LARGE STUDIES OF MESON PRODUCTION AT CELSIUS*

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At the CELSIUS cooler storage ring in Uppsala, a detector facility for the study of meson production in light ion collisions has recently come into operation. Neutral mesons, *i.e.* π^0 and η, are detected through their decay into two photons. Charged particles and nuclei recoiling in the forward direction are observed in coincidence with the produced mesons. In this paper, the current status of the detector performance is presented together with the experimental program on meson production.

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1. Introduction

Storage rings with cooled ion beams have opened up new possibilities for precise measurements in nuclear physics. Thin windowless targets reduce background from non-target associated particles to a minimum, and the detection of slow recoil particles becomes possible. Recirculation of the beam leads to luminosities comparable to those obtained by more traditional methods. The cooling improves the quality of the beam, reducing the momentum spread and lateral dimensions. In this paper, a detector facility to study neutral pion and eta meson production at the CELSIUS cooler ring in Uppsala is presented. Recent data from Saclay and the Indiana cooler suggest that there are many open questions to be addressed in this field.

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2. The CELSIUS facility

The CELSIUS storage ring [1] in Uppsala is an accelerator for storage and cooling of ions from the Gustaf Werner synchrocyclotron. CELSIUS has a circumference of 81.8 metres, and can accelerate protons to a maximum kinetic energy of 1.36 GeV. For ions with a charge to mass ratio of $^1/_2$, the maximum energy is 470 MeV/A. The present status of CELSIUS is summarized in Table I together with some basic machine parameters.

TABLE I

Some parameters of the CELSIUS ring.

Some parameters of the CELSIUS ring	
Circumference	82 m
Max. magnetic field	1.0 T(1.2 T planned)
Max. momentum	$2.1 \times Z$ GeV/c (at present)
Max. energy ($Z/A = {}^1/_2$)	$470 \times A$ MeV (at present)
Q_x, Q_y	1.63, 1.83
β_x, β_y at internal targets	1.4 m, 1.5 m
Electron beam voltage	5–300 kV
Electron beam current	0–3 A
Electron beam diameter	2 cm
Achieved intensities	
Proton intensity	2×10^{11}
Deuteron intensity	4×10^{10}
α-particle intensity	1×10^{10}
^{16}O intensity	3×10^{8}
Internal targets	
Cluster jet target	hydrogen 3×10^{14} atoms/cm^2
	nitrogen 4×10^{13} atoms/cm^2
	argon 2×10^{13} atoms/cm^2
Fibre target	7μm carbon filaments
Pellet target[1]	20μm hydrogen pellets

[1]Under development

A schematic top view of the accelerator is shown in Fig. 1. The ring is equipped with electron cooling and facilities for experiments using internal targets. The electron cooler has a maximum electron energy of 300 keV, corresponding to a beam energy of 550 MeV/A. Above this energy limit, ions cannot be cooled. The cooled beam has a momentum spread of about $\Delta p/p = 2 \times 10^{-4}$ whereas the uncooled beam has spread of about $\Delta p/p = 2 \times 10^{-3}$. An internal cluster jet target is presently available for physics

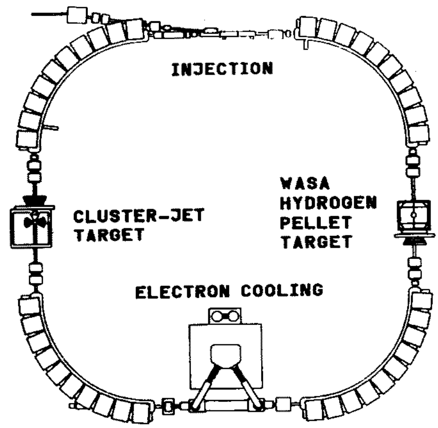


Fig. 1. Schematic top view of the CELSIUS facility

experiments, and an internal pellet target system is under development. The cluster beam is formed by pressing gas through a cooled nozzle under pressure-temperature conditions close to the transition point to liquid of the gas. A target thickness of 3×10^{14} atoms/cm^2 can be achieved with hydrogen, and with a coasting beam of 10^{11} protons, a typical luminosity in order of $10^{31}\text{cm}^{-2}\text{s}^{-1}$ is obtained. In future experiments, the gas jet will be replaced by a hydrogen pellet target.

3. The detector setup

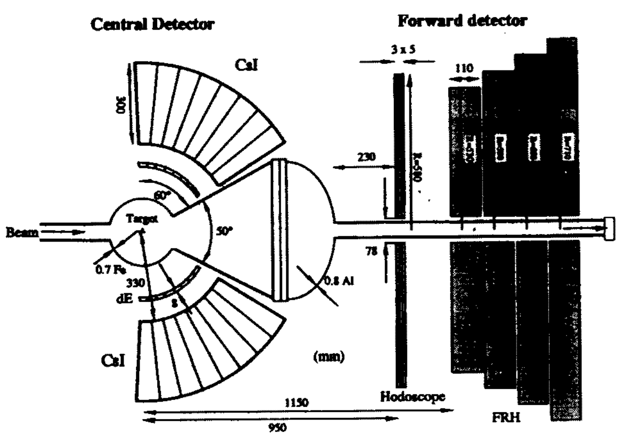


Fig. 2. Top view of the experimental setup around the cluster jet target.

A detector facility for the study of meson production in light ion collisions has been constructed around the gas jet target at CELSIUS. The present status of the setup is shown in Fig. 2. This first stage has been in operation since September 1992, and data have been collected at various energies using different target and beam nuclei. The goal of the initial experiments is to study the production of neutral mesons (π° and η) in light-ion collisions. The setup has two main components: a central detector consisting of a two-arm calorimeter to detect neutral mesons through their decay into two photons, and a forward detector to detect simultaneously nuclei and charged particles recoiling in the forward direction.

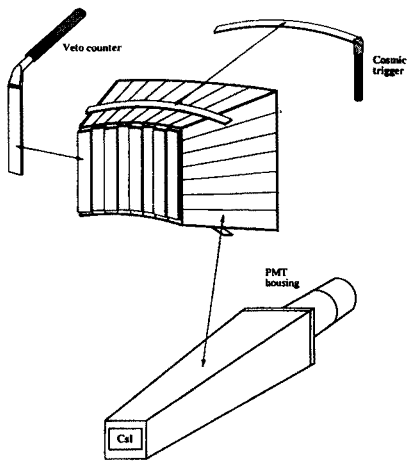


Fig. 3. One 7 × 8 array of the central detector

The central calorimeter includes 112 tapered, 30 cm long CsI(Na) crystals stacked in two 7 × 8 arrays (Fig. 3). The crystals are grown in the Ukraine and machined, surface treated and wrapped in Novosibirsk, before being sent to Uppsala. As a scintillator, CsI(Na) is in many respects similar to the more commonly used NaI(Tl). CsI is however only slightly hygroscopic, and so the crystals are easier to handle. The decay time is longer (650 ns instead of 250 ns as for NaI(Tl)), but this is not expected to have any negative consequences at CELSIUS, where the use of thin internal targets does not lead to large fluxes of final particles. The light output of CsI(Na) is slightly higher than that of NaI(Tl), and the emission spectrum is well suited to photomultiplier read-out. The crystals are read with Russian FEU 84-3 PMTs, which have a photocathode diameter of 25 mm. An energy resolution of 26% (FWHM) is obtained for 662 keV photons from a Cs-137 source.

The most commonly used method of calibrating this kind of electromagnetic calorimeter is through the use of the decay photons from neutral pions. However, this method requires a large sample of pions. Having thin targets in regions where the pion cross sections are expected to be low (*i.e.* near reaction thresholds), a sufficient quantity of pions cannot always be collected.

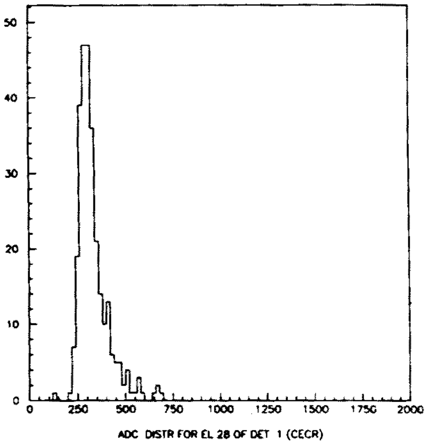


Fig. 4. Cosmic muon energy deposition spectrum when requiring coincidence in the cosmic trigger counters together with a signal from seven crystals (one column).

To avoid having to dedicate special beam time for calibration purposes, an alternative method using cosmic muons and radioactive sources has been developed. Muon trigger counters are situated above and below the crystal arrays to provide a trigger for muons traversing a well defined path through the crystals. These counters have a curved shape to follow the spherical geometry of the crystal arrays (Fig. 3). Muons that give coincident signals in the counters traverse the same crystal thickness for all crystals in one row. The observed peak in the energy deposition spectrum (Fig. 4) corresponds to the energy lost by minimum ionizing muons, in this case $\sim$ 34 MeV. By the symmetry of the setup, the energy deposition is the same for all crystals in one row, giving a relative calibration of the elements. The absolute calibration is made using photons from an Am/Be source ($E_\gamma = 4.4$ MeV). In Fig. 5, the on-line adc spectrum obtained with such a source is shown. By rejecting cases where more than one crystal has been hit, Compton, single escape, and double escape events can be rejected, leaving only the full energy peak. The linearity of the crystals, PMTs, and voltage dividers makes it possible to extrapolate this calibration to higher energies.

The fronts of the crystals are covered by 8 mm thick veto counters for charged particle rejection. Neutral mesons are detected through their decay into two photons, and are identified at the trigger level as coincident signals between the left and right crystal arrays, with no hits in the veto counters. The corresponding invariant mass is calculated using the detected energy deposition and the opening angle between the two tracks. In Fig. 6 is shown the invariant mass spectrum for such events obtained in p + d collisions at a bombarding proton energy $T_p = 200$ MeV (1.3 MeV above the p + d $\rightarrow$ ^{3}He $+\pi^\circ$ reaction threshold). The observed invariant mass resolution for neutral

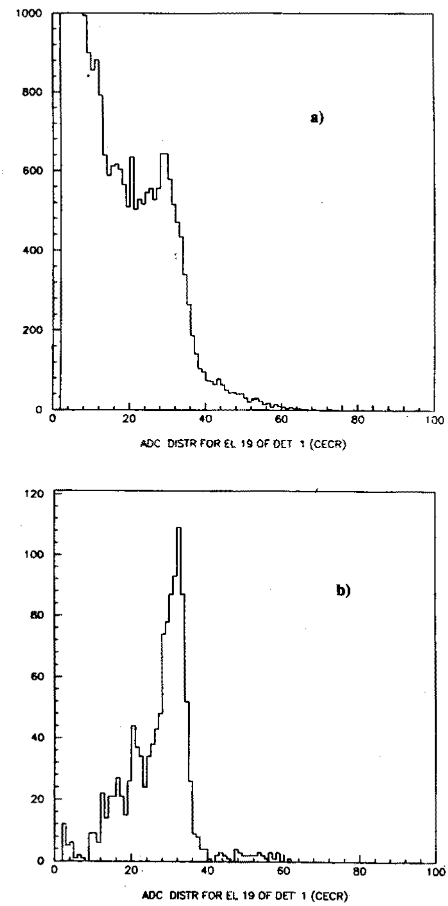
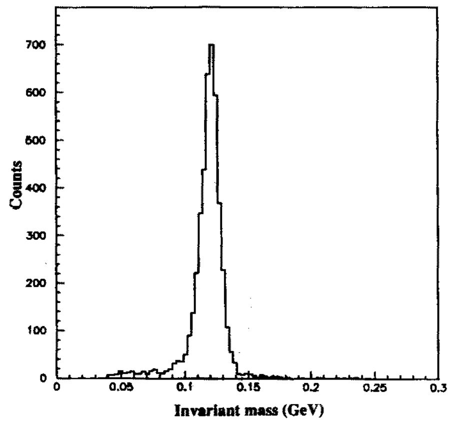


Fig. 5. Calibration of the CsI(Na) crystals using 4.4 MeV photons from an Am/Be source. In (a), the on-line ADC spectrum is shown. The ADC range is 4000 channels, and the peak corresponds to about 30 channels. In (b), Compton, single escape and double escape events have been rejected.

pions is approximately 11% (FWHM). It is expected that this resolution could be improved somewhat by fine-tuning the calibration. Eta mesons can be observed in a similar manner, with the disadvantage that their branching ratio into two photons is 39% instead of the 99% for pions. In Fig. 7 the invariant mass spectrum for neutral coincidences in p + d collisions at a bombarding proton energy of 1276 MeV is shown. In addition to the pion and eta invariant mass peaks, there is a broad continuum corresponding to multiple pion production.

The central calorimeter currently comprises 112 crystals, covering a solid angle of about 15% of 4π. In the future, it will be extended to approx-



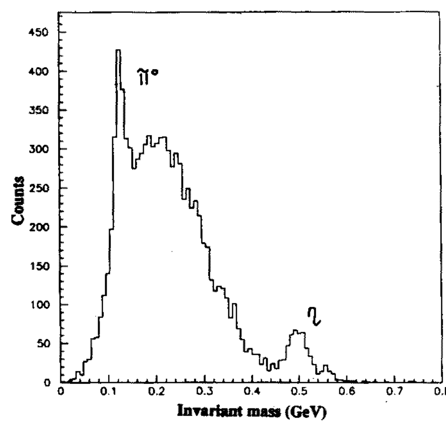


Fig. 6 & 7. Invariant mass spectra recorded in pd collisions at T_p = 200 MeV (fig 6) and T_p = 1276 MeV (fig 7). The invariant mass is calculated using only the central detector. The pion and eta peaks are shifted downwards from the true masses due to shower leakage out from the detector volume and a systematic shift in the absolute calibration.

imately 1000 crystals, covering nearly 4π steradians. The detector presently includes 600 kg of CsI, and another 300 kg has been delivered to Uppsala. The remaining 3000 kg of the final detector has been delivered to Novosibirsk for machining and wrapping.

The forward part of the detector facility now has two different detectors: a circular, segmented, thick plastic scintillator in four layers for total energy measurements, and a thin three-layer plastic hodoscope for angle and dE measurements (Fig. 8). The forward detector covers scattering angles in the range 3° – 25° and is intended to detect charged particles and nuclei recoiling in the forward direction. In conjunction with the central detector, it becomes possible to observe all final state particles in meson-producing

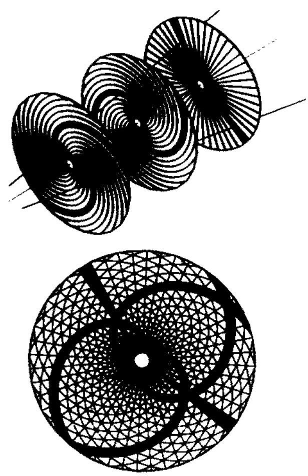


Fig. 8. Thin three-layer plastic hodoscope for angle and dE measurements in the forward direction. It is followed by four thick scintillator planes for total energy measurements.

light ion reactions. A tracker made of four blocks of thin-walled (26μm) straw chambers is under construction, and is intended to be put in front of the existing forward detector modules to increase the angular resolution for particles in the forward direction.

4. Preliminary results

The present setup has been operating since September 1992, and data from several different reactions at various energies are now being analyzed. Total cross sections are currently obtained by normalizing collected samples with known pp and pd elastic cross sections. Differential cross section information is obtained using both the central and forward detector information.

In Fig. 10 are shown a series of invariant mass plots recorded in pp collisions near the $p + p \rightarrow p + p + \pi^{\circ}$ reaction threshold (279.64 MeV). This reaction has been measured at the Indiana cooler by Meyer *et al.* [2], and the total cross section close to threshold was found to be larger than the existing theoretical predictions by more than a factor of five [3]. In the experimental facility at CELSIUS described above, the recoiling protons as well as the neutral pion, from its decay into two photons, can be detected. However, very close to threshold, the available kinetic energy is not sufficient to kick the protons out from the dead angle subtended by the beam pipe, and only the two photons can be detected. The goal is to verify the Indiana data and also extend the measurement even closer to threshold. The analysis of the

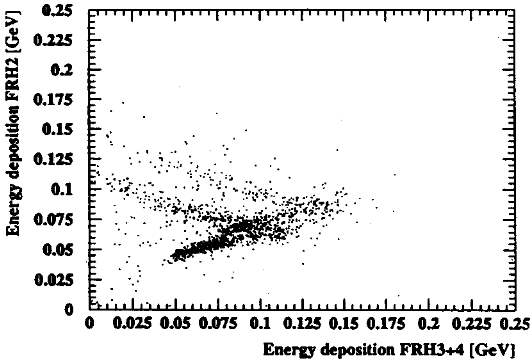


Fig. 9. dE-E plot (preliminary) obtained using the energy deposition in different planes in the forward detector. The data were recorded in dd collisions at $T_d = 570$ MeV, and events with pions detected in the central detector were selected. Protons and deuterons can be distinguished as two separate bands.

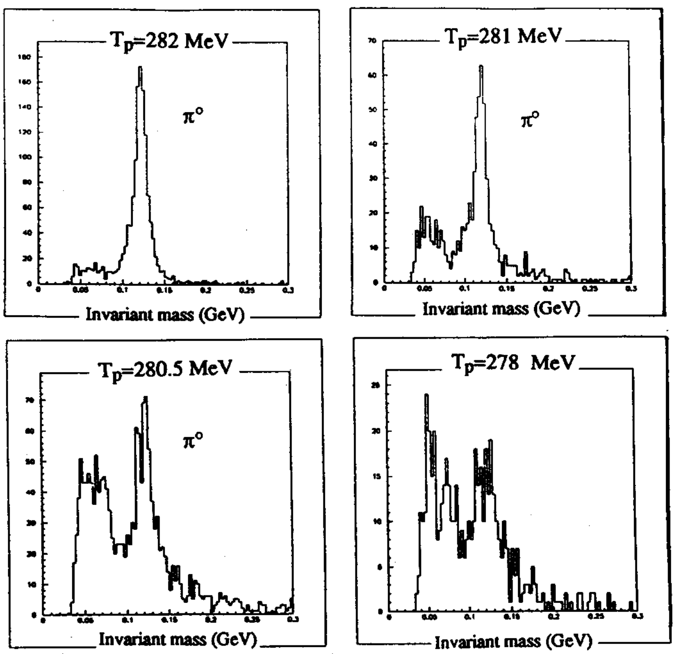


Fig. 10. Invariant mass spectra recorded in pp collisions close to the π^0 production threshold (279.64 MeV) using the pion two-photon decay. The pion peak decreases as the threshold is approached, leaving a background cross-section of about 1 nb below the NN threshold (278 MeV). These background events either originate from reactions in the vacuum equipment or from contamination in the target gas.

data is not finished yet, but a rough estimate of the measured cross sections indicates quite good agreement with the Indiana results.

Data have also been recorded in pd collisions at a bombarding proton energy of 200 MeV, *i.e.* 1.3 MeV above the $p + d \rightarrow {}^3He + \pi^\circ$ reaction threshold. The photons from the pion decay have been recorded (Fig. 6) as well as the recoiling ^3He nucleus using a small angle spectrometer placed after the first quadrant of the accelerator downstream from the target. This detects recoil nuclei inside of the otherwise dead angle defined by the beam pipe (Fig. 11). One quadrant of the accelerator is thus used as a magnetic spectrometer.

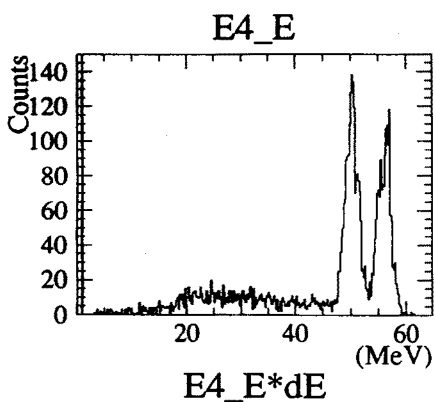
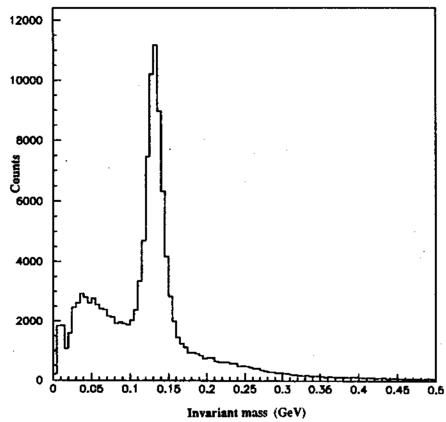


Fig. 11. Energy spectrum obtained with the small angle spectrometer in pd collisions at $T_p = 200$ MeV. The two peaks correspond to ^3He nuclei recoiling in the forward and backward directions, respectively.

As an example of the simultaneous use of the central and forward detectors, pions have been detected in the reaction $d + d \rightarrow X + \pi^\circ$ at $T_d = 570$ MeV. Here, X can denote several different states involving p, n, d, ^3He *etc.* The resulting invariant mass spectrum is shown in Fig. 12. Selecting events with an invariant mass in the vicinity of the real pion mass, the corresponding recoil particles in the forward detector can be identified. Fig. 9 shows a preliminary dE-E plot for different planes in the forward detector, where protons and deuterons can be separated. Of special interest in this case is to search for the isospin violating reaction $d + d \rightarrow d + d + \pi^\circ$, where the pion as well as the two deuterons can be identified.

Tests have also been made to see to what extent pion production from heavier target nuclei can be observed. Fig. 13 shows the invariant mass spectrum obtained from a small data sample collected in proton-^{14}N collisions at a proton bombarding energy $T_p = 180$ MeV, *i.e.* well below the nucleon–nucleon pion production threshold. The background seems to be fully comparable with that which is observed in light ion collisions.



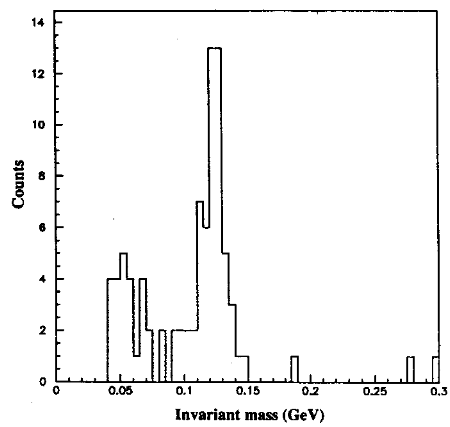


Fig. 12 & 13. Invariant mass spectra recorded with the central detector in dd collisions at $T_d = 570$ MeV (Fig. 12) and $p^{14}N$ collisions at $T_p = 180$ MeV (Fig. 13).

5. Conclusion and future outlook

So far, the beam conditions at CELSIUS have favored studies of pion production at energies well below the eta production threshold. The goal is to extend the mentioned pion experiments to the eta region and observe the corresponding η-channels. Theoretically very little is known about the η–nucleon interaction and even less about the η interaction with nuclei. Unexpectedly large cross sections for η-production near threshold in the $p + d \rightarrow {}^3He + \eta$ reaction have been observed at Saclay [4]. This reaction is believed to be dominated by the $N^*(1535)$ resonance. Measurements on η production in p + p and p + d collisions can therefore give valuable information on both the interaction of the η meson and the $N^*(1535)$ resonance. We intend to explore this region during our next run.

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