Particle and Nuclear Physics Programs at the Joint Project of High Intensity Proton Accelerator Facility

Yoshitaka KUNO,
Department of Physics, Graduate School of Science, Osaka University,
Machikane-yama 1-1, Toyonaka, Osaka 560-0043

Abstract

The potential particle and nuclear physics programs which would be considered at the Joint Project of High Intensity Proton Facility are briefly presented.

1 THE JOINT PROJECT OF THE HIGH INTENSITY PROTON FACILITY

The Joint Project of the High Intensity Proton Facility [1] is a new accelerator project in Japan to build a complex consisting of a 400-MeV proton linac, a 3-GeV proton synchrotron, and a 50-GeV proton synchrotron. It aims to provide the highest beam intensity among the accelerators of such energies in the world. For instance, the 3-GeV synchrotron (3-GeV PS) and the 50-GeV proton synchrotron (50-GeV PS) are designed to provide high-intensity beams of 333 μA (1 MW) and 15 μA (0.75 MW), respectively. The 50-GeV PS will have a cycle time of about three seconds with one second slow extraction time. As possible future upgrade path, it is considered to increase a beam power from 0.75 MW to 4.4 MW at the 50-GeV PS.

The physics programs at the 50-GeV PS cover a bread range of science from material-sciences physics to high-energy physics, using the various primary and secondary beams from the accelerators. Among those various physics programs, only the particle and nuclear physics which could be potentially done at the 50-GeV PS will be discussed in this paper. The topics selected herein are not all inclusive, but reflect the authors preference.

2 OVERVIEW OF PARTICLE PHYSICS AT THE 50-GEV PS

The particle physics at the 50-GeV PS will be mostly fixed target experiments. They are aiming at a discovery of new phenomena with high-precision measurements with the high intensity beams (either primary or secondary) available. In the path of progress in particle physics in the past, there have been two distinguished streams: one is the high-energy frontier and the other is the high-precision frontier. The former includes the discover of W and Z bosons, and that of the top quark, etc., whereas the latter includes the discovery of neutral weak current processes, that of CP violation, the measurement of the anomalous $(g-2)$ muon magnetic moment, the neutron electric dipole moment, etc. These two streams are complementary one another, and have contributed constructively to our understanding of particle physics over the past decades. The particle physics programs at the 50-GeV PS belong to the latter streams.

The potential programs at the 50-GeV PS are such as (1) Particle Physics with Kaons, (2) Particle physics with Muons, and (3) Particle physics with Neutrinos. In short, the shopping list with wished goals are summarized in Table 1. The details will be described in the following sections.

Table 1: Margin specifications

category	**decay modes**	**goals**
KAON	$K^+ \to \pi^+\nu\overline{\nu}$	about 100 events.
	$K_L^0 \to \pi^0\nu\overline{\nu}$	about 1000 events.
	T viol. in $K^+ \to \pi^0\mu\nu$	$P_T < 10^{-4}$
MUON	$\mu^- + N \to e^- N$	B< 10^{-18}
	$\mu^+ \to e^+\gamma$	B< 10^{-15}
	$\mu^+ \to e^+e^-e^+$	B< 10^{-15}
NEUTRINO	long baseline	$\delta(\Delta m_{23}^2) = 10^{-4}eV^2$
	oscillation	$\delta(\sin^{22}\theta_{23}) = 0.01$

3 PARTICLE PHYSICS: KAON

Studies of K decays provide good opportunities to study flavor physics with the s quark. The primary purpose of kaon physics is to study the Kobayashi-Maskawa (KM) quark mixing matrix elements and its CP-violating imaginary phase. After the recent discovery of CP violation at the B-meson system, the major remaining issues on CP violation are whether the CP violation effects in the K- and B-meson systems are the same, or whether the KM triangle is unitary with just the three generations or needs more generation. Flavor Changing Neutral Current Process (FCNC) would give good testing grounds, Among the various FCNC processes, the most promising modes to stud the Standard Model are $K^+ \to \pi^+\nu\overline{\nu}$ and $K_L^0 \to \pi^0\nu\overline{\nu}$ decays. They have small theoretical ambiguities and therefore allow us to extract the KM matrix elements more cleanly than the others.

3.1 $K^+ \to \pi^+\nu\overline{\nu}$

$K^+ \to \pi^+\nu\overline{\nu}$ is sensitive to the KM element, V_{td}. It has a small theoretical uncertainty in the prediction of the branching ratio. The hadronic matrix element can be empirically obtained from $K^+ \to \pi^0 e^+ \nu$. The long distance contribution is known to be smaller than the short-distance contribution by three-orders of magnitude. However, a more accurate determination of V_{cb} and an understanding of the charm-quark contribution would be required to determine V_{td} to better than about 20% accuracy. The Standard Model prediction of the branching ratio is of order 10^{-10}. It is studied by BNL-AGS E787 and its successor E949 which uses K^+ decays at rest. The observation of one event of $K^+ \to \pi^+ \nu\overline{\nu}$ has been reported by E787. At the 50-GeV PS, it should be possible to collect about 100 events or more. The option of in-flight K^+ decays as well as K^+ decays at rest might be considered at the 50-GeV PS.

3.2 $K_L^0 \to \pi^0 \nu\overline{\nu}$

$K_L^0 \to \pi^0 \nu\overline{\nu}$ is sensitive to the CP-violating phase, η, in the Wolfenstein parameterization of the KM matrix. Therefore, if $K_L^0 \to \pi^0 \nu\overline{\nu}$ is observed, it would imply the discovery of the direct CP violation, which is CP violation in the decay amplitude. This process has very small long-distance contribution as in $K^+ \to \pi^+ \nu\overline{\nu}$. The Standard Model prediction of the branching ratio is about 10^{-11}, which has less theoretical uncertainty than $K^+ \to \pi^+ \nu\overline{\nu}$ since there is no charm-quark contribution. Experimentally, the measurement of $K_L^0 \to \pi^0 \nu\overline{\nu}$ is quite challenging, since a neutral particle (K_L^0) comes in and only neutral particles (π^0 and neutrinos) come out. There have been several ideas of how to proceed with the measurement which are now being discussed among many experimentalists. Currently, the KOPIO experiment is being prepared at BNL/AGS with a sensitivity of a few tens of the Standard Model events. Beyond that, since the KAMI proposal at FNAL has been rejected recently (in year 2001), a demand to construct a new experiment at the 50-GeV PS is growing strongly.

3.3 T-violation in $K^+ \to \pi^0 \mu^+ \nu$

The search for violation of the fundamental symmetries, such as the time-reversal invariance, is one of the keys to pin down clues to new physics beyond the Standard Model. A search for T violating transverse muon spin polarization ($P_\mu^\perp$) in $K^+ \to \pi^0 \mu^+ \nu$ decay has two advantages, compared with the searches with the other systems. First, it has a very small final state interaction (FSI), of the order of 10^{-6}, which would otherwise mimic a fake T-odd effect. For instance, nuclear β decays or $K^0 \to \pi^- \mu^+ e^-$ decay are expected to have a FSI of 10^{-3}. Secondly, it has no contribution from the Standard Model CP violation, and is thereby very sensitive to new physics, in particular an extension to the Higgs sector. Among various models, the one which predicts a large $P_\mu^\perp$ is the three Higgs doublet model (3HDM). Recently, it is pointed out that SUSY contribution to T-violation could be significant, as large as 10^{-3}, when the squark family mixing maximally occurs. At present, there is an experiment (E246) at KEK-PS, which could achieve the upper limit of $P_\mu^\perp < 10^{-3}$. The final data analysis is under way. An experiment with a sensitivity of 10^{-4} can be considered at the 50-GeV PS.

4 PARTICLE PHYSICS: MUONS

Lepton flavor violation (LFV), in particular in the muon system, has been known to be one of the most important topics in particle physics [2]. The LFV searches were initiated back in the 1940's. Since then, the limits have been improved at a rate of two orders of magnitude per decade ! It is in general discussed that the searches for rare LFV decays can potentially explore at a very high energy scale, like a few 100 TeV. However, the recent growing interest in LFV is motivated by supersymmetric extension to the Standard Model, in particular supersymmetric grand unification (SUSY-GUT), which predicts a large branching ratio of the LFV processes. They are only one or two orders of magnitudes smaller than the present experimental limits. Therefore, if the predictions are correct, there will be a chance of a big discovery. A list of the current searches for LFV decays at a low energy are $\mu^+ \to e^+ \gamma$, $\mu^- - e^-$ conversion in nuclei, muonium-anti-muonium conversion, and so on.

4.1 $\mu^- N \to e^- N$

The neutrinoless conversion of $\mu^- + (Z, A) \to e^- + (Z, A)$ is an important LFV process. The event signature is a single mono-energetic electron with an energy of $(m_\mu - B)$ MeV, where B is an atomic binding energy of the muon. The backgrounds are (1) muon decay in orbit, (2) radiative muon capture with asymmetric γ conversion, (3) comic rays, and (4) pions in the beam. Currently, BNL-AGS E940 (MECO) [3], which aim at a sensitivity of 10^{-16}, is being prepared. At the 50-GeV PS, an experimental proposal to search for $\mu^- - e^-$ conversion at a sensitivity of less than 10^{-18} is being considered. The proposal is based on a new muon source with higher intensity , narrower beam energy spread, and higher purity (no pion contamination in a muon beam). Such an advanced muon beam is being designed by the PRISM working group. The details on the beam will be presented in the next subsection. A new experiment requires a pulsed beam with high beam extinction between the beam pulses. The proton beam from the 50-GeV PS is more suitable to manipulate a proton beam structure than that from the 3-GeV PS.

4.2 PRISM

In order to carry out experiments with muons in extraordinarily high sensitivity, a new highly intense muon source is required. We are promoting a project to construct such a high intensity muon beam beam called **PRISM** at the 50-GeV PS. PRISM stands for a "Phase Rotated Intense Slow Muon source". It consists of a large solid angle pion capture, phase rotation section which accelerates slow muons and decelerate fast muons by RF to make the muon-beam energy spread smaller. To achieve phase rotation, instead

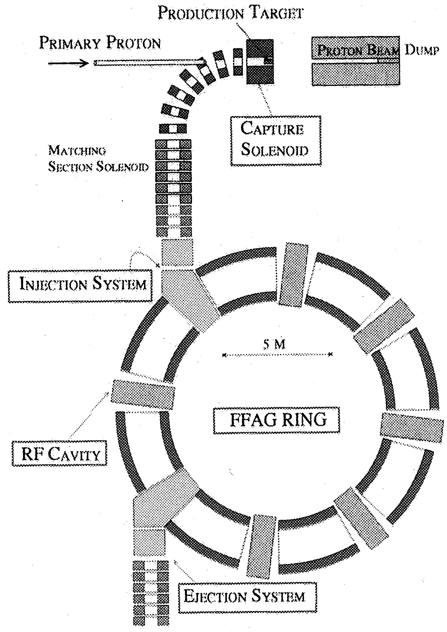

Figure 1: Schematic layout of PRISM

of a linear system, a circular system based on fixed field alternating gradient synchrotron (FFAG) has been adopted. The advantage of FFAG for PRISM is that it has a large momentum acceptance, and a large transverse geometrical acceptance. The layout of PRISM is shown in Fig.1.

The expected muon beam intensity is about 10^{11} – $10^{12}\mu^{\pm}$ /sec, which is four orders of magnitude larger than the presently available at Paul Sherrer Institute (PSI). A high intensity would be achieved by either high-field solenoid capture or a conducting target with high current drawn. The mean muon energy is 20 MeV in kinetic energy (which corresponds to 68 MeV/c in momentum). The beam energy spread of a few % after phase rotation is expected.

4.3 $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$

$\mu^+ \to e^+\gamma$ decay is another important LFV process. Its event signature is a e^+ and a photon of 52.8 MeV ($= m_\mu c^2/2$), which are collinear back-to-back one another in time coincidence. The two main backgrounds are (1) a physics background from radiative muon decay $\mu^+ \to e^+\nu\overline{\nu}\gamma$ in which neutrinos carry small energy off, and (2) an accidental coincidence of the normal muon decay $\mu^+ \to e^+\nu\overline{\nu}$ and a high-energy photon in the $\mu^+ \to e^+\nu\overline{\nu}\gamma$. The current limit of $\mu^+ \to e^+\gamma$ decay is 1.2×10^{-11} by the MEGA collaboration at LANL.

What will be future improvements ? First of all, the coincidence experiment like this is usually limited by the instantaneous beam intensity. Therefore, a continues beam with 100 % duty factor is necessary. There is an idea to suppress the backgrounds by using polarized muons [4]. For $\mu^+ \to e^+e^-e^+$ decay, search for T-odd correlation is very important, which attracts interests in terms of the leptogenesis.

5 PARTICLE PHYSICS: NEUTRINO

The JHF-Kamioka neutrino project [5] is a second generation long base line neutrino oscillation experiment, after the current K2K experiment (which is from KEK, Tsukuba to Kamioka) that probes the neutrino masses and mixing in high precision. A high intensity narrow band neutrino beam is produced by secondary pions created by the 50-GeV PS. The neutrino energy is tuned to the oscillation maximum at about 1 GeV for a baseline length of 295 km toward the world largest water Cerenkov detector (50 kton), Super-Kamiokande, as shown in Fig.2. Its excellent energy resolution and particle identification enable the reconstruction of the initial neutrino energy, which is compared with the narrow band neutrino energy, through the quasi-elastic interaction.

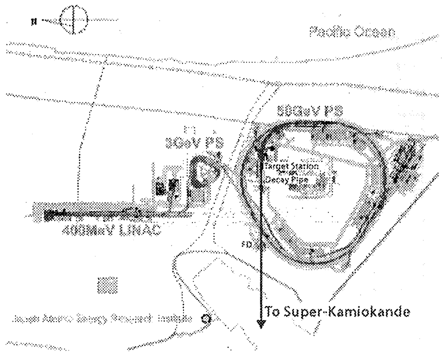

Figure 2: Neutrino beam line from the 50-GeV PS to Super-Kamiokande.

The physics goal of the first phase is an order of magnitude better precision in the ν_μ to ν_τ oscillation measurement ($\delta(\Delta m^2_{23}) = 10^{-4}eV^2$ and $\delta(\sin^{22}\theta_{23}) = 0.01$), a factor of 20 more sensitive search in the ν_μ to ν_e appearance ($\sin^{22}\theta_{\mu e} \sim 0.5\sin^{22}\theta_{13} > 0.003$), and a confirmation of the ν_μ to ν_τ oscillation or discovery of sterile neutrinos by detecting the neutral current events. In the second phase, an upgrade of the accelerator from 0.75 MW to 4 MW in beam power and the construction of 1 Mt Hyper-Kamiokande detector at Kamioka site are envisaged. Another order of magnitude improvement in the ν_μ to ν_e oscillation sensitivity, a sensitive search of CP violation in the lepton sector (CP phase "δ_{CP}" down to 10-20 degrees), and an order of magnitude improvement in the proton decay sensitivity is also expected.

6 OVERVIEW OF NUCLEAR PHYSICS PROGRAMS AT 50-GEV PS

Among many frontier topics in nuclear physics in the next century, the one which might be important at the 50-GeV PS is to study the deep inside in a nucleus. It could be

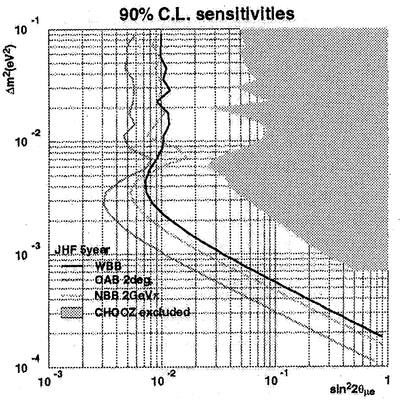

Figure 3: 90 % C.L. sensitivity contours for 5 years exposure of WBB (wide band beam), OAB (off-angle beam) and NBB (narrow band beam) configurations. The 90 % C.L. excluded region of CHOOZ is plotted as a comparison. for CHOOZ contour, maximum mixing of $\sin^2\theta_{23} = 0.5$ is assumed to convert from $\sin^2 2\theta_{13}$ to $\sin^2 2\theta_{\mu e}$.

phrased symbolically as "from surface to matter"[1] or "nuclear matter physics". To be more concrete, some basic questions relevant to it is whether a nuclear shell model is still viable in the deep inside nucleus, or whether a nucleon inside the nucleus keep its free-particle identity in the interior of nuclear matter. As for the former, the nuclear shell model has been successful but we do not understand whether it is still viable deeply inside the nucleus. For the latter, it is known that the nucleon radius is about 0.8 fm, which is only a half of the average inter nuclear distance. The tail of nuclear density distribution is overlapped to adjacent nucleons.

In order to study the nuclear matter physics, there are various ways to approach. One is to use lepton beams such as electrons or muons shooting nuclei to see the interior of the nuclei. The other way is to implant impurity hadrons inside the nucleus. The latter is relevant to the 50-GeV PS.

7 HYPERNUCLEAR SPECTROSCOPY

Hypernuclei physics is one of those topics with impurities, where a hyperon such as Λ, Σ, even two Λ's, are implanted in an ordinary nucleus. With particular kinematics arrangement, it could be done to have a hyperon occupying levels close to the ground state. Thus, it could serve as the probe of the interior of the nucleus. In Japan we have strong groups of the hypernuclei physics. As a matter of facts, at the present 12-GeV Proton Synchrotron (PS), a high resolution superconducting spectrometer called SKS is constructed, and collecting interesting data for various hypernuclei. It gives about a 2 MeV momentum resolution in sigma. For further hypernuclear spectroscopy with high resolution, some groups are considering to have γ spectroscopy.

More exotic in the hypernuclear spectroscopy is a study of the strangeness (S) = -2 hypernuclei. The S=-2 hypernuclei can be created by (K^-, K^+) reactions where either Ξ^- and $\Lambda\Lambda$ are produced in nucleus. It is speculated that Ξ would form a sharp and deeply bound hypernuclear state.

To study the behavior of a hyperon inside the nuclear matter, understanding of the hyperon-nucleon (YN) interaction is essential. In general, the YN interaction can be regarded, together with the NN interaction, as one of the flavor SU(3) baryon-baryon interaction, although this SU(3) flavor symmetry is broken. The study of YN (or even YY) interaction would give genuine information on the dynamics of fundamental baryon-baryon interaction. Unfortunately there have been no sufficient data existing for the YN interaction, and therefore data of high-quality and high-statistics comparable to the NN scattering data are needed. At the 50-GeV PS, a proposal to measure hyperon-nucleon scattering is presented, where the data quality of YN scattering might be approaching the nucleon-nucleon (NN) scattering data.

8 VECTOR MESONS IN NUCLEI

Among method of studying the interior of the nucleus is to implant vector mesons, such as ω, ϕ, and J/ψ, inside the nucleus. It has been speculated that there might be a nuclear matter effect called "partial restoration of chiral symmetry". It implies that the vector-meson mass could be modified in nuclear matter. The theoretical prediction of the mass change as a function of temperature and density of nuclear matter has been studied. To measure the mass of vector mesons in nuclear matter, the most powerful method is dilepton spectroscopy, since dileptons are immune to final-state interactions in nuclei. Meson beams are efficient to create vector mesons in normal nuclear matter. For producing a J/ψ inside a nucleus, an antiproton beam might be useful. If heavy-ion beams are available at a later stage, the study can be extended into a high-density matter regime.

9 HADRON SPECTROSCOPY

Hadron spectroscopy is quite important to study the strong-coupling scheme in QCD. One of the goals is to identity exotic hadron states with gluonic degrees of freedom. In particular, the search for glueballs attracts much interest, because lattice QCD predicts a light scalar glueball (0^{++}) in the mass region from 1.5 to 1.8 GeV/c^2 with a width of about 100 MeV. The mass of the tensor glueball is predicted to be well above 2.0 GeV/c^2. A 4π detector with multi-track capability and good particle ID will enable much better identification of normal and exotic mesons than existing experiments. Also the K flux available at the 50-GeV PS will allow two orders of magnitude improvement over the best previous experiments. The anti-proton beam will enable very important studies of charmed states including the search for charmed hybrids, which are expected to be narrow states.

10 LONG TERM FUTURE EXTENSION : POSSIBILITY OF NEUTRINO FACTORY

Recently, a high intensity proton machine of 1-4 MW beam power has been attracting much interest from many accelerator physicists and experimental particle physicists in world-wide because of future possibility of a neutrino factory and a $\mu^+\mu^-$ collider. At the 50-GeV PS with about a MW beam power, it is natural to consider such a possibility as future extension.

The neutrino factory is based on muon decay ($\mu^\pm \to e^\pm \nu\overline{\nu}$), instead of pion decay ($\pi^\pm \to \mu^\pm \nu$). The muons are accelerated to 20-50 GeV and are stored in a storage ring of a race-track shape. The neutrino and anti-neutrinos from muon decays in the straight section of the muon storage ring can be used as a high intensity source of neutrino beams. The physics program at a neutrino factory is (1) studies of neutrino oscillation physics (including the determination of Maki-Nakagawa-Sakata (MNS) neutrino mixing matrix elements, and a search for CP violation in the neutrino sector), (2) studies of non-oscillating neutrino physics. The latter includes neutrino-nucleus deep inelastic scattering (DIS) experiments, and neutrino-nuclear physics as well.

The Japanese Neutrino Factory (NufactJ) working group has been formed to study the case [6]. Whereas the US and CERN studies of a neutrino factory are based on muon ionization cooling and recirculating linac, the Japanese scheme of a neutrino factory is based on a series of FFAG acceleration. The advantage of the FFAG-based scheme is that it does not require muon ionization cooling. The neutrino intensity The schematic view of a neutrino factory is shown in Fig.4. The expected neutrino beam intensity is about 10^{20} muon decays/straight section/year. It is about 100 times larger the presently available at the same neutrino energy.

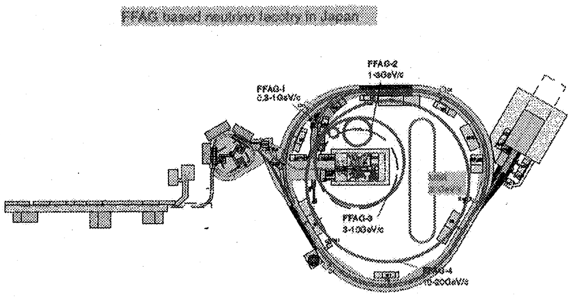

Figure 4: Possible layout of Neutrino Factory at the Tokai campus.

11 CONCLUSION

A shopping list of the potential physics programs has been presented. They are only examples. It would be desirable to have new ideas and proposals from potential users in the worldwide. This entire facility should be open to the international community.

12 REFERENCES

[1] The Joint Project Team of JAERI and KEK, The Joint Project for High-Intensity Proton Accelerators, KEK-report 99-4, JAERI-Tech 99-056, JHF-99-3, july 1999, unpublished.

[2] Y. Kuno and Y. Okada, Reviews of Modern Physics, **73** (2001) 151–202.

[3] W. Molzon et al., BNL-AGS proposal E940, 1996, unpublished.

[4] Y. Kuno and Y. Okada, Phys. Rev. Lett. **77** (1996) 434.

[5] Y. Itow, *et al.*, The JHF-Kamioka Neutrino Project, hep-ex/0106019.

[6] The NufactJ study report (version one) is available at http://www-prism.kek.jp/ nufactj/.