrum and E_ν window cut greatly helps to reject both of the background, since the background show broad "reconstructed" E_ν distribution while that for the signal concentrates at the original peak of the ν_μ spectrum.

In the T2K experiment, a dedicated analysis algorithm is developed to reject the π^0 background as much as possible [3]. The expected reconstructed E_ν distribution after 5 years of exposure is shown in Fig. 8. The oscillation parameters of $\Delta m^2 = 3 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{13} = 0.1$ are assumed. A clear appearance peak is seen at the oscillation maximum of $E_\nu \sim$0.75 GeV. Also shown in Fig. 8 is 90%C.L. contours for 5 year exposure assuming 10% systematic uncertainty in background subtraction. In the plot, CP violation and matter effect is neglected. The sensitivity of $\sin^2 2\theta_{13} = 0.006$ at 90% confidence level can be achieved in five years of operation. If $\sin^2 2\theta_{13}$ is larger than 0.018, then discovery of ν_e appearance is possible with the significance greater than 3σ.

3.3.3 NC measurements

The ν_τ content in the beam after the oscillation can be estimated from the number of NC interactions at SK, because the neutrino flux estimated from the NC measurements is a sum of the fluxes of all active neutrinos, ν_e, ν_μ and ν_τ. Any reduction of the ν_τ flux compared with the predicted one from near detector measurements imply the existence of oscillation to non-active neutrino. In the T2K experiment, NC events can be selected by requiring one or two e-like rings without any decay electron signal associated with 84% purity. Expected number of events in 5 years of OA2° operation is 680, while it becomes 280 if 100% ν_μ goes to ν_s.

3.3.4 CP violation

Main goal of the second phase of T2K experiment is a search for CP violation in lepton sector. The CP violation can be observed only with appearance experiments. Especially $\nu_\mu \leftrightarrow \nu_e$ oscillation is known to provide the best chance in measuring the CP asymmetry in lepton sector. This is because the leading CP conserving term of $\nu_\mu \leftrightarrow \nu_e$ oscillation is highly suppressed due to small Δm^2_{12} and the sub-leading terms, such as θ_{13} related and CP violating terms, give leading contributions.

In the T2K experiments, difference of the probabilities between $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ will be searched for. In Fig. 9, relevant oscillation probabilities are plotted. As shown in the figure, the CP asymmetry can be as large as 40% even at $\delta = \pi/4$. Matter effect also produces the difference and mimics the CP violation effect. The size the matter effect increases linearly with neutrino energy. In Fig. 9, the size of the matter effect is also drawn. At the 1st oscillation maximum in 295 km case, the size of the matter effect is much smaller than the CP violation effect.

The expected sensitivity on CP violation in 2nd phase T2K experiment is plotted in Fig. 10. In the plot, matter effect is neglected. If θ_{13} is of the order

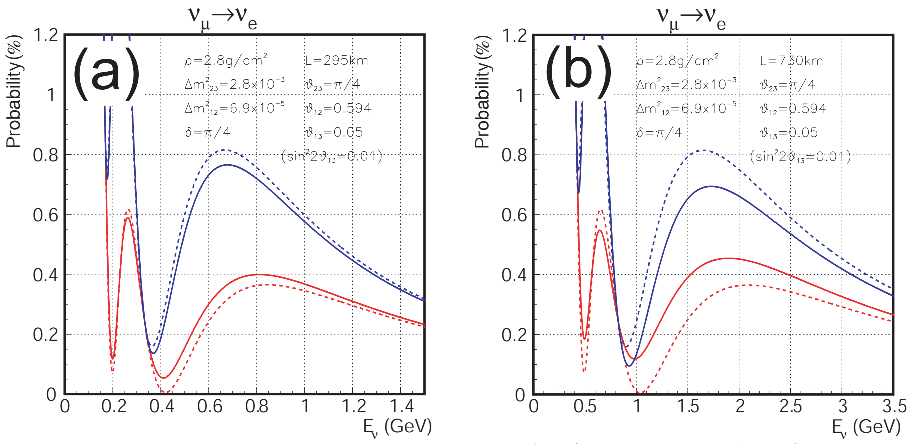

Figure 9: Oscillation probabilities for $\nu_\mu \to \nu_e$(red) and $\bar{\nu}_\mu \to \bar{\nu}_e$(blue) for baseline length of (a) 295 km and (b) 730 km. The solid curves includes asymmetry due to matter effect. For the dashed curves, the matter effect is subtracted and the difference between $\nu_\mu \to \nu_e$(red) and $\bar{\nu}_\mu \to \bar{\nu}_e$(blue) are all due to CP effect.

of 0.01 or larger, the CP violation phase δ can be explored down to $\sim 20°$.

4 summary

J-PARC, a multi purpose proton accelerator complex is being constructed since 2001. The accelerators, material and life science experimental facility and hadron experimental facility will be completed in 2008. The neutrino facility in J-PARC for T2K experiment is approved and started construction in April 2004. The R&D and design of the beamline components are in progress. Expected number of ν_μ CC interactions is ~ 3000/yr in the case of no oscillation. Sensitivity on ν_e appearance is $\sin^2 2\theta_{13} > 0.006$ at 90% C.L., which is 20 times higher than present upper bound by CHOOZ experiment. Expected precision on ν_μ disappearance is 3% and 1% for Δm^2 and mixing angle, respectively. In the 2nd phase of T2K with 4MW machine and possible Hyper-Kamiokande, CPV can be explored down to about $\delta \sim 20$deg. The construction of the neutrino facility will be completed in 5 years and the physics experiment will start in 2009.

References

1. http://j-parc.jp

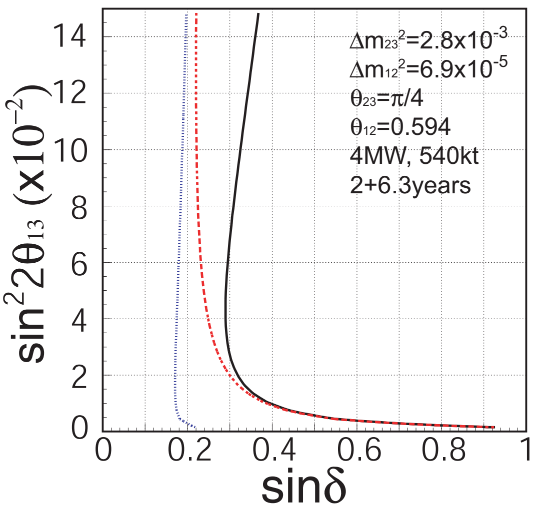

Figure 10: Expected 3σ discovery regions of $\sin\delta$ as a function of $\sin^2 2\theta_{13}$ after 2 (ν_μ) and 6.3 ($\bar{\nu}_\mu$) years of exposure in the phase II of T2K experiment. The (blue) dotted curve is the case of no background and only statistical error of signal, (red) dashed one is 2% error for the background subtraction, and (black) solid curve is the case that systematic errors of both background subtraction and signal detection are 2%. The values of other parameters are shown in the plot.

2. *"ACCELERATOR TECHNICAL DESIGN REPORT FOR J-PARC"*, Accelerator Group, J-PARC project team, http://hadron.kek.jp/member/onishi/tdr2003/index2.html

3. Y. Itow, *et al* , hep-ex/0106019; http://neutrino.kek.jp/jhfnu;

4. M. Koshiba, *Phys. Rep.* **220**, 229 (1992); K. Nakamura, *Neutrino Oscillations and Their Origin*, (Universal Academy Press, Tokyo, 2000), p. 359.

5. D. Beavis *et al* , Proposal of BNL AGS E-889 (1995).