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SELEX in a Nutshell

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(compiled from SELEX documentation for the collaboration)

Abstract

This report provides a simple introduction to the SELEX/E781 experiment at Fermilab. It discusses briefly the goal and the main detection systems. This fixed target experiment uses 650 GeV Sigma and pion beams to study charm baryon and Primakoff physics with superior tracking and statistics.

1 Introduction

During the last decade there has been significant progress in the understanding of charm hadroproduction data. Several results from Fermilab and CERN fixed target programs established the short lifetime of the Λ_c^+ baryon, confirmed the difference in D_s^+ production from π and K beams, and confirmed the existence of the Ξ_c^+ baryon. From both hadronic experiments and e^+e^- annihilation data emerged new evidence of the Σ_c^{++} and Σ_c^o. Nevertheless, the baryon sector remains largely unexplored. There is a rich potential for new physics in charm baryon decays. Because there are three quarks involved in the baryons, the opportunity for suppression effects, enhancement effects, and other wave-function modifications of the simple spectator charm decay diagrams, is much greater in baryon studies then in the meson case. To probe these effects requires an extensive data set, correlating different decay modes of different baryons.

SELEX [1] employs a variety of beam particles to carry out systematic comparisons of charm baryon production from different beams at large x, where valence quark effects are the most prominent.

Separating baryons from mesons in the present spectrometers relies frequently on kinematic fitting of tracks from the observed secondary vertex. By limiting the angular spread of the particles to be identified, the detector problem is greatly simplified. SELEX aims at full particle identification (π,K,p) over the whole momentum range of interest for large-x charm baryons.

experiment	trigger recorded	charm reconstructed	x-range
E769	0.3 x 10^9	6500 (mesons)	-0.05 to 0.8
E687 (γ beam)	2 x 10^9	1.5 x 10^6 (mesons)	-0.05 to 0.8
E781	6 x 10^{10}	1.5 x 10^6 (baryons)	0.1 to 1.0

Table 1: Charm yields from SELEX and previous experiments.

This experiment uses silicon strip devices (SSD) for on-line charm identification. An ensemble of 20 silicon strip detector planes, in X,Y,U,V views, located immediately after the target, and further downstream tracking, allow one to estimate the secondary vertex of a potential charm decay. An ensemble of 8 silicon strip detector planes, located before the target, allow one to estimate the primary vertex position. A vertical miss distance at the central plane of the production target, of more then 30 μm indicates a charm decay, and is a basis for an intelligent charm trigger.

SELEX has good acceptance and triggering over the x range from 0.1 to 1.0. As such, it is unique among charm spectrometers in its abilities to study the transition from central to leading production. We should also note that the emphasis here is on baryons, because that field is less studied. However, SELEX can do a superb job of exploring meson physics as well. The particle identification arguments made for baryons hold equally well for mesons. The forward RICH can operate with different gases for different purposes. Magnetic fields can be adjusted to transmit different momentum particles through the SELEX spectrometers.

As we see in Table 1, the potential yield in this second-generation experiment far exceeds the sample sizes expected in the near future. Thus, we are in position to look at physics beyond the elementary charm production characteristics.

2 Physics goals

2.1 Study of charm baryons

The aim is to make a systematic survey of charm baryon production and decay mechanisms. Such a data set is needed to understand if perturbative QCD can account for charm production under different circumstances and to establish which mechanisms dominate decay processes. By having complete particle identification for hadrons, electrons, and gammas, one can normalize branching ratios to the semileptonic rates. This aids the theoretical analysis of the hadronic modes. The ability to measure π^o and η^o states is also important in analyzing these ratios for evidence of resonant substructure.This substructure is clearly a dominant feature of meson decay.

The semileptonic modes are especially important in understanding the question of suppression or enhancement of hadronic decays. If the semileptonic rates are not influenced by the various mechanisms which affected the overall lifetime, then measuring the relative branching ratios of different charm baryons, normalized to their semileptonic rates, is sensitive to wave function effects in the decay.

Finally, we are interested in measuring correlation effects in charm baryon production. It is especially interesting to see if there is a change in the correlation as one goes from small x to large x, as well as to compare meson correlations with baryon correlations. In SELEX, the trigger is on the large x system. However, the acceptance is quite good for slower partners if there is a positive correlation, i.e. if the mass of the $c\bar{c}$ system is not too large or if the color attraction of one c quark to the spectator system is not too strong.

2.2 Search for new baryon states

As has been mentioned earlier, three of the expected ground state charm baryon multiplet properties have been measured with low precision: Σ_c^+, Ξ_c^+, and Ω_c^o. In this experiment, we plan to acquire a large data set containing various decay data modes of all singly charmed baryons. The Σ_c^+ decay, whether by γ or π^o, to Λ_c^+ is difficult to detect. The de-excitation particle is slow, emitted along the baryon line of flight. For γ decays, this means that one must find a low energy photon at 0^o – a formidable job. SELEX has a photon calorimeter far from the target, so that such photons can be separated from the bulk of the primary interaction π^o decays. The photons from the de-excitation π^o would be at wide angles in x$\sim$0 baryon decays. However, the Lorentz boost from large x baryons sends the π^o forward into the downstream Pb glass arrays. The segmentation is fine enough so that the average occupation probability is low. That is what is needed to pick up these gammas with good efficiency.

2.3 Study of charm production mechanisms

There are several hints in the systematics of charm production that various charm states are flavor-dependent in their production mode. From the earliest experiments, there are suggestions that D_s is produced diferently with K beams than with π beams, and Ξ_c^+ states appear to be produced differently with n and Σ^- beams. In Fermilab Proton Center, the hyperon facility can readily supply hyperon, p, n, and π beams to the SELEX apparatus. This allows a variety of QCD studies to be made, not only on charm systems, but on heavy strange states like Ξ^* and Ω^* as well. The experiment plans to use different target materials in a high-statistics study to find any x-variation of the A dependence in charm production.

2.4 Primakoff physics

Due to the large spatial extension of SELEX setup of about 50 m (which results in good small angle resolution), long run period, excellent tracking and the high beam energy, Primakoff physics measurements are also feasible. Among these physics interests, we mention hadron radii, pion polarizability and chiral anomaly amplitude. Precise pion polarizability (chiral anomaly amplitude) measurements requires the reconstruction of the $\pi\gamma^* \rightarrow \pi\gamma$ ($\pi\gamma^* \rightarrow \pi\pi^o$) reactions with high statistics. See the last section for more details.

3 Beam and targets

The Fermilab Proton Center hyperon facility provides a variety of beams which are brought to the SELEX spectrometer. At a secondary momentum of 600 GeV/c it can provide a negative beam that is about 50% Σ^-, 50% π^- 10 m downstream of the production target. Beam tagging by a TRD system gives very clean Σ^- or π^- selection, as shown in Fig 1. Positive beams (30% π^+) of comparable momentum may also be delivered, and also a good quality neutron beam from Σ^- decay in flight.

To produce a secondary flux of 2 x 10^6 negative particles/second takes 1.6 x 10^{10} incident protons per second at 800 GeV. Thus for a 20 second spill we need 3.2 x 10^{11} primary protons delivered by the Tevatron. The hyperon magnet channel was reconfigured to select a secondary beam momentum of 30−650 GeV/c, with variable hadron composition.

For each of the possible secondary beams, the exit beam profile has a spot size of order 0.5 to 1.0 cm^2, divergence of order 1 mrad, and flux including muons in the beam of order 2 MHz. The muon background in this area is rather broadly dispersed. Most of the muon flux comes from channeling through the Al coils of the hyperon magnet, rather than directly through the hyperon channel. The muons are not a serious problem for the silicon detectors in the apparatus. They are most troublesome for the large area drift chambers.

The targets are arranged to satisfy several requirements for the apparatus. It must be possible to reconstruct the primary interaction point fast and accurately. The experiment aims to measure particle life times in the range from 0.1 to 1.5 psec. This requires excellent vertex resolution along the beam direction and low multiple Coulomb scattering after the decay. SELEX uses different materials in the target string. Each foil will be of order 1 mm or less in thickness, and will have 10 mm spacing between neighboring target foils, to permit fast reconstruction of the z-vertex associated with a charm decay. For charm studies, we intend to operate with up to 3% total interaction length in the target foils, with up to 5 foils, depending on material. The ensemble of charm targets include C, Si, Cu. In addition, SELEX has an independent 3% interaction length Pb target for Primakoff reactions, located 1 m upstream from the charm targets.

4 Experimental setup

A schematic layout of the SELEX setup is shown in Fig. 2. It consists of three magnetic spectrometers, centered on three magnets of increasing momentum kick, and a multitude of silicon detectors, proportional wire chambers, drift chambers, photon calorimeters, and TRD detectors and a RICH for particle identification. In this section, we describe briefly the main SELEX elements, together with their function and performance.

SELEX is a multi-stage spectrometer, extendable to cover different physics regimes as needed. The initial goal is the study of large-x physics for charmed baryon production and decay, as outlined above. Even at this stage, however, SELEX supplies coverage for many small-x particles. This allows additional physics studies. For example, one may observe resonant states produced in heavy flavor decay, where their decay products have appreciable momentum into the backward hemisphere. SELEX is designed with a large-acceptance first stage, very similar to that now seen in $x \sim 0$ spectrometers. This stage sweeps out many of the prongs from the underlying event before they enter the trigger region after magnet M2. It also picks up de-excitation pions from excited baryon or meson states, so it is crucial to the major goal of the experiment to have this large acceptance. Of course, the heart of the experiment is the high resolution high-momentum spectrometer and the subsequent trigger and particle identification systems. It is this part of the apparatus that allows SELEX to be selective, to aim for 10^{11} interactions during a one year run, rather than the 10^9 limit achieved till now. We consider each SELEX component in turn.

1. Beam spectrometer

The beam system, located before the target, consists of 10 planes of beam transition radiation detectors (BTRD) for the beam particle ID, an 8 plane beam silicon detector (BSSD) for beam tracking, and an ensemble of scintillator detectors for beam definition and timing. The BTRD consist of a stack of thin mylar foils, followed by a PWC, which detects the X-rays produced by the passage of a fast charged particle through the foils. The number of emitted X-rays depends on the particle speed. Since pions and Sigmas have very different masses and the same momentum, they may be clearly separated.

The beam particle identification problem is the separation of Σ^- from π^-, the main compoments of a 650 GeV/c momentum beam. The admixture of other hyperons is too small to be of concern at this momentum. The K^- flux is also negligible. Consequently, a TRD system will work very efficiently to separate Σ/π. The problem is to make it fast enough. In the present design, the charge collection is done in 100 nsec.

The BSSD is designed to measure the incident beam trajectory to a precision of 3μm in x and y, using 20 μm pitch silicon strip detectors. The beam flux through the detectors is high, $\sim$ 2 MHz, but well dispersed. The lifetime of the SSD should exceed four years of operation. The readout electronics is designed for fast charge collection and shaping. These silicon detectors track the beam particles, impinging on the target, on a one by one basis, at an average of 500 nsec time intervals.

Surrounding the target region, there are several transmission and veto scintillators for timing and beam envelope definition.

2. Vertex silicon strip detectors (VSSD)

   The large size and small pitch and commercial availability of SSDs is responsible for much of the progress in charm physics over the past decade. Our silicon detectors themselves are of a new type. We use an array of 20 silicon strip detectors immediately after the target to identify the charm decay vertex. By a new concept, we digitize the analog readout by high density ADC converters, for increased spatial resolution and double-hit detection. We use a new FSDA/FSCC/FASTBUS readout system to handle this large amount of data at about a 50 kHz interaction rate.

   One of the problems seen in present vertex silicon applications is the multiple Coulomb scattering in the detector elements themselves. This affects extrapolations to find miss distance parameters. It also converts photons in the VSSD, making extra tracks. However, these detectors implemented on a 200 μm Si substrate offer greatly reduced scattering and conversion. In SELEX, going to high momentum reduces the scattering problem, but having double-sided detectors opens the very crowded vertex region for easier access, better mounting and surveying.

   The detector geometry ensures 150 mrad coverage. This angular range is wider than required for studying forward charm production. It encompasses a large fraction of two-charm production in the forward hemisphere.

3. Slow particle spectrometer

   This spectrometer consists of two small angle SSDs mounted on the exit of magnet M1 and entry of magnet M2, and an ensemble of large angle drift chambers (DC) and proportional wire chambers (PWC), positioned in between.

   After the first weak-field ($\triangle p_t = 0.3$ GeV/c) of magnet M1, a drift-chamber spectrometer is inserted to pick up the slow tracks from the backward hemisphere, separating them from large-x charm particles. This is also the region of the detector in which de-excitation $\pi^{\pm}$ from baryon (or meson) excited states must be detected.

   Because we must measure particles in the same phase space region as the beam, and because the hyperon beam profile is large (about 1 cm^2), the centers of all drift chambers of this region must be deadened. We cannot afford to give up this forward information, so 50 μm pitch SSD are mounted on skeletal frames to give high resolution measurements in the central 5×5 cm^2 area. The detectors and lightweight mounts are connected to an external frame outside the active region of the drift chambers. In this way, the large-x baryons are measured with 15 μm accuracy in the silicon, while the slower, wider-angle mesons are measured with 150 μm precision in the drift system. The SSD can handle the beam rate with no problem. The DCs and PWCs, operated with magic gas, see only the much lower interaction rate, dispersed over a much larger area.

4. Wide angle Pb glass array

   One of the goals of this experiment is to study a complete set of baryon decay modes, including those with π^os. For backward-hemisphere π^o decays the photon lab angles go out to 100 mrad. According to previous E653 results, for 800 GeV proton interactions, the photon density in the angular range 30-100 mrad is about 10 photons/event. A Pb glass array of several hundred blocks is well-matched to this detection problem. These photons tend to be soft; Pb glass has good low-energy photon efficiency. This gives good reconstruction efficiency for wide angle π^os. This photon detector (PHT1) views the target through the low mass PWC/DC active volume and the 4% of radiation length mass of silicon of the VSSD.

5. Fast particle spectrometer

   The particles of chief interest in this experiment are small-angle high momentum tracks that traverse the second dipole magnet M2 ($\triangle p_t$=1 GeV/c) and are tracked in a second set of drift chambers spread over 2 meters. The beam is still too intense for unprotected beam chamber operation. The central region is covered by silicon mosaic detectors. This gives excellent tracking for the highest momentum particles, for which drift chamber resolution and two-track separation are not good enough. The remaining tracks are well-measured in the drift system.

   For triggering purposes, 7 PWC (in X,Y,U,V views) with 2 mm wire spacing are interspersed in this region. They play a crucial role in reconstructing tracks online in the trigger processors. These chambers are of conventional size and construction. The beam is dispersed over several wires, so the rate/wire doesn't exceed 500 kHz. The tracks recognized in the PWC system will be followed into the drift chambers in off-line processing for optimal mass and momentum resolution.

6. Electron transition radiation detector (ETRD)

   Downstream electron ID gives us a very important handle on tagging the semileptonic decays of heavy flavor states. The ETRD system is composed of 6 TRD detectors, similar in construction to the BTRD system described above, except for a much larger aperture. It is positioned between the M2 PWC tracking system and the RICH. This highly-segmented electron detector system is used in a relatively low-rate environment. Electron-hadron rejection is very good (~1000/1 off-line with 90% electron efficiency).

7. Ring-imaging Cherenkov (RICH) counter

   The RICH is one of the major systems in SELEX. It is located between magnets M2 and M3, in the Λ^o decay region, between an ensemble of PWC and DC tracking stations. For SELEX the angular coverage is limited by the transmission through magnet M2 to ±20 mrad vertically and ±65 mrad horizontally.

   We rely on good particle identification over the complete kinematic range transmitted by M2 (30-600 GeV) to look for structure in the different baryon decay modes; and in some cases, to implement a particle ID tag in the trigger.

   Cherenkov light emited by fast charged particles passing through the radiator is reflected back upstream by a spherical mirror, and imaged into rings at its focal plane where a matrix of small phototubes is positioned. Using phototubes, has the advantage that the quantum efficiency is a well-known, large number (~ 17% on the average between 300 – 550 nm). For a Ne radiator, one expects 1.3 photoelectrons/meter; the RICH has a 10 m radiator to compensate the packing losses of mounting 15 mm phototubes with 10 mm photocathodes in a hexagonal close-packed array. Winston light cones allow one to exploit the limited angle and to improve photostatistics to 9 photoelectrons/ring on average, resulting in a good detection efficiency. With the noble gas fill, chromatic aberration is small and the phototube matrix resolution determines the ring radius resolution, and hence the π/K separation limit. With these phototubes, the π/K separation limit is 1.2σ at 250 GeV. We require 2800 phototubes to cover an azimuth of about 180°.

8. VEE decay chambers (VEEC)

   The chambers in this region are a combination of PWCs in X,Y,U,V views for precise tracking, and three DC stations, composed of three X,Y,U planes each, to enhance the tracking resolution at each station. They span a decay region of Λ^o of about 35 m. Each DC unit has a special design, having 8 (6) consecutive sense wires along the beam direction, in the central (peripheral) regions. This construction offers high redundancy for track segment definition for each chamber unit.

   For the high momentum Λ^os, the opening angle of the VEE decay is a few milliradians. Thus, the angular region covered by these chambers is determined chiefly by the angular range of interest for the Λ^os themselves, about 10 mrad. Even at the end of the decay region of 35 meters, the chamber sizes are modest, of the order 80×80 cm^2. The mean charged particle occupancy of these chambers is low after the sweeping of the M1 and M2 magnets.

   Λ^o momentum accuracy is $\sim$5% from opening angle alone in this system. So most decays will have at least one particle momentum-analyzed in the M3 magnet, a large-aperture dipole at the end of the decay region.

9. Forward Pb glass arrays

   The need to measure gamma rays well has been discussed earlier. For de-excitation π^os from baryon (or meson) excited states, a Lorentz boost of γ=150-300 can be expected from large-x production. This means that the π^o decay angles will be a few milliradians for symmetric decay, tens of milliradians for asymmetric ones. The downstream PHT2 photon detector covers the forward 30 mrad aperture left open in the upstream PHT1 Pb glass detector. Because this forward array is 34 meters downstream of the target, the blocks can be relatively coarse and still subtend a sufficiently small solid angle to have low occupancy probability. The PHT2 Pb glass, mounted in front of the M3 Λ^o analyzing magnet, covers the range 7-30 mrad.

10. Downstream Pb glass array

    This third Pb glass photon calorimeter (PHT3) is of major importance for Primakoff physics since it measures the position and energy of photons at forward angles. It covers the whole forward region, and the whole azimuth, except for a small opening which is offset to the left, to allow passage of the negative charged beam after deflection in magnets M1–M3. This calorimeter consists of 328 Pb glass blocks, each with a size of 3.82x3.83x45 cm^3, and able to nearly contain a 650 GeV shower. A photon is identified by the Cherenkov light emitted by the EM shower in a 3x3 block volume. The shower centroid may be determined with a resolution of 2 mm.

11. Neutron calorimeter (NCAL)

For handling the decays of charmed baryons and also for identifying Σ^- decays which occur part way through the system, neutron detection is a very important element. The existing neutron calorimeter from E497 is used in the SELEX system.

The NCAL, located after PHT3, is the last detector in the SELEX setup. It consists of 50 absorber plates made of iron, each 4 cm thick, interspaced with scintilator plates, readout by phototubes. Each of the first 14 absorbers is backed by a PWC with 10 mm wire spacing, which provides the hadron shower localization. The NCAL covers the central 5 mrad cone, a good match for large-x production. The timing signal from its scintillation counters can be used in the trigger system as needed. The neutron interaction point information from the PWC readout will give high precision neutron angle information, and the calorimeter signal will measure the energy to $\sim 100\%/\sqrt{E}$. At 250 GeV neutron energy, this would be a 6% energy measurement. This is good enough to be useful for testing reconstruction hypotheses.

5 Primakoff physics

Primakoff physics represents the field of interest and contribution for the Petersburg NPI, Tel Aviv U. [2], and Heidelberg MPI groups. The Petersburg NPI is responsible with the construction of the Primakoff scatter trigger [3], the Tel Aviv U. constructed the laser monitoring system of the photon detectors [4], and Heidelberg MPI constructed the DSSD and LASD silicon detectors.

The pion polarizability is extracted from the measured distribution of the photon, in the projectile frame. The chiral anomaly amplitude $F_{3\pi}$ is extracted from the $\pi \rightarrow \pi\pi^o$ production cross section. Both measurements have been carried out before at lower energy, and with small (about 7000 events for polarizability, 300 events for $F_{3\pi}$) statistics.

5.1 Primakoff experimental setup

Pion polarizability (chiral anomaly) requires accurate identification and tracking of the $\pi\gamma^* \rightarrow \pi\gamma$ ($\pi\gamma^* \rightarrow \pi\pi^o$) reactions, respectively. The major difficulty derives from the very small emission angles of the photons relative to the beam, which require a fine angular resolution.

The Primakoff setup is integrated into the SELEX experiment, shown in Fig. 2. The first level trigger selects a valid single beam particle on the target. The second level trigger selects Primakoff target interactions (see next section) followed by one pion and one (two) gammas in the final state, for polarizabiliy (chiral anomaly) studies. The π^- is measured by the tracking system, while the gammas are measured in the Pb glass array of the PHT3 calorimeter. As discussed above, SELEX employs a highly redundant tracking system consisting of silicon detectors, proportional wire chambers, and drift chambers with a total of 129 planes in X,Y,U,V views in three magnetic spectrometers. This results in a high 80% tracking efficiency, a momentum resolution of 0.1%, and a fine charged track angular resolution of 15 μrad. The large $\approx$ 50 m distance to the PHT3 calorimeter Pb glass array, together with its position resolution of 2 mm results in an angular resolution of 40 μrad. Finally, we use the BTRD (RICH) for pion identification, before (after) the target.

5.2 Primakoff hardware scatter trigger

SELEX employs an intelligent and fast Primakoff trigger, running in parallel with the charm trigger, such that data for both physics topics is taken in parallel. The Primakoff trigger is based on an ensemble of 3 stations of silicon strip detectors, located before the target (two stations), and after the target (one station). Each station consists of two silicon strip detectors, with a size of 50×50 mm^2 and with 50 μm strip pitch, in x and y views. The detection efficiency is larger than 92%. The analog signals of all six detector planes are preamplified, discriminated and then readout via the CROS readout system. The position information for a maximum of two hits per plane, from all six planes, is fed to a processor, which generates the trigger decision after 100 nsec. The processor runs a simple algorithm, which uses the position information from the first two stations (before the target), to predict a window in the third station (after the target) where an undeflected beam particle would hit. The processor generates a trigger if no hit is recorded in that window, within a given angular range θ, over the whole azimuth. We set the condition $\theta > 100\mu$m for the deflection angle in a valid Primakoff grazing collision in the target. By Monte Carlo simulations and preliminary analysis of SELEX data, this trigger is expected to suppress the beam at the 0.1% level, making the Primakoff trigger rate compatible with the charm trigger rate. At the same time, it will result in an acceptance cut for Primakoff events at forward/backward angles in the projectile frame, and a loss of 30% of the events. Data at these angles are however not sensitive to the pion polarizability.

5.3 Polarizability measurement significance

We estimate, as an example, the expected SELEX statistics for the case of the pion polarizability measurement. The chiral anomaly statistics estimate is based on similar considerations. The SELEX hyperon beam rate is 2 MHz. For a 50% beam content of pions, and 70% trigger lifetime, we expect a first level trigger rate of 0.7 MHz. We use a 3% interaction length Pb target, with a total inelastic cross section of 1.8 barn, and a Primakoff cross section of $\approx$ 300 μbarn. Thereby, we expect a $\pi \to \pi\gamma$ rate of 4 events/sec. The Fermilab beam spill is 20 sec. long, and the interspill is 40 sec., so that we expects 80 events per spill, and 4800 events/hour. Since SELEX is approved to run for 1600 beam hours, we have an optimistic expectation of 7.7 million events. This figure will be reduced by the 70% scatter trigger efficiency and about 80% offline event reconstruction efficiency, leaving 3.2 milion useful events. This statistics by far exceeds the 7000 events used by Antipov et al. [5] for the only existing pion polarizability measurement to this date. Based on our Monte Carlo simulations, we expect to determine the pion polarizability at the 5% level.

References

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[5] see Antipov et al., Z.Phys. C Particles and Fields **26**, 495, (1985) and references within.