Status and plans of the ion program of NA61 at the CERN SPS

Zoltán Fodor
KFKI – Research Institute for Particle and Nuclear Physics

for the NA61/SHINE Collaboration

11. WINTER SCHOOL ON HEAVY ION PHYSICS, Budapest 2011
Fixed target experiment in the north area of the CERN SPS
Based on the upgraded NA49 detector
Started in 2007
Beams:
ions (Be, Ar, Xe) at 13A - 158A GeV
hadrons (p, π) at 13 - 158 GeV

SHINE – SPS Heavy Ion and Neutrino Experiment
Hadron production in p+p, p+A, h+A, A+A at various energies

**Search for the critical point** of strongly interacting matter

**Study of the properties of the onset of deconfinement**

**Study high pT particles (energy dependence of nuclear modif. factor)**
Motivation: suppression of high pT particles at RHIC and LHC energies (manifestation of parton energy loss in a dense medium)
Hypothesis: for lower energy collisions, where deconfined matter is *not* formed, such suppression should disappear

**Obtain precision data on hadron production (spectra)**
reference measurements of p+C interactions for the T2K experiment for computing neutrino fluxes from the T2K beam targets
reference measurements of p+C, p+p, p+p, and p+C interactions for cosmic-ray physics
(Pierre-Augier and KASCADE experiments) for improving air shower simulations

Pion spectra in p+C interactions at 31 GeV are published (PR C84, 034604 (2011)). They are already used to improve beam neutrino flux predictions and to adjust models (UrQMD 1107.0374, Fritiof 1109.6768) used in neutrino and cosmic-ray experiments
Reference measurements for T2K $\nu$ physics

- Precision measurements of hadron production for the prediction of neutrino fluxes at T2K
- Measures initial neutrino flux

The T2K experiment published results on $\theta_{13}$ angle of the neutrino mixing matrix. Systematic error estimate based on the NA61/SHINE results.
Reference measurements by NA61/SHINE for cosmic-ray physics with collaboration of Auger experiment

- Measurement of particle production spectra
- Special 'cosmic runs': p-C at 158 and 350 GeV/c
- p+C at 31 and 158 GeV/c
- p+p scan from 13 to 158 GeV/c

Cosmic ray composition of central importance for understanding sources, kink, ankle...

Modern detector installations: high statistics/quality data

Indirect measurement (extensive air showers): simulations needed

Strong model dependence: due mainly to simulation of μ production

μ production related to hadronic interactions at fixed-target energies
Data sets planned to be recorded by NA61 within the ion program

and those recorded by NA49

We measured also p+C at 31 GeV and π+C at 158 and 350 GeV
Comprehensive scan in the whole SPS energy range (13A-158A GeV) with light and intermediate mass nuclei

First time in history when such a 2D scan (energy, system size) will be performed

Estimated (NA49) and expected (NA61) chemical freeze-out points according to Beccatini, Manninen, Gaździcki, PRC73, 044905 (2006)
Search for the onset of the horn in collisions of light nuclei

Expectation for energy and system size scan: similar structures (kink, horn, step); vanishing for small systems size.

In particular the "horn" like structure is expected to be similar for Ar+Ca and Pb+Pb collisions and then rapidly disappear for smaller systems.
increase of critical point signal (multiplicity and average pT fluctuations, intermittency, etc.) for system freezing-out near the critical point

Non-monotonic dependence of critical point signal on control parameters (energy, centrality, ion size) can help to locate the critical point

Already observed in NA49: fluctuations of average pT, multiplicity, multiplicity of $\pi^+\pi^-$ pairs, net proton density tend to a maximum in Si+Si collisions at 158A GeV

→ strong motivation for future experiments
Successor of the NA49 experiment

**Main upgrades:**

**2007:** Construction of the forward ToF wall to identify particles with $p < 3$ GeV/c and $\Theta < 400$ mrad (extended ToF acceptance to $p \approx 1$ GeV/c)

**2008:** Replacement of the TPC digital read-out and DAQ (increase of the event rate by a factor of $\approx 10$; important i.e. for high pT particles)

**2011:** Replacement of Forward Calorimeter (VETO) by Projectile Spectator Detector with resolution $\sigma(E)/E \approx 0.55/\sqrt{E/(1\text{GeV})}$

5 x better than in NA49

**Resolution of 1 nucleon !**

Important for fluctuation analysis

**2011:** Installing helium beam pipes

Installed for 2011 Be run: Z-detectors (measure ion charge for on-line selection of secondary ions, A-detector (measures mass composition of secondary ion beam)

Low Momentum Particle Detector (LMPD), for centrality determination in p+A, is ready and the pilot p+Pb data were registered in 2011
Fragmented beam

- **Pb**: primary Pb beam from the SPS
- **Fragmentation target**: Pb beam fragments
- **Fragment separator**: Fragment separator will be used by NA61 to produce clean light-ion beams (for example Be)
Double magnetic spectrometer to separate ion fragments corresponding to selected magnetic rigidity $B_\rho$

Fragmentation target (T2) length optimized to the desired fragment production

Degrader (Cu plate where ions lose energy $dE/dx \sim Z^2$) allow to reach required beam purity at lower energies

Tested in 2010 for 13.9A and 80A GeV Pb ion beams

Used in 2011 for 150A, 80GeV (and planed 40AGeV)
Fragmented beam composition at 13 GeV

From T2 target

After degrader, at NA61 target
Channeling of high intensity heavy ion beam through the gas volume of the Vertex TPCs has limitations when compared to proton beam.

Delta electrons produced in the gas volume inside VTPCs from heavy ion beam-gas interactions (electrons kicked off from TPC gas atoms by beam ions/spectators) may significantly increase the background in TPCs and distort measurements of event-by-event fluctuations.

Example of the effect from a single d-electron in VTPC-1 (spiralling low-energy knock-on electron) registered in 2009.

Installation of the helium beam pipes in the VTPC gas cage (around the beam line) - a reduction of the delta-electron background by a factor of 10.
• Helium-filled beam pipes were successfully mounted inside fragile detectors (in both Vertex TPCs)

• Measurements show significant decrease of secondary interactions with He beam pipes installed

Position of the reconstructed interaction point along the beam direction
p+p collisions at 158 GeV

Without He beam pipes

With He beam pipes
Precise measurement of the energy of projectile spectators.

- centrality selection (on trigger level)
- measurement of event-by-event fluctuations (to reduce Npart fluctuations)
- Reconstruction of the reaction plane

Main features of PSD:
- high energy resolution ~55%/\sqrt{E}
- high granularity: transverse homogeneity of energy resolution, reaction plane measurements

Total weights 17 T
Simulation of fragments distribution

44 modules
2011: 32 modules
(16 small and 16 large)

Used in the trigger

40A GeV, 17m (from the target)  
40A GeV, 23 m
80A GeV, 23 m
158A GeV, 23 m
75 GeV Be beam

Counts

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<th>RMS</th>
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hEdepModSumCalib_1_16_T1

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<th>Mean</th>
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<tr>
<td>3435</td>
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<td>93.78</td>
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</table>

\(^{7}\text{Be} \text{ beam at 75A GeV/c for NA61/SHINE at CERN SPS}\)
Centrality measurement in pA reaction

Projectile (p, h) hits nucleons when passing through a nucleus (A). Some of hit nucleons can knock out other nucleons (“grey” nucleons). **Centrality of p+A/h+A is correlated to the number of grey target protons with low momenta.**

**LMPD – physics objectives:**
- h+A interactions: low momentum (grey) particles measurement (energy and identification). Number of these slow particles is sensitive to the centrality of the collision → centrality detector
- A+A interactions: backward multiplicity (if it can work in high multiplicity environment)

See next presentation of K. Marton
Particle identification

Positive particles

- Acceptance 50% at $p_T \approx 5$ GeV/c
- Tracking efficiency $\geq 95%$
- $\sigma(p)/p^2 = 10^{-4}$ (GeV/c)$^{-1}$

- Extended ToF acceptance at low momenta ($\approx 1$ GeV/c)
  - TOF-L/R: $\sigma(t) \approx 60$ ps
  - ToF-F: $\sigma(t) \approx 120$ ps

- $\sigma(dE/dx)/<dE/dx> \approx 0.04$
- $\sigma(minv) \approx 5$ MeV
$\pi^-$ spectra in p+C at 31 GeV

Pb+Pb points divided by the number of wounded projectile nucleons

p+C rapidity spectrum is shifted towards target rapidity with respect to Pb+Pb due to the projectile-target asymmetry of the initial state

NA61 p+C results at the energy of the onset of deconfinement confirm approximate proportionality of the pion yield to the mean number of wounded nucleons
• Shape of transverse mass spectra at mid-rapidity changes from a convex form in p+C to a concave one in central Pb+Pb (with respect to corresponding exponential fits)
• According to hydrodynamical approach this is due to strong radial collective flow in Pb+Pb collisions, which is absent in p+C interactions
Inverse slope parameter of $m_T$ spectrum of $\pi$

Transverse mass spectra fitted with:

$A \exp(m_T/T)$

at $0.2 < m_T - m_p < 0.7$ GeV

$p+C$ at 31 GeV → $T=151\pm3$ MeV

$Pb+Pb$ at $30A$ GeV → $T=157\pm2$ MeV

Inverse slope parameter increases with the collision energy, and the number of wounded projectile nucleons.
Kaons in reaction p+C at 31 GeV

Data from the 2007 test production, from the 2009 run has 10 times higher statistics, more detailed analysis is going on
$\Lambda$ and $K^0_s$ measurement in $p+C$ at 31 GeV

Armenteros-Podolansky plot after application of the V0 selection cuts.

$\pi^-+C$ interactions at 350 GeV
Δ++ signal in p+C at 31 GeV

- Invariant mass of $\Delta^{++} \rightarrow \pi^+ p$
- Mass identification using the energy loss measurement in the TPC and time of flight in TOF detectors
Multiplicity fluctuations in p+C at 31 GeV

\[ \langle N \rangle = \sum N \cdot P(N) \]
\[ V(N) = \langle N^2 \rangle - \langle N \rangle^2 \]

**Scaled variance** \( \omega = \frac{V(N)}{\langle N \rangle} \)

- \( \omega \) (all charged) = 1.08 ± 0.03 (stat)
- \( \omega \) (neg. charged) = 0.93 ± 0.03 (stat)
- \( \omega \) (pos. charged) = 0.83 ± 0.03 (stat)

Results uncorrected for on-line and off-line event selection biases

- Multiplicity distributions for all three charge combinations are close to Poisson one
- The correction for non-target interactions affect \( \omega \) strongly (12% for all charged, 5% for neg. charged and 10% for pos. charged)

Results from p+p energy scan (6 energies) will appear soon
Average $p_T$ fluctuations in p+C at 31 GeV

$M(p_T) = \frac{1}{N} \sum_{i=1}^{N} p_{T,i}$

- Events with zero accepted particle multiplicity are not taken into account
- Results uncorrected for on-line and off-line event selection biases

• The width of the $M(p_T)$ distribution strongly decreases with increasing colliding system size as expected from the increasing particle multiplicity
• The same effect when going $p+p \rightarrow Si+Si \rightarrow Pb+Pb$ at 158A GeV (see PR C70, 034902 (2004))
Complementary experiments

The NA61/SHINE ion program gives the unique opportunity to study exciting physics in a very efficient and cost effective way. It will be complemented by the efforts of other international and national laboratories, FAIR, JINR and BNL and by the heavy ion program at the CERN LHC.

<table>
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<tr>
<th>Facility</th>
<th>SPS</th>
<th>RHIC</th>
<th>NUCLOTRON-M</th>
<th>NICA</th>
<th>SIS-100/300</th>
<th>LHC</th>
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<td>BNL Brookhaven</td>
<td>JINR Dubna</td>
<td>JINR Dubna</td>
<td>FAIR GSI Darmstadt</td>
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<td>Experiment</td>
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<td>STAR PHENIX</td>
<td>BM@N</td>
<td>MPD</td>
<td>HADES + CBM CBM</td>
<td>ALICE ATLAS CMS</td>
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<td>7.7 (5?) – 200</td>
<td>&lt; ~ 3.5</td>
<td>4 – 11</td>
<td>2.3 – ~4.5 ~4.5 – ~8.5</td>
<td>up to 5500 14000 (p+p)</td>
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<td>CP &amp; OD</td>
<td>CP &amp; OD</td>
<td>HDM</td>
<td>OD &amp; HDM</td>
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<td>PDM</td>
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CP – critical point
OD – onset of deconfinement, mixed phase, 1st order phase transition
HDM – hadrons in dense matter
PDM – properties of deconfined matter
New period in the experimental study of A+A collisions at the SPS energy range started in 2009 with the p+p energy scan of NA61/SHINE at the CERN SPS.

RHIC Beam Energy Scan program began last year. We look forward to the start of the corresponding programs at NICA and FAIR as well as to data from the CERN LHC.
NA61/SHINE is a large hadron spectrometer at the CERN SPS performing measurement for three different programs:

- Critical point and onset of deconfinement (ion program)
- Neutrino physics
- Cosmic-ray physics

**Ion program:**

- Numerous detector upgrades needed for data taking with ion beams are completed
- Data already taken: p+p at 13, 20, 31, 40, 80, and 158 GeV, Be+Be at 150 and 75A GeV
- The run with Be+Be is ongoing (40AGeV Be+Be collisions will be registered and continuation in 2011 with 30, 20 and 13 AGeV). It is the first NA61 run with ions and first with secondary ion beams
- Ar+Ca, Xe+La at all 6 energies will be taken by the end of 2015

Results on p+C at 31 GeV:

- y-distribution of pions: yields at 31 GeV increase approximately in proportion to projectile wounded nucleons (WNM works)
- Inverse slope parameter of transverse mass \(\pi\) spectra increases significantly from p+C to Pb+Pb and from 31 to 158 GeV
- First results on \(K^0_s, \Lambda, \Delta^{++}\) were obtained
- Event-by-event multiplicity and average \(p_T\) fluctuations were measured for the complete rapidity range available in NA61
KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
The Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
Faculty of Physics, University of Warsaw, Warsaw, Poland
Faculty of Physics, University of Sofia, Sofia, Bulgaria
Karlsruhe Institute of Technology, Karlsruhe, German
Joint Institute for Nuclear Research, Dubna, Russ
Warsaw University of Technology, Warsaw, Polar
Fachhochschule Frankfur, Frankfurt, Germany
Jan Kochanowski University in Kielce, Poland
University of Geneva, Geneva, Switzerland
University of Belgrade, Belgrade, Serbia
Jagiellonian University, Cracow, Poland
University of Silesia, Katowice, Poland
University of Athens, Athens, Greece
ETH, Zurich, Switzerland
University of California, Irvine, USA
University of Bern, Bern, Switzerland
University of Bergen, Bergen, Norway
University of Wroclaw, Wroclaw, Poland
Rudjer Boskovic Institute, Zagreb, Croatia
University of Frankfurt, Frankfurt, Germany
Institute for Nuclear Research, Moscow, Russia
State University of New York, Stony Brook, USA
LPNHE, University of Paris VI and VII, Paris, France
National Center for Nuclear Studies, Warsaw, Poland
St. Petersburg State University, St. Petersburg, Russia
Institute for Particle and Nuclear Studies, KEK, Tsukuba, Japan
Laboratory of Astroparticle Physics, University Nova Gorica, Nova Gorica, Slovenia

139 participants from 28 institutes and 15 countries