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Status of NEPTUN-A[*]

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I will report on the experiment NEPTUN-A[1], which will be done in the SS-3 area along with the NEPTUN experiment[2]. NEPTUN-A aims to measure the analyzing power, A, in large-$P_\perp^2$ proton-proton elastic scattering first at 400 GeV and then later at 3 TeV. Spin measurements at large transverse momentum provide information about the inner-structure of the proton by studying small impact parameter, which is the distance of closest approach of the two protons and is canonically conjugate to $P_\perp$. The list of NEPTUN-A participants is shown in Fig. 1; there are about 20 Russians and 20 Americans.

O.V. Buyanov, V.V. Churakov, O.A. Grachov, V.N. Grishin, V.A. Kachanov, Yu.V. Kharlov, V.Yu. Khodyrev, Yu.M. Melnik, A.P. Meschanin, N.G. Minaev, V.V. Mochalov, S.B. Nurushev, D.I. Patalakha, A.F. Prudkoglyad, V.V. Rykalin, P.A. Semenov, V.L. Solovianov, M.N. Ukhanov, A.N. Vasiliev, A.E. Yakutin; IHEP (Protvino).

V.V. Fimushkin, Yu.K. Pilipenko, V.V. Shutov; JINR (Dubna).

V.A. Anferov, B.B. Blinov, J.A. Bywater, S. Chin, C.M. Chu, D.G. Crabb[*], Ya.S. Derbenev, W.A. Kaufman, A.V. Koulsha, A.D. Krisch , A.M.T. Lin, V.G. Luppov[§], T.S. Nurushev, D.C. Peaslee, R.A. Phelps, J.S. Price, L.G. Ratner, R.S. Raymond, D.S. Shoumkin, J.A. Stewart, S.E. Sund, V.K. Wong; MICHIGAN (Ann Arbor).

G.R. Court[†], D. Kleppner; MIT (Cambridge).

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Fig. 1 NEPTUN-A Collaboration List.

Since we hope to study the inner-structure of the proton by measuring spin effects in large-$P_\perp^2$ proton-proton elastic scattering, I will define the spin-polarization:

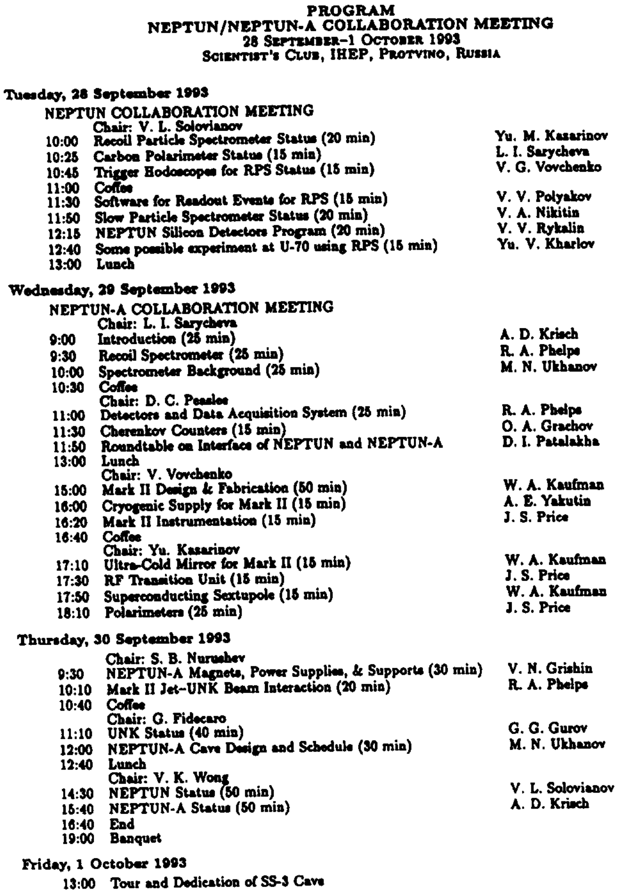
$$P = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}.$$

If the beam and target are both unpolarized, then one can only measure the spin-averaged differential elastic cross-section. If either the beam or the target is polarized then one can measure one-spin quantities, such as A, the analyzing power or left-right asymmetry. If both the beam and the target are polarized then one can measure the two-spin A_{nn}, the spin-spin correlation parameter. Recall that A is related to the spin orbit force and A_{nn} is related to the spin-spin force.

The last Collaboration Meeting of NEPTUN and NEPTUN-A was held in Protvino in late September 1993. Each year, we have one meeting in Protvino and one meeting in Ann

Arbor. As shown in Fig. 2, we had many detailed talks about the progress of the two experiments and a presentation by G. G. Gurov on the UNK Status. On October 1 there was a dedication of the SS-3 cave, in which Drs. Hess and O'Fallon of the U.S. Department of Energy participated. As Professor Myznikov said, we also had a football game in the cave following this dedication. The TONOT tunnelers' team defeated the NEPTUN/NEPTUN-A physicists' team by 5 to 1. Yesterday, we again visited the cave and pointed out that the TONOT team has 800 tunnelers to choose from, while NEPTUN and NEPTUN-A together have only about 100 physicists. We proposed a rematch during the 17-19 May 1994 Collaboration Meeting, with the physicists' team chosen from among all physicists in Protvino. Mr. Redko, the deputy chief of TONOT, modestly announced that his tunnelers could easily beat a team chosen from all the physicists in the world. Thus, we may need some help from other IHEP physicists.

Fig. 3 is a 1978 plot of our Argonne ZGS data.[3] This graph shows perhaps the first indication of a large spin effect at high energies. The differential elastic cross-section is plotted against the scaled $P_\perp^2$ variable for p-p elastic scattering near 12 GeV with the two spins either parallel or antiparallel; some much higher energy unpolarized CERN ISR data is shown for comparison. Note that the elastic scattering diffraction peak drops rapidly for many decades; then there is an interference dip followed by the large-$P_\perp^2$ hard-scattering component. This large-$P_\perp^2$ component is probably associated with the direct collisions between the proton's constituents which are usually called quarks.



PROGRAM
NEPTUN/NEPTUN-A COLLABORATION MEETING
28 SEPTEMBER–1 OCTOBER 1993
SCIENTIST'S CLUB, IHEP, PROTVINO, RUSSIA

Tuesday, 28 September 1993

NEPTUN COLLABORATION MEETING

	Chair: V. L. Solovianov	
10:00	**Recoil Particle Spectrometer Status (20 min)**	**Yu. M. Kasarinov**
10:25	**Carbon Polarimeter Status (15 min)**	**L. I. Sarycheva**
10:45	**Trigger Hodoscopes for RPS Status (15 min)**	**V. G. Vovchenko**
11:00	**Coffee**	
11:30	**Software for Readout Events for RPS (15 min)**	**V. V. Polyakov**
11:50	**Slow Particle Spectrometer Status (20 min)**	**V. A. Nikitin**
12:15	**NEPTUN Silicon Detectors Program (20 min)**	**V. V. Rykalin**
12:40	**Some possible experiment at U-70 using RPS (15 min)**	**Yu. V. Kharlov**
13:00	**Lunch**	

Wednesday, 29 September 1993

NEPTUN-A COLLABORATION MEETING

	Chair: L. I. Sarycheva	
9:00	**Introduction (25 min)**	**A. D. Krisch**
9:30	**Recoil Spectrometer (25 min)**	**R. A. Phelps**
10:00	**Spectrometer Background (25 min)**	**M. N. Ukhanov**
10:30	**Coffee**	
	Chair: D. C. Peaslee	
11:00	**Detectors and Data Acquisition System (25 min)**	**R. A. Phelps**
11:30	**Cherenkov Counters (15 min)**	**O. A. Grachov**
11:50	**Roundtable on Interface of NEPTUN and NEPTUN-A**	**D. I. Patalakha**
13:00	**Lunch**	
	Chair: V. Vovchenko	
15:00	**Mark II Design & Fabrication (50 min)**	**W. A. Kaufman**
16:00	**Cryogenic Supply for Mark II (15 min)**	**A. E. Yakutin**
16:20	**Mark II Instrumentation (15 min)**	**J. S. Price**
16:40	**Coffee**	
	Chair: Yu. Kasarinov	
17:10	**Ultra-Cold Mirror for Mark II (15 min)**	**W. A. Kaufman**
17:30	**RF Transition Unit (15 min)**	**J. S. Price**
17:50	**Superconducting Sextupole (15 min)**	**W. A. Kaufman**
18:10	**Polarimeters (25 min)**	**J. S. Price**

Thursday, 30 September 1993

	Chair: S. B. Nurushev	
9:30	**NEPTUN-A Magnets, Power Supplies, & Supports (30 min)**	**V. N. Grishin**
10:10	**Mark II Jet–UNK Beam Interaction (20 min)**	**R. A. Phelps**
10:40	**Coffee**	
	Chair: G. Fidecaro	
11:10	**UNK Status (40 min)**	**G. G. Gurov**
12:00	**NEPTUN-A Cave Design and Schedule (30 min)**	**M. N. Ukhanov**
12:40	**Lunch**	
	Chair: V. K. Wong	
14:30	**NEPTUN Status (50 min)**	**V. L. Solovianov**
15:40	**NEPTUN-A Status (50 min)**	**A. D. Krisch**
16:40	**End**	
19:00	**Banquet**	

Friday, 1 October 1993

13:00	**Tour and Dedication of SS-3 Cave**	

Fig. 2. Collaboration Meeting Program.

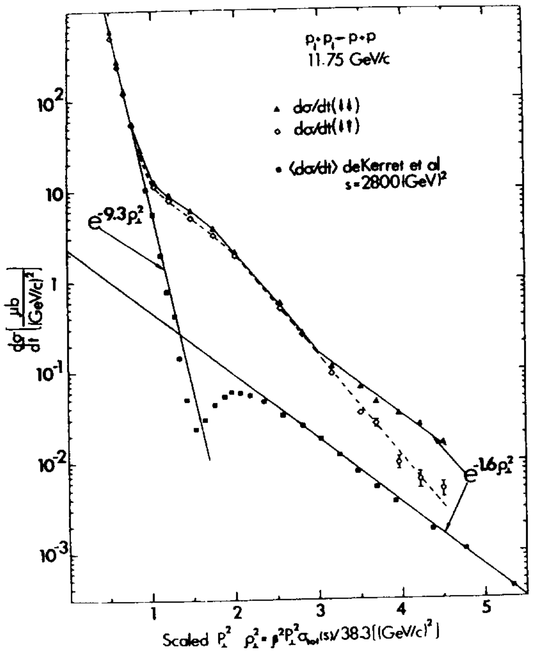


Fig. 3 Spin-spin effects in p-p elastic scattering.

In the diffraction peak of Fig. 3, we found that all three sets of data (the higher energy unpolarized data, the spin-parallel data, and the spin-antiparallel data) were exactly on top of each other. This showed that at small $P_{\perp}^2$, where the collisions are only glancing and not very violent, the protons do not much care what their energy is or what their spin state is; they just look at the outside of each other. Indeed by Fourier transforming the diffraction peak slope of $e^{-9.3P_{\perp}^2}$, one finds that the outer size of the proton is about 1 Fermi, just as Hofstadter found when he scattered electrons from protons.

However, there were surprising spin effects in the large-$P_{\perp}^2$ hard-scattering region, where the slope was 1.6 $(\mathrm{GeV}/c)^2$ at high energy. We saw the same slope of 1.6 $(\mathrm{GeV}/c)^2$ at the ZGS, but only when the spins were parallel. When the spins were antiparallel, the protons seemed to just pass through each other and have no violent head-on collisions; we found a factor of 4 cross-section difference at our maximum $P_{\perp}^2$. This was a very surprising result; to this day it has not really been explained. Perturbative Quantum Chromodynamics predicted that the maximum of the ratio $d\sigma/dt(\uparrow\uparrow) : d\sigma/dt(\uparrow\downarrow)$ was 2; instead we found 4.

Back in the late 1970's, during seminars about this unexpected result, two of our most distinguished colleagues, Professor Bethe and Professor Weisskopf, both made the same comment: at our fixed energy of about 12 GeV the spin effect only becomes large near 90°_{cm}. For two identical protons, one can have special particle identity effects which become important near 90°_{cm}. Therefore, perhaps this large spin effect is not a large-$P_{\perp}^2$ hard-scattering effect, but instead a 90°_{cm} particle identity effect. After some thought, we decided that we could not answer the concerns of these two distinguished physicists theoretically, but perhaps we could answer them experimentally. Therefore, we did a second experiment[4] where we held fixed the scattering angle at exactly 90°_{cm} and varied $P_{\perp}^2$ by varying the incident energy. Fig. 4 is a 3-dimensional plot from *Scientific American*[5]; the ratio of the spin-parallel to spin-antiparallel cross-sections are plotted against $P_{\perp}^2$ and the incident energy. The 12 GeV data from Fig. 3 is shown again; note that at small $P_{\perp}^2$ there are only small differences between the different spin states, but at large-$P_{\perp}^2$ the ratio increases to 4. The 90°_{cm} data shows clearly that the spin effects only become large at large-$P_{\perp}^2$. The small-$P_{\perp}^2$ points where the spin effects are small are just as much at 90°_{cm} as the large-$P_{\perp}^2$ points where the spin effects are large. Therefore, these large spin effects are due to hard scattering.

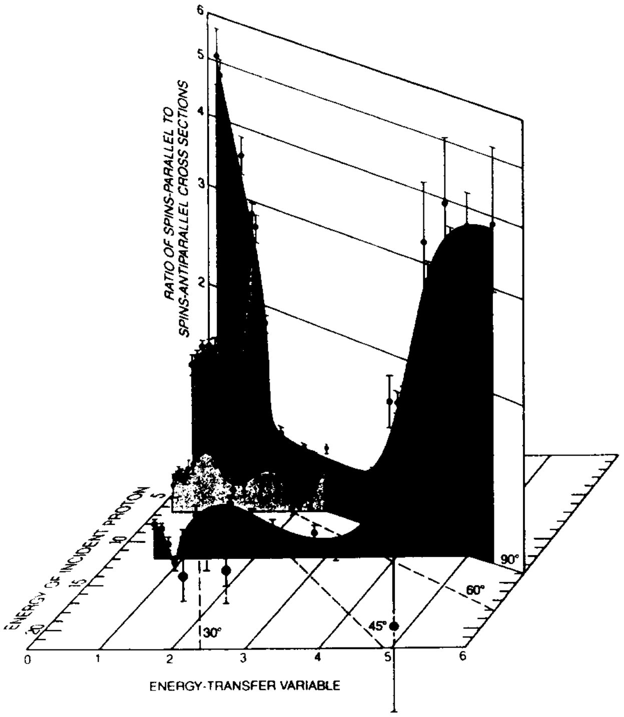


Fig. 4 Three-dimensional plot of p-p elastic scattering.

Other experiments also found large spin effects at high $P_\perp$. A series of inclusive experiments[6] found a large polarization in hyperon production at large transverse momentum. The lambda polarization is plotted against $P_\perp$ in Fig. 5 for proton-proton and proton-beryllium inclusive production. In the upper plot the KEK proton-beryllium data at 12 GeV falls exactly on top of the fit to the precise 400 GeV Fermilab p-p data from a Wisconsin/Minnesota/Brookhaven/Michigan team. In the lower plot, notice the agreement between the Fermilab 400 GeV p-p data and the ISR p-p data at 2000 GeV. Thus, there are quite large spin effects above $P_\perp$ of 1 GeV/c, which appear to be independent of energy from 12 GeV to 2000 Gev.

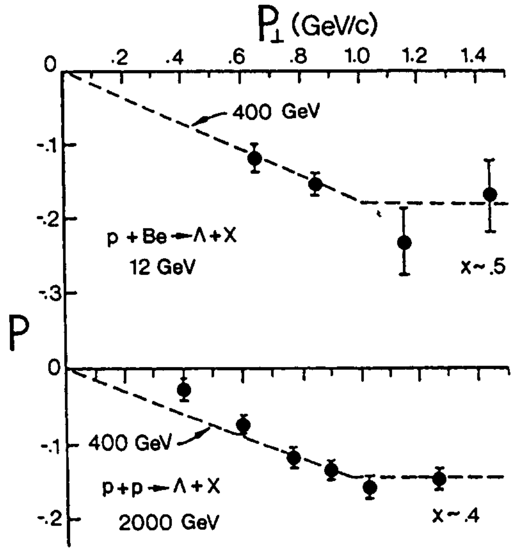


Fig. 5 Inclusive Λ polarization.

In the mid-1980's, we measured the one-spin analyzing power, A, in p-p elastic scattering at the AGS. As shown in Fig. 6, we first confirmed some data by the CERN/Oxford group[7], which had very good precision at small-$P_\perp^2$ and showed dips near $P_\perp^2$ of 1 and 3 $(\mathrm{GeV/c})^2$; we then proceeded to larger transverse momentum. Many theoreticians, who believed in Perturbative QCD, said that they did not understand our earlier two-spin effects, but that there was still a firm PQCD predication that the one-spin analyzing power, A, should go to zero; moreover, this prediction should get better at higher energy and larger $P_\perp^2$. Instead, we found that A seemed to be increasing at larger $P_\perp^2$; however our errors were rather large and at conferences some people suggested that perhaps these 28 GeV large-$P_\perp^2$ points[8] were wrong.

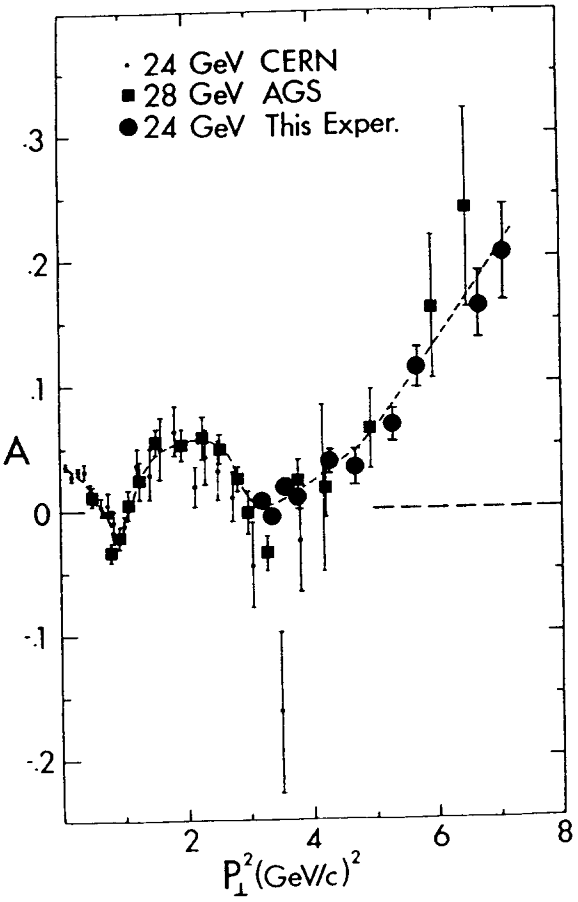


Fig. 6 Plot of A against $P_\perp^2$ for $p + p \rightarrow p + p$.

We then built a new polarized proton target which allowed us to use a very high beam intensity of 10^{11} protons per sec, while maintaining a temperature of 1°K. We could then measure the good precision points[9] shown as circles in Fig. 6; this precise 24 GeV data confirmed our previous result that A was growing at large-$P_\perp^2$. Thus, there are also large one-spin effects at high-$P_\perp^2$.

We next decided to go to higher energy; this was not possible at the Brookhaven AGS. Fortunately, IHEP-Protvino was then starting to build UNK; this seemed an excellent facility to test if these spin effects persist at higher energy. This test is the goal of the NEPTUN-A experiment. Fig. 7 shows UNK, U-70, and the town of Protvino. Notice that the NEPTUN and NEPTUN-A experiments at SS-3 are about 11 km from our meeting here in the Theory Building. With the unfortunate death of SSC, UNK should soon become the largest diameter proton facility in the world; I hope that it can eventually become a 3 TeV fixed target and collider facility.

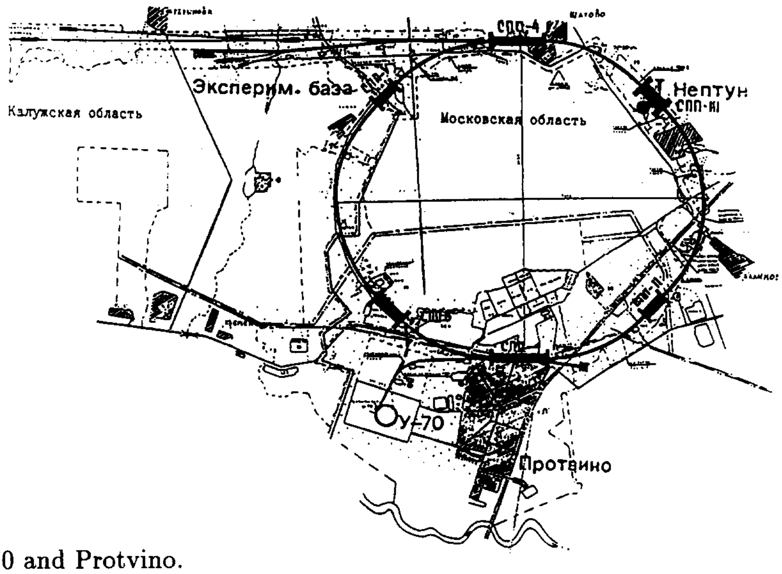


Fig. 7 UNK, U-70 and Protvino.

Fig. 8 shows the SS-3 underground experimental area; the UNK beam comes in from the right. Also shown are: the electronics hall, the 9 m shaft for heavy equipment, the 7 m shaft for light equipment and people, and the various NEPTUN spectrometers. The Michigan team's largest contribution is the Mark II Polarized Gas Jet Target, which will be used by the spectrometers of Solovianov et al., Kazarinov et al., and Sarycheva et al., and by our long NEPTUN-A spectrometer.

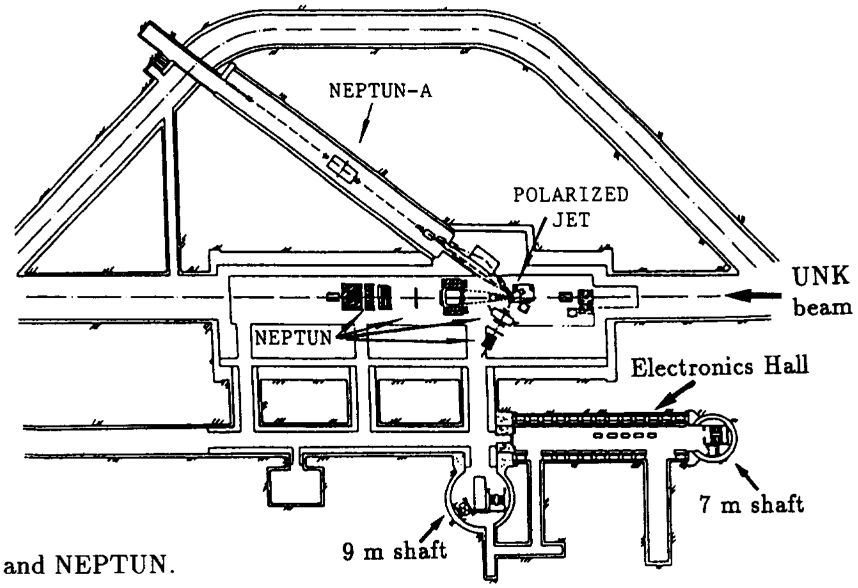


Fig. 8 SS-3 with NEPTUN-A and NEPTUN.

Our NEPTUN-A spectrometer is shown in Fig. 9; it will detect p-p elastic scattering at $P_\perp^2$ of about 2 to 8 $(\mathrm{GeV/c})^2$. Notice the two very small forward hodoscopes near the UNK beam; they measure the vertical angle of the forward scattered proton. Each hodoscope is only a few cm in size, because the Lorentz transformation squeezes the forward protons into a very small cone at 400 GeV. On the recoil side, the Lorentz transformation fans out the recoil protons into a rather large angular range. Near the jet, the Q_1 and Q_2 quadrupoles focus the recoil protons into the 55-meter-long spectrometer. The M_4 and M_5 bending magnets then bring the protons back onto the 37° axis; the Q_3 and Q_4 quadrupoles then focus the protons some more. The M_6 bending magnets bend the protons vertically up by 12°. The recoil protons' momenta are measured using upstream multi-wire proportional chambers and downstream drift chambers. Note that the momentum of each recoil proton is independent of incident energy for p-p elastic scattering from a fixed target; it depends only on the momentum transfer. Thus, at $P_\perp^2 = 2$ $(\mathrm{GeV/c})^2$, each recoil proton has an angle near 50° with a momentum near 1.5 GeV/c at the 28 GeV AGS, at the 400 GeV UNK, or at 3 TeV. This low recoil momentum can be measured with much higher precision than the 400 GeV forward proton. The wire chambers W_1, W_2, W_3, and W_4, which will be connected by helium bags, will measure the momentum of the recoil proton with a precision of about 10^{-3}. This momentum precision will allow good discrimination against inelastic scattering by comparison with the horizontal recoil angle measured by RH1 and RH2 using the unique P-θ relation for elastic scattering. We will also measure coplanarity by comparing the FV1 and FV2 measurement of the forward vertical angle with the RV1 and RV2 measurement of the recoil vertical angle. The C_1 and C_2 Cherenkov counters may help to discriminate against inelastic background and may also allow some inclusive measurements.

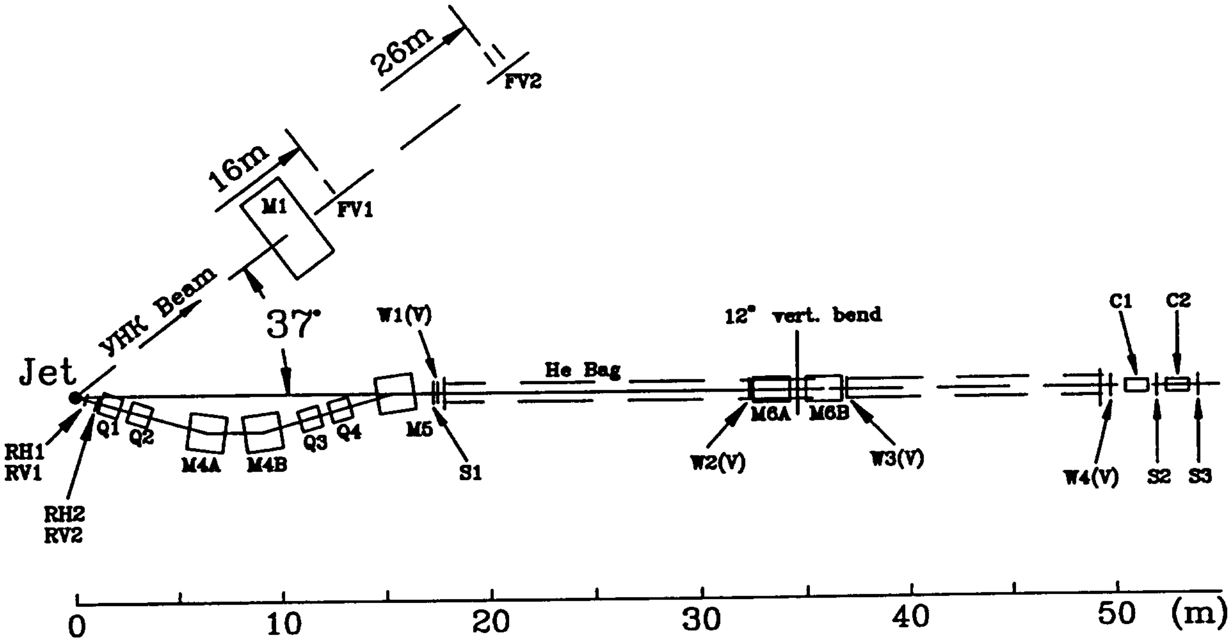


Fig. 9 NEPTUN-A Spectrometer and Jet.

Fig. 10 shows the front end of the NEPTUN-A spectrometer which includes all of the magnets except the M_6 vertical bending magnets. All four quadrupoles are now fabricated. During 1993, we decided to replace the two 3-meter-long M_4 and M_6 dipoles and the 1-meter-long M_5 dipole with five identical 1.4-meter-long dipoles. The design for these dipoles was just finished by the Efremov Institute in St. Petersburg and these five dipole magnets should be constructed during 1994 and the first half of 1995. The magnet stands which rotate around the Jet axis and the M_5 axis should be constructed at IHEP during this same period.

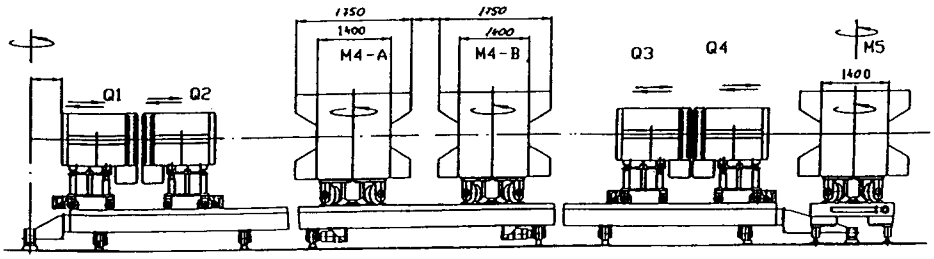


Fig. 10 NEPTUN-A Spectrometer Front End.

Fig. 11 shows the Mark II ultra-cold spin-polarized atomic hydrogen jet.[10] At the top are a pumping tee and a dilution refrigerator; this cryogenic dilution refrigerator uses a mixture of ^{3}He and ^{4}He where the cooling occurs across the surface boundary inside the ^{3}He/^{4}He mixture. A dilution refrigerator is the only practical way to reach temperatures below 0.5°K; its cooling power will be about 100 mW at about 0.3°K. The stabilization cell separates the different spin states. The superfluid-helium-coated quasi-parabolic mirror focuses the emerging electron-spin-polarized hydrogen atoms. The transition unit changes the electron polarization into proton polarization. The superconducting sextupole focuses the jet of proton-spin-polarized atoms at the interaction region, where the UNK beam passes through the jet. Notice also the helium tank, the nitrogen tank, and the 12 T solenoid magnet.

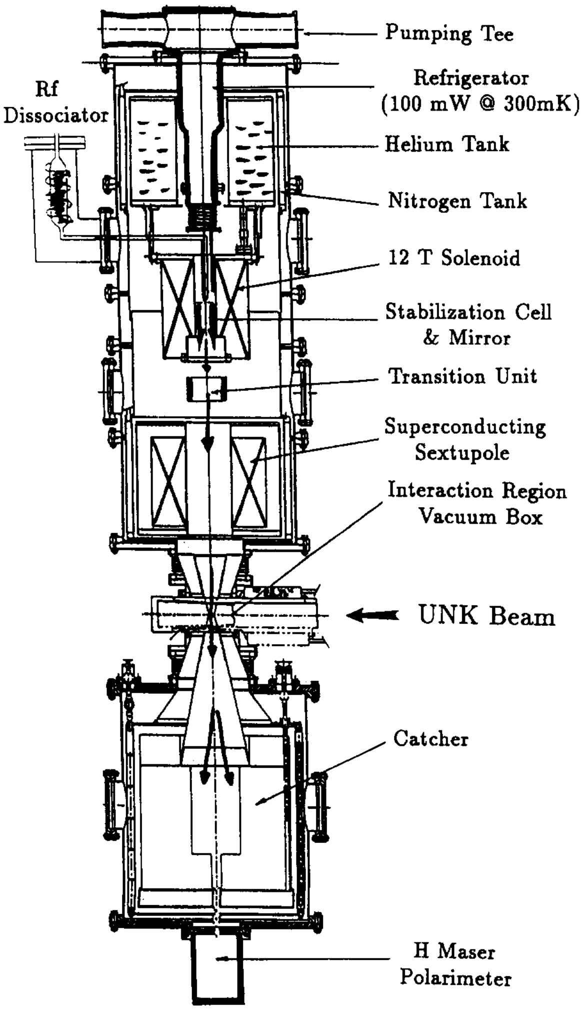


Fig. 11 Ultra-Cold Spin-Polarized Hydrogen Jet.

Most of the Mark II hardware already exists. We have fabricated all of the outer vacuum chambers except for the chamber surrounding the superconducting sextupole, because we have not yet finalized its length. These outer vacuum chambers and most of the Catcher were built commercially. The Catcher will operate at about 3° K to trap the hydrogen atoms after they pass through the UNK beam; this should avoid contaminating the good vacuum of the UNK accelerator. We are now building in the Michigan Shop the dilution refrigerator with design help from G. R. Court; the design is completely finished and much of the hardware is finished.

The 12 T solenoid was built by Cryomagnetics; it was tested and works quite well. It should operate at 14 T, if cooled to 1.8° K, but we tentatively decided to only operate it at 4° K where the field is 12 T. We are concerned that at 1.8° K the magnet may quench if some beam halo hits it. We are reluctant to operate near an accelerator a superconducting magnet that could quench if it went above the lambda point; perhaps Professor Rubbia is more optimistic about LHC magnets.

The superconducting sextupole magnet is now being built by the Michigan Shop and Oxford Instruments in England. Michigan is fabricating the iron yolk, pole tips, and the cryostat. Oxford Instruments is providing the six superconducting coils. In view of the new UNK schedule, we decided to further improve and test the Jet at Michigan; we hope to move it to Protvino around the end of 1995.

Since about 1989, we have been operating a smaller Prototype Jet for studies which aim to improve the Mark II Jet. One of the studies recently produced a quite interesting result. Our visiting colleague from Dubna, Vladimir Luppov, proposed a very nice idea. He noted that Berkhout et al.[11] had shown that a surface coated with superfluid ^{4}He below 0.5° K would reflect hydrogen atoms with a 90% probability. Luppov proposed using this idea to make a focusing mirror just as astronomers use a parabolic-shaped mirror to focus parallel light to a point.

The mirror used in the Prototype Jet is shown in Fig. 12; a beam of hydrogen atoms enters from the left into a 8 T magnetic field, which decreases rapidly towards the right. This field separates the hydrogen atoms according to their spin state. Those whose spins are parallel to the magnetic field are called high field seekers; it is energetically favorable for them to move into a high magnetic field. Those whose spins are anti-parallel are called low-field seekers; it is energetically favorable for them to move into a low magnetic field. Therefore, the low-field seekers emerge as a jet of hydrogen atoms which are all in one electron-spin state. They exit in a fairly large angular cone; we then use a downstream sextupole magnet to catch and focus as many as possible.

To test Luppov's idea, we built in the Michigan Shop a parabolic-shaped cylindrical copper mirror which we coated with superfluid ^{4}He. We then conducted an experiment to see if this parabolic mirror increased the intensity at the detector which was about 80 cm away. Unfortunately, this parabolic mirror gave essentially no increase in intensity. We

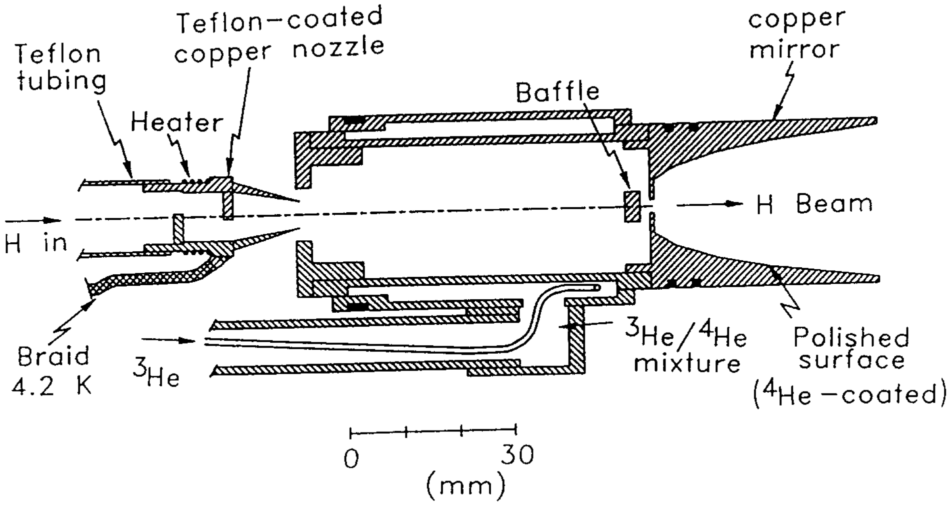


Fig. 12 ^{4}He Coated Quasi-Parabolic Mirror.

then realized that a parabola is only the correct shape for a mirror in free space; light is slightly bent because of the gravitational force near the sun. Here we had a similar problem, because just inside the mirror was a very strong magnetic field gradient. Therefore, we did not want an exact parabola but some other shape. Bill Kaufman then did calculations including the 8 T field gradient; he found another shape, which is somewhat more narrow than a parabola. We then built a copper mirror with this quasi-parabolic shape and used it to reflect hydrogen as shown in Fig. 12. With this ^{4}He-coated quasi-parabolic mirror, our intensity increased by a factor of 7.5.[12] We now plan to install a similar mirror in the Mark II Jet; this will allow the 11 cm diameter sextupole to catch and focus much of the beam. This superfluid-helium-coated mirror seems a nice mixture of high energy physics, low temperature physics, and atomic physics.

The NEPTUN-A spectrometer and Mark-II Jet should work rather well in the $P_\perp^2$ range from 2 to 8 (GeV/c)^2. With the expected luminosity of about 10^{32} cm^{-2} s^{-1}, we can measure out to $P_\perp^2 = 6$ (GeV/c)^2 with good precision, and study $P_\perp^2 = 8$ (GeV/c)^2 with about 5% precision. Perhaps some day both the UNK intensity and our Jet's intensity may improve; if the luminosity reaches 10^{33} cm^{-2} s^{-1}, then we could study even larger $P_\perp^2$. Fortunately, with 10^{32} cm^{-2} s^{-1} we can do a quite respectable experiment.

Fig. 13 is a three-dimensional graph of the analyzing power, A, plotted against P_{Lab} and against $P_\perp^2$. This graph summarizes most of the world's data on the p-p analyzing power from 2 to 28 GeV/c; it was compiled by our student, Doug Finkbeiner. At small $P_\perp^2$ there are quite large spin effects at low energy. At high energy these small-$P_\perp^2$ spin effects clearly decrease. In fact, the 150-200 GeV SPS data[13] from Professor Fidecaro et al. and the 300 GeV Fermilab data[14] from Professor Chamberlain et al. both show proton-proton elastic spin effects of only about 1%. Both experiments had a precision of about 0.1%, but they found only small values of A. Our AGS data indicates that at high-$P_\perp^2$ there are large spin effects at 24 and 28 GeV. The goal of NEPTUN-A is to extend these large-$P_\perp^2$ studies out to 400 GeV; we hope to determine if these large spin effects, which perturbative QCD says should not exist, continue to exist at UNK energies.

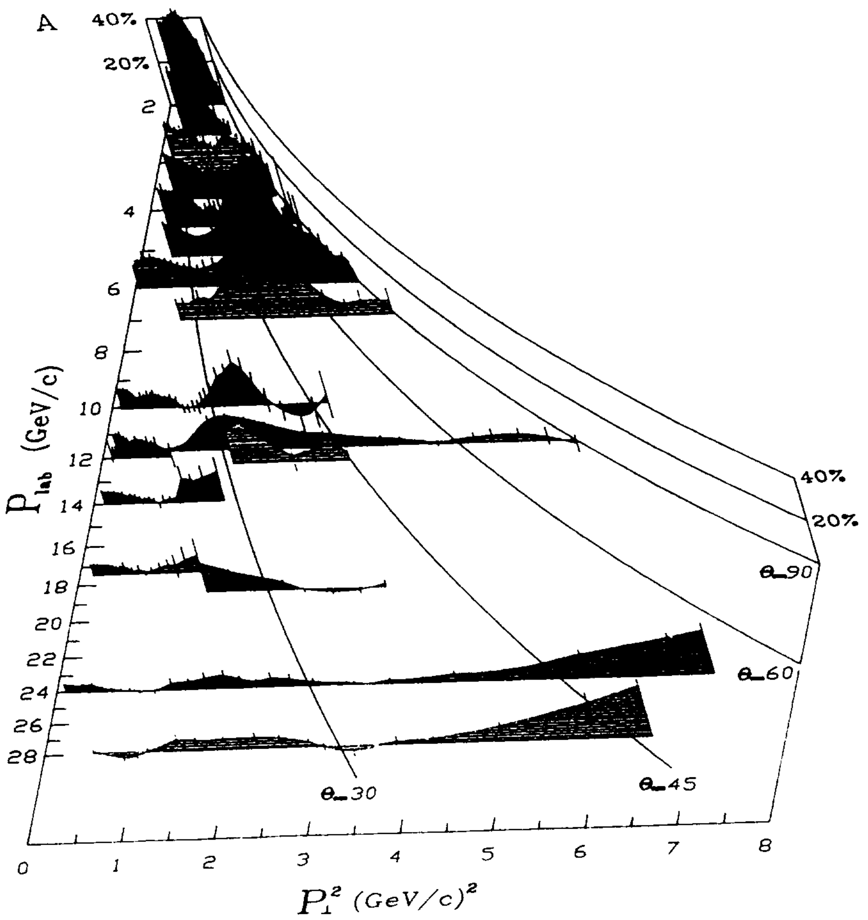


Fig. 13 Plot of p-p Analyzing power from 2 to 28 GeV/c.

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* Supported by Research Grants from the U. S. Department of Energy.

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