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Proposal
to study helium-induced hadron production for the atmospheric-neutrino flux
(Addendum to the HARP proposal)

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1 Introduction

The HARP experiment at the CERN PS is performing a programme of measurements of secondary hadron production, over the full solid angle, produced on thin and thick nuclear targets by beams of protons and pions with momenta in the range 2 – 15 GeV/c.

The first aim of this experiment is to acquire adequate knowledge of pion yields for an optimal design of the proton driver of the Neutrino Factory. The second aim is to reduce substantially the existing $\sim 30\%$ uncertainty in the calculation of absolute atmospheric-neutrino fluxes and the $\sim 7\%$ uncertainty in the ratio of neutrino flavours, desired for a refined interpretation of the evidence for neutrino oscillation from the study of atmospheric neutrinos in present and forthcoming experiments.

The HARP experiment is a large-acceptance charged-particle magnetic spectrometer of conventional design, located in the East Hall of the CERN PS and using the T9 tagged charged-particle beam. The main detector is a cylindrical TPC inside a solenoid magnet which surrounds the target. Downstream, the TPC is complemented by a forward spectrometer with a dipole magnet. The TPC and the forward spectrometer together ensure nearly full 4π coverage for momentum measurement. The identification of charged secondary particles is achieved by $\mathrm{d}E/\mathrm{d}x$ in the TPC, by time-of-flight, by a threshold Cherenkov detector, and by an electromagnetic calorimeter.

The intention was noted already in the original HARP proposal [1] to complement the measurements with protons and pions by measurements with deuterium and helium nuclei. However, later investigations on the feasibility of such beams led to the conclusion that only a helium beam could be relatively easily provided, as the present transfer line from the PS linac to the PS booster does not easily allow spill-by-spill switching between protons and deuterons.

This Addendum to the HARP proposal is motivated by the need to remove yet another element of uncertainty in the calculation of the atmospheric-neutrino flux: since a sizeable fraction of the charged-particle cosmic-ray flux consists of helium nuclei, the calculations demand a good knowledge of hadron production not only in proton–nitrogen and proton–oxygen interactions, but also in helium–nitrogen and helium–oxygen interactions.

The helium beam is also motivated by the expectation that the π^+ and π^- production on heavy nuclei is more symmetric for helium than for proton projectiles. This could be an important consideration for the Neutrino Factory, which for the detection of matter effects and of leptonic CP violation relies on quantitative comparisons between neutrino and antineutrino reactions, and hence demands comparable event rates from neutrino and antineutrino beams. In practice, this might mean the operation of the Neutrino Factory's driver with deuterium rather than with hydrogen, with a view to enhancing π^- production.

The CERN PS will be able, from the second PS subperiod in 2002 onwards, to deliver He^{++} ions in the T9 beam line. The HARP cryogenic nitrogen and oxygen targets and the HARP spectrometer would be re-used without modification.

The cost of the proposed experiment comprises the construction expenditure for a 'stripper' (to reduce He^{+} to He^{++}) for the PS beam, and the exploitation costs for maintaining and operating the HARP spectrometer during the second PS subperiod in 2002.

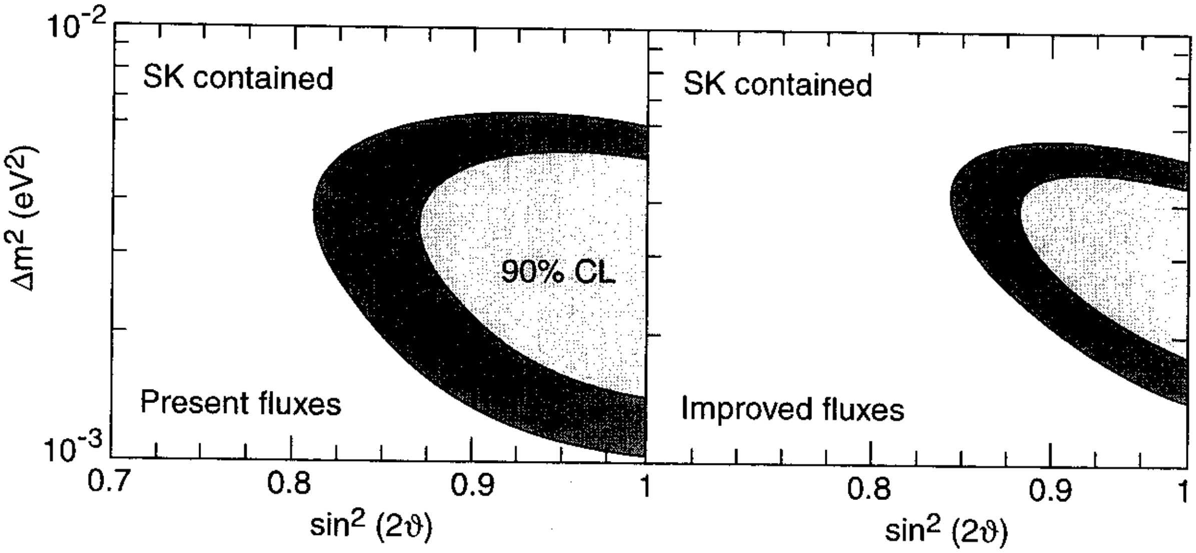

Figure 1: SuperKamiokande neutrino-oscillation results with current and improved atmospheric-neutrino-flux error (see text).

2 The physics case

The relevance of the atmospheric-neutrino flux is no longer questioned since the SuperKamiokande Collaboration [2, 3, 4] has almost certainly observed the oscillation of atmospheric ν_μ, presumably into ν_τ. This observation has strongly boosted interest in the prediction of the atmospheric-neutrino fluxes.

2.1 Why is a precise atmospheric-neutrino flux of interest?

The SuperKamiokande results are obtained with a $\sim 30\%$ uncertainty in the calculation of absolute atmospheric-neutrino fluxes and a $\sim 7\%$ uncertainty in the ratio of ν_e and ν_μ flavours. While SuperKamiokande's observation of a zenith-angle-dependent deficit of ν_μ is largely independent of the precision of the atmospheric-neutrino flux, a more detailed interpretation of the SuperKamiokande data, a more precise determination of oscillation parameters, and the comparison with measurements at other detector locations and with different detection techniques would profit from a more reliable calculation of fluxes of atmospheric neutrinos. (In this context, it is of interest to note that at present the absolute rate of atmospheric electron-neutrino events is poorly understood.)

With a view to assessing quantitatively the impact of reduced uncertainties of the atmospheric neutrino flux, a re-analysis of SuperKamiokande data has been performed for a hypothetical situation where the absolute fluxes are known with an uncertainty of 5%, and the ratio of neutrino flavours with an uncertainty of 1%. The results are shown in Fig. 1. The improvement in the oscillation parameters resulting from the higher precision of the neutrino flux is equivalent to an increase of the running time by a factor of four (i.e. 4800 days instead of 1200 days). It is important to note that this estimate is made for the specific experimental conditions of the SuperKamiokande experiment, whose systematic error is dominated by additional uncertainties in reconstructing the incoming neutrino energy and direction. Therefore, a significant reduction of the uncertainties of the atmospheric-neutrino flux is even more important for the high-precision, high-statistics data expected from future experiments. In these, absolute flux normalizations for ν_μ and ν_e, and for neutrinos and antineutrinos, should be available and used, in contrast to today's analyses where the absolute normalization is essentially treated as a free parameter, with ν_μ and ν_e fluxes strongly correlated.

There are good prospects that the study of oscillations of atmospheric neutrinos will remain an important topic. An outstanding issue is the prospect of determining the neutrino mass hierarchy by measuring the sign of Δm^2_{23} in atmospheric-neutrino oscillations [5] through the MSW-effect [6], which is out of reach of accelerator experiments until the advent of the Neutrino Factory. The Neutrino Factory itself needs large-mass detectors at distances of about 700 and 3000 km, which at the same time will serve as long-baseline and atmospheric-neutrino detectors. To exploit this forthcoming physics potential fully, precise calculations of the atmospheric-neutrino flux will be imperative.

2.2 What cosmic-ray energy range is of interest?

Atmospheric neutrinos originate from the decay of π and K mesons and muons which are generated in the showers initiated by the interaction of primary cosmic-ray particles with nitrogen and oxygen nuclei of the Earth's atmosphere.

For lower-energy neutrino events such as the 'sub-GeV' sample of SuperKamiokande, which is the energy region with the highest event statistics, the parent cosmic-ray primaries have energies in the range 5 – 100 GeV, as shown in Fig. 2 taken from Ref. [7].

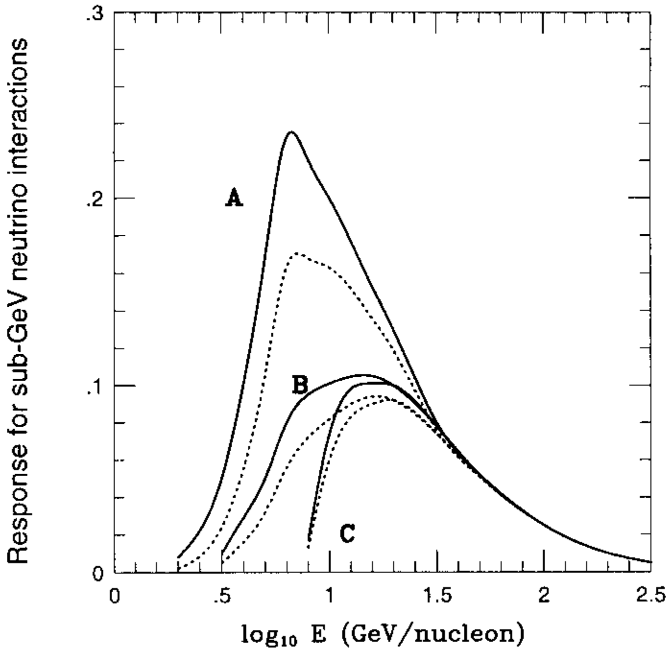

Figure 2: Response curves for 'sub-GeV' neutrino events in SuperKamiokande versus the energy of cosmic-ray primaries: no geomagnetic cut-off (A); events from below (B); events from above (C). Each pair of curves gives the range of solar activity between minimum (solid) and maximum (dotted).

2.3 What affects the prediction of atmospheric-neutrino events?

Several one-dimensional calculations of the flux of atmospheric neutrinos have been published [8, 9, 10, 11]. In recent years, more sophisticated three-dimensional calculations have become available [12, 13]. However, it has been claimed by Battistoni *et al.* [12] that for practical purposes the one-dimensional calculations give adequate results. Honda *et al.* [14] largely agree with this conclusion. Therefore, it makes sense to include both one- and three-dimensional calculations in the comparison of the results of different calculations.

The various calculations quote large errors and differ significantly in their results. These differences have been extensively analysed [15, 16, 17]. The dominant sources of discrepancies were traced back to

- the assumed energy spectrum and the chemical composition of the primary cosmic rays;
- the representation of pion production in collisions of the primaries with nitrogen and oxygen nuclei;
- the neutrino–nucleon cross-section, which has a surprisingly large uncertainty of $\sim 15\%$ at low energy.

2.4 What is known about the primary cosmic-ray flux?

Until ten years ago, there were sizeable (up to 50%) differences between measurements of the primary charged-particle cosmic-ray flux; however, thanks to several new measurements [18, 19, 20, 21] there is a strong tendency towards convergence, and hopes are that with a new round of long-duration balloon flights, with the PAMELA satellite mission and with the AMS spectrometer on the International Space Station this uncertainty will be further reduced and will become negligible within a few years [22].

Today, the uncertainty of the cosmic-ray proton flux in the important range 5 – 30 GeV (relevant for neutrino energies around 1 GeV) is already less than 10%, while the uncertainty of the helium flux is higher. For the cosmic-ray flux leading to neutrino energies of 100 GeV and beyond, the uncertainty is still higher as the experimental data on the relevant cosmic-ray flux are scarce and uncertain.

Expectations are that all these errors will be considerably reduced in the next few years, as there is increasing awareness in the cosmic-ray community of the importance of these measurements.

The current knowledge on the primary cosmic-ray composition is shown in Fig. 3 compiled by T. Stanev [23]. At the kinetic energy of 10 GeV, protons contribute 75% of all nucleons in the primary cosmic-ray flux, and helium contributes 16%.

2.5 Hadron production in the atmosphere

The above considerations leave the modelling of π and K production by the primary cosmic-ray particles on light nuclei as the only remaining major obstacle to a precise calculation of the atmospheric-neutrino fluxes.

A further source of uncertainty is the common practice in calculations of treating all nucleons of the primary cosmic-ray flux, whether free or bound in nuclei, in the free-nucleon approxima-

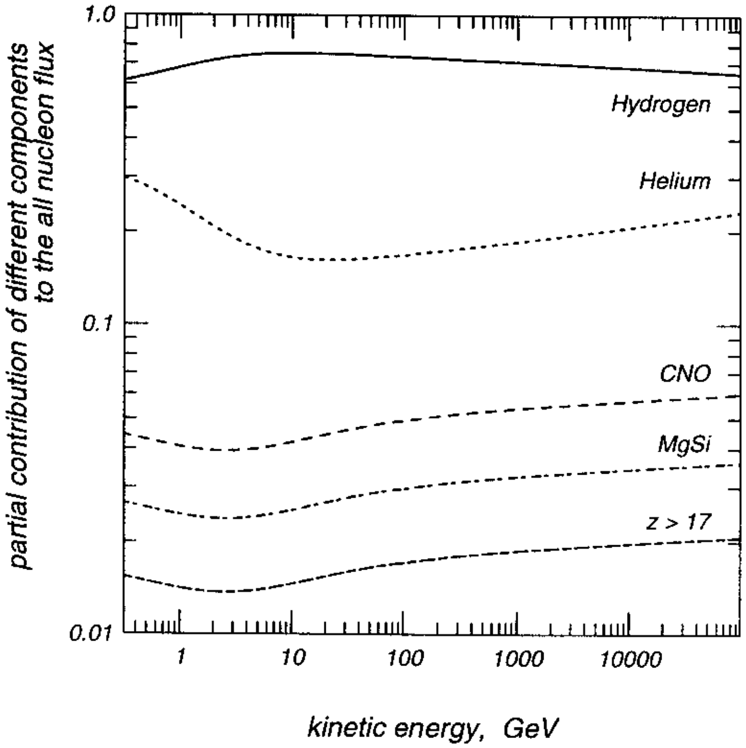

Figure 3: Relative contributions of protons and nuclei to the all-nucleon flux.

tion [24], and of assuming that isospin symmetry between neutrons and protons holds (apart from Λ and K production which is treated differently). To give an estimate of the possible reduction in the error of the atmospheric-neutrino flux: if the free-nucleon approximation and isospin symmetry together are wrong by 30%, the resulting error of the atmospheric-neutrino flux is 5%, which can be eliminated by precise hadron-production measurements in helium–nitrogen and helium–oxygen interactions.

The HARP experiment is designed, *inter alia*, to remove hadron production in proton–nitrogen and proton–oxygen interactions as the dominant uncertainty of the atmospheric-neutrino fluxes. In the proposed additional run of HARP with a helium beam, the proton–nucleus data would be complemented by helium–nucleus data.

2.6 Proton–helium interactions

The proposed experiment also permits the investigation of proton–helium interactions which are of interest for the understanding of the composition of the primary cosmic-ray flux, and for the understanding of the production of antiprotons in the Earth's atmosphere. Time permitting, for a small fraction of the running time the HARP cryogenic targetry would be filled with hydrogen.

The investigation of the secondaries from p + ^{4}He interactions would give insight in

- the flux of the secondary light nuclei D and ^{3}He which are believed to arise from the fragmentation of ^{4}He nuclei on interstellar hydrogen; accurate measurements in the energy range accessible to the HARP experiment would remove the large uncertainties on nuclear cross sections and make possible the study of D/^{4}He and ^{3}He/^{4}He ratios of the primary cosmic-ray flux, and thus help understanding the galactic propagation of cosmic rays;

- the flux of secondary antiprotons which are believed to arise primarily from $p + p \rightarrow \bar{p} + X$ and $p + {}^4\mathrm{He} \rightarrow \bar{p} + X$ interactions in the Earth's atmosphere; this would permit a better evaluation of the antiproton background relevant for balloon and satellite experiments, and for the AMS spectrometer on the International Space Station, in their search for the exotic production of antiprotons arising from, for example, primordial black holes or supersymmetric particles; presently, the uncertainty on the antiproton production cross sections constitutes the limiting factor in the search for new (astro)physics [25].

2.7 Neutrino–nucleon cross-section

Concerning the neutrino–nucleon cross-sections in the 1 GeV range, it is expected that the K2K experiment at KEK will reduce the current uncertainty of 15% to approximately 5%. In the longer run, measurements in so-called 'near' detectors at the Neutrino Factory will eliminate this source of error.

2.8 Isoscalar beam for the Neutrino Factory

The use of isoscalar beams has been advocated for the Neutrino Factory as a means to enhance the production of negative pions. In the low-energy region, which is relevant for the CERN project of a 2.2 GeV Superconducting Proton Linac (SPL), negative pions are preferentially produced in neutron–neutron production in the same way as positive ones are preferred in proton–proton collisions. Existing computer codes predict a deficit of the order of 30% of negative pions when running a proton beam on a heavy-metal target such as mercury or lead. The deficit becomes worse for lighter, less neutron-rich targets such as carbon.

The lower production of negative pions is a disadvantage, both at the Neutrino Factory and for a low-energy conventional neutrino beam. For studies of matter effects or of CP violation, the oscillations of neutrinos are compared with those of antineutrinos. The antineutrinos, which are produced by the decay of negative pions, are further disfavoured by their lower ($\sim 1/3$) cross-section on isoscalar targets of which all massive neutrino detectors are made. As a result, the running time is dominated by the antineutrino exposure. The increase of the ratio of negative to positive pion production that one can expect from isoscalar beams would immediately have a positive effect equivalent to an increase of total intensity which is estimated to be around 40%.

There are large uncertainties on these numbers. A direct and precise measurement with a helium beam permits a sound exploration of this possibility.

3 Implications for the CERN PS

A possible and relatively simple scheme of running with a helium beam has been proposed by R. Cappi *et al.*, which builds on the advantage that He^+ ions have nearly the same charge/nucleon-mass ratio Z/A as Pb^{+53} (~ 0.25) which is the standard for heavy ion running at CERN.

The use of Linac2 is not considered as it would need a new RFQ. Instead, the use of Linac3 is envisaged. D^+ or He^{++} ions cannot pass the transfer line from Linac3 to the PS Booster because of incompatibility with proton acceleration in other PS cycles. He^+ ions are compatible, though.

Therefore, first He^+ ions are produced, accelerated in Linac3 and then in the PS Booster, all with settings similar to those for Pb^{+53}.

Since He^+ ions can be accelerated in the PS but not slowly ejected, in contrast to He^{++} ions, the He^+ ions are stripped to He^{++} just before injection into the PS, accelerated there and slowly extracted into the external beam line. This can be done in one PS cycle while other PS cycles within the super-cycle would operate with protons.

The slow extraction would have to be done at non-standard momenta, compared with normal PS operation, for physics reasons and because of the limitation of the T9 beam line to 15 GeV/c. As a default, all magnet settings would be scaled down, but optimization work is still deemed necessary. This will need time and the result may not be perfect (i.e. non-flat intensity over time). The PS experts estimate that two weeks will be needed to set up the acceleration and extraction system.

The momenta are limited. The T9 beam supports a maximum of 7.5 GeV/c (= 15/2) per nucleon. Momenta around the 'transition point' (about 5 – 6 GeV/c per nucleon) are to be avoided. This leaves about 2 and 4 GeV/c per nucleon, and 6.5 and 7.5 GeV/c per nucleon as likely choices.

During running with a helium beam, HARP would be the sole user of the East Hall, as the slow extraction of helium prohibits the *slow* extraction of protons at a different momentum within the same super-cycle. However, the *fast* extraction of protons into TT2 in other PS cycles, at different momentum, is compatible with helium running.

Removing the primary target and running the helium beam down to the HARP spectrometer is not considered a major problem by the PS beam experts.

This proposed scheme would need no major hardware modifications except a 'stripper' set-up which would be inserted into the beam during the 'ion' cycle within the PS super-cycle. The stripper mechanism needs to be designed and constructed.

4 The HARP spectrometer

The HARP spectrometer is shown in Fig. 4. At the time of submission of this proposal, the T9 beam and the spectrometer are in the final stages of commissioning. Figure 5 shows a recent photograph of the HARP spectrometer.

For running with a helium beam, the HARP cryogenic targetry, filled with liquid nitrogen, oxygen and hydrogen, would be used. The HARP spectrometer would be used for the proposed extension of the programme without modification or addition.

5 Resources

5.1 Financial expenditure

Apart from a stripper, which inserts a metal foil into the PS beam in order to reduce He^+ to He^{++}, no construction work is necessary, neither in the PS nor in the HARP spectrometer.

The cost of the stripper has been estimated by the PS experts to be 70 kCHF.

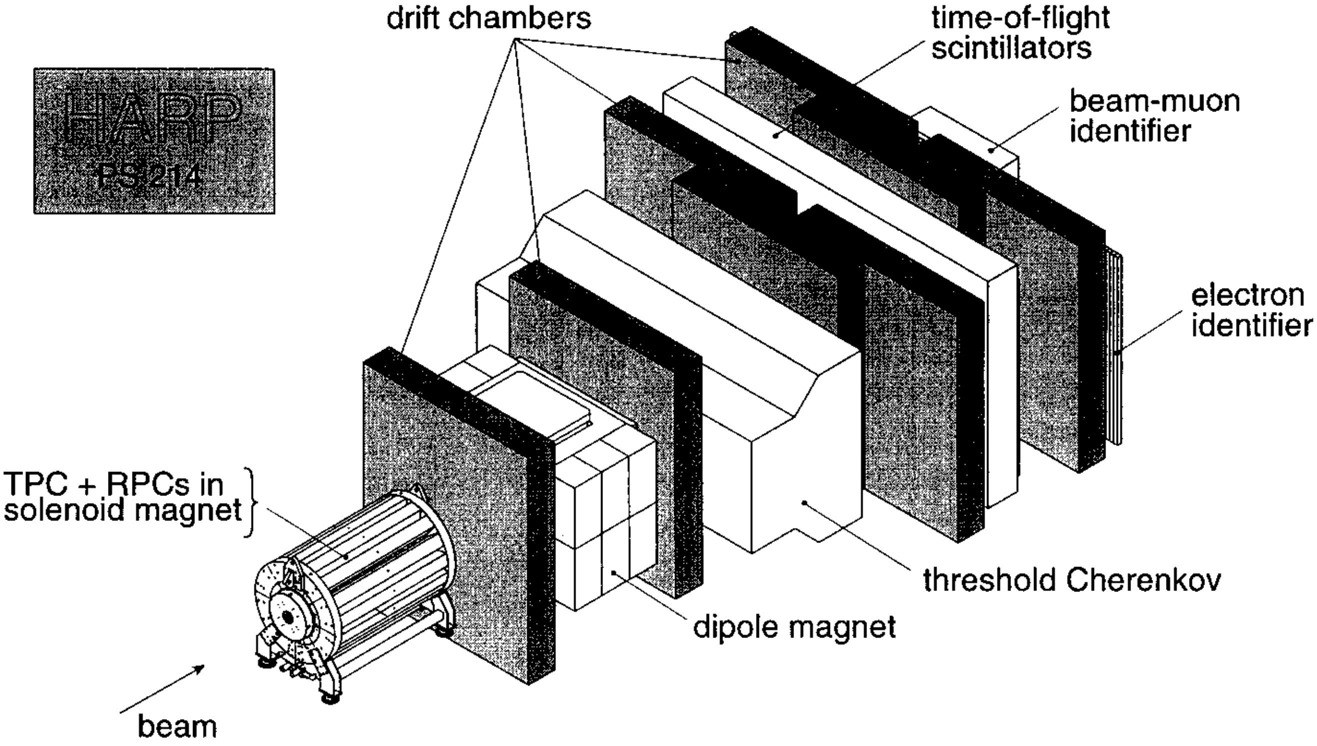

Figure 4: Layout of the HARP experiment

Figure 5: Photograph of the HARP experiment

Table 1: Exploitation expenditure

	Cost (kCHF)
Gases	25
Electronics rental fee for six months (EP Pool)	90
Data recording media	30
Maintenance and repairs	20
Total	165

The main expenditure of the experiment is given by the exploitation expenses, which are estimated to add up to 165 kCHF (see Table 1).

5.2 Manpower needs

The design of the ion stripper will require 2 – 3 man-months of work. The tuning of the ion beam will be done by the relevant PS experts, and the estimated need is two man-months.

For the HARP Collaboration, the programme amounts to a minor extension of the experiment's running time, which can be handled with the Collaboration's existing manpower resources.

6 Schedule

The experts from CERN's PS Division insist on date slightly after the 2001/02 winter shutdown, with a view to avoiding interference between the start-up work and the additional tuning needed for the transport of helium nuclei through the PS and its injector system. Their choice is the second PS subperiod in May – June 2002.

The dominant running time will de devoted to helium–nitrogen interactions. Minor running time will be devoted to helium–oxygen and, time permitting, to helium–hydrogen interactions.

Assuming that the second PS subperiod in 2002 will be allocated to data-taking with a helium beam, HARP will be interested in proton data-taking in the first PS subperiod in 2001.

After the completion of helium data-taking, the HARP Collaboration plans to dismount the experiment.

7 Summary

The study of helium-induced hadron production with the HARP spectrometer is proposed, in the T9 beam line of CERN's East Hall, with momenta from 2 up to 7.5 GeV/c per nucleon. The experiment is proposed to be carried out in the second PS subperiod in 2001.

The HARP experiment is in a unique position to make an important contribution to a precise atmospheric-neutrino flux. Also, the proposed measurements may well prove useful for the design of the driver of the Neutrino Factory. The measurements can be carried out with a minimum of expenditure since essentially only continued operation of the existing HARP spectrometer is requested.

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