Exotic nuclei studied in Light-ion induced reactions at the NESR storage ring (EXL)

Executive Summary

FAIR provides unique opportunities in experimental studies on nuclei far off stability, exploring new regions in the chart of nuclides which are of paramount interest in the fields of nuclear structure and astrophysics. The objective of the EXL-project (Exotic nuclei studied in Light-ion induced reactions at the NESR storage ring), which is part of the NUSTAR program, is to capitalize on light-ion induced direct reactions in inverse kinematics by using novel storage ring techniques and a universal detector system. Due to their spin-isospin selectivity, light-ion induced direct reactions at intermediate to high energies are an indispensable tool in nuclear structure investigations as evident from investigations of stable nuclei in the past.

The essential nuclear structure information is deduced from high-resolution measurements at low-momentum transfer. Because of the kinematical conditions of inverse kinematics in case of beams of unstable nuclei, low-momentum transfer measurements turn out to be an exclusive domain of storage ring experiments. Luminosities are superior by orders of magnitude compared to experiments with external targets. The EXL program thus utilizes one of the outstanding features of FAIR, i.e., the availability of a multi-storage-ring complex coupled to the super-conducting fragment separator (Super-FRS).

The key physics issues being covered within the EXL program address

- nuclear matter distributions near the drip lines (halo -, skin - structures, etc.),
- the isospin-dependence of the single-particle shell structures (magic numbers, shell gaps, spectroscopic factors),
- nucleon-nucleon correlations and cluster formation,
- new collective modes (different deformations for protons and neutrons; giant and pygmy resonances of various multipolarities),
- in-medium interactions in asymmetric and low-density nuclear matter,
- the astrophysical r- and rp-processes (Gamow-Teller transitions; dipole strength; neutron-capture).

A variety of light-ion induced direct reactions, such as elastic scattering of type (p, p), (α, α), inelastic scattering of type (p, p'), (α, α'), charge exchange reactions of type (p, n) , (d, ^{2}He), quasi-free scattering of type (p, 2p), (p, pn), (p, p + cluster), and transfer reactions of type (p, t), (p, ^{3}He), (p, d), (d, p), serve in such investigations. The relevant physics observables (energy and momentum transfer) need to be extracted from the kinematical quantities (recoil momentum and kinetic energy). Since the domain of low momentum transfer is of interest, extremely thin targets are requested, resulting in too low luminosities if external targets would be used. Likewise, due to their production mechanism, a large momentum spread and large emittance are inherent to the secondary ion beams which would deteriorate a measurement of the target-recoil momenta and kinetic energies if not counteracted.

These problems can be overcome using stored and cooled secondary beams of unstable nuclei interacting with thin internal gas-jet targets. This method provides

- high luminosities due to the continuous beam accumulation and beam recirculation,
- high resolution detection of low-energy recoil particles due to beam cooling, and thin targets,

- low-background conditions due to pure, windowless H, He, etc. targets,
- the possibility to reduce beam components populating isomeric states.

For studies with the EXL apparatus, the FAIR storage rings are operated in the following scheme: Secondary beams of unstable nuclei are produced by fragmentation or fission reactions, are separated in the Super-FRS fragment separator, and then accumulated in the Collector Ring (CR). Bunch rotation and stochastic precooling improves the beam quality to a level already sufficient for most of the envisaged measurements. If required, fast beam energy variation (down to tens of MeV per nucleon) is achieved in the RESR ring. Finally, the beam is transferred into the NESR ring where the measurement is performed. Continuous accumulation of the beam in the NESR can be provided by longitudinal stacking simultaneously to the measurement, and electron cooling compensates an emittance growth from beam-target interactions. Since beam-cooling time constants of around one second are expected at FAIR, sufficient luminosities for reaction experiments with stored beams can be reached for unstable nuclei with nuclear lifetimes of several hundreds of milliseconds or above, sufficient production rates supposed. Depending on the specific reaction to be studied, luminosities in between 10^{24} and 10^{28} s^{-1} cm^{-2} are required since the relevant cross sections range from tens of μb sr^{-1} to hundreds of mb sr^{-1}. Expected luminosities over the full chart of nuclei are shown in Figure EX.1.

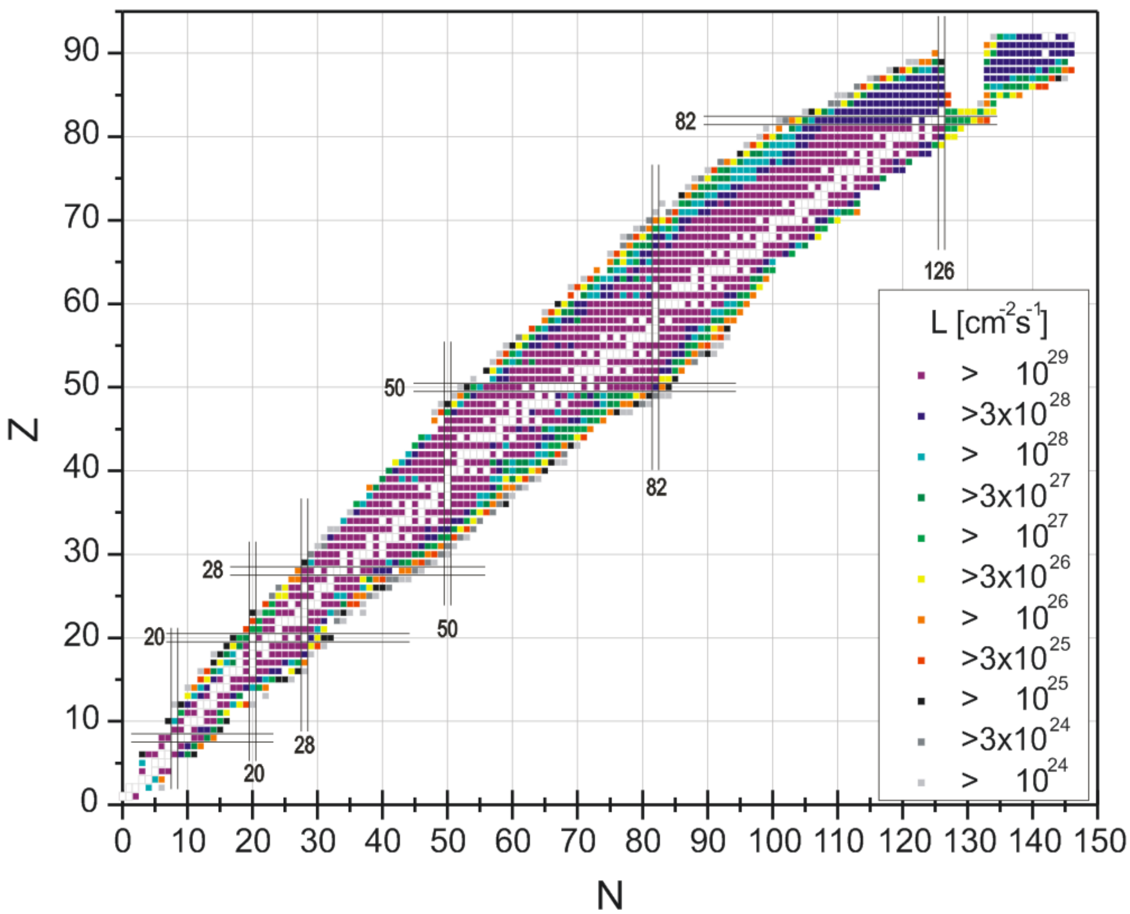

Figure EX.1: *Luminosities expected at the FAIR NESR storage ring using an internal hydrogen gas-jet target of 10^{14} atoms/cm^2.*

Within the EXL Technical Proposal, the design of a complex detection set-up was investigated with the aim to provide a highly efficient, high-resolution universal detection system, applicable to a wide class of reactions (see Figure EX. 2). The apparatus is foreseen being installed at the internal target of the NESR storage cooler ring. Since a fully exclusive measurement is envisaged, the detection system includes

- a Si-strip and Si(Li) detector array for recoiling target-like reaction products, completed by slow-neutron detectors, and a scintillator array of high granularity for γ-rays and for the total-energy measurement of more energetic target recoils ,
- detectors in forward direction for fast ejectiles from the excited projectiles, i.e., for neutrons and light charged particles,
- heavy-ion detectors for the detection of beam-like reaction products.

All detector components will practically cover the full relevant solid angle and have detection efficiency close to unity.

Major research and development work is required for the design and technical implementation of the target-recoil detector; it will be the most challenging task of the present research project. In particular, the detector components need to fulfil strong demands concerning angular and energy resolutions, detection thresholds, dynamic range, granularity, vacuum capability, etc., partly not available from standard detection systems. A second major task is to achieve high densities in the internal gas-jet target, of the order of 10^{14} - 10^{15} atoms/cm^3 or above with a well localised interaction zone. Presently existing devices need to be improved substantially, also new lines of developments are followed, e.g. towards liquid micro-jet or droplet targets. In testing prototype detectors under realistic conditions up to a full feasibility demonstration of the entire concept, the existing ESR storage ring at GSI will be very instrumental and be utilized to full extent. First test runs at the ESR were already carried out very recently.

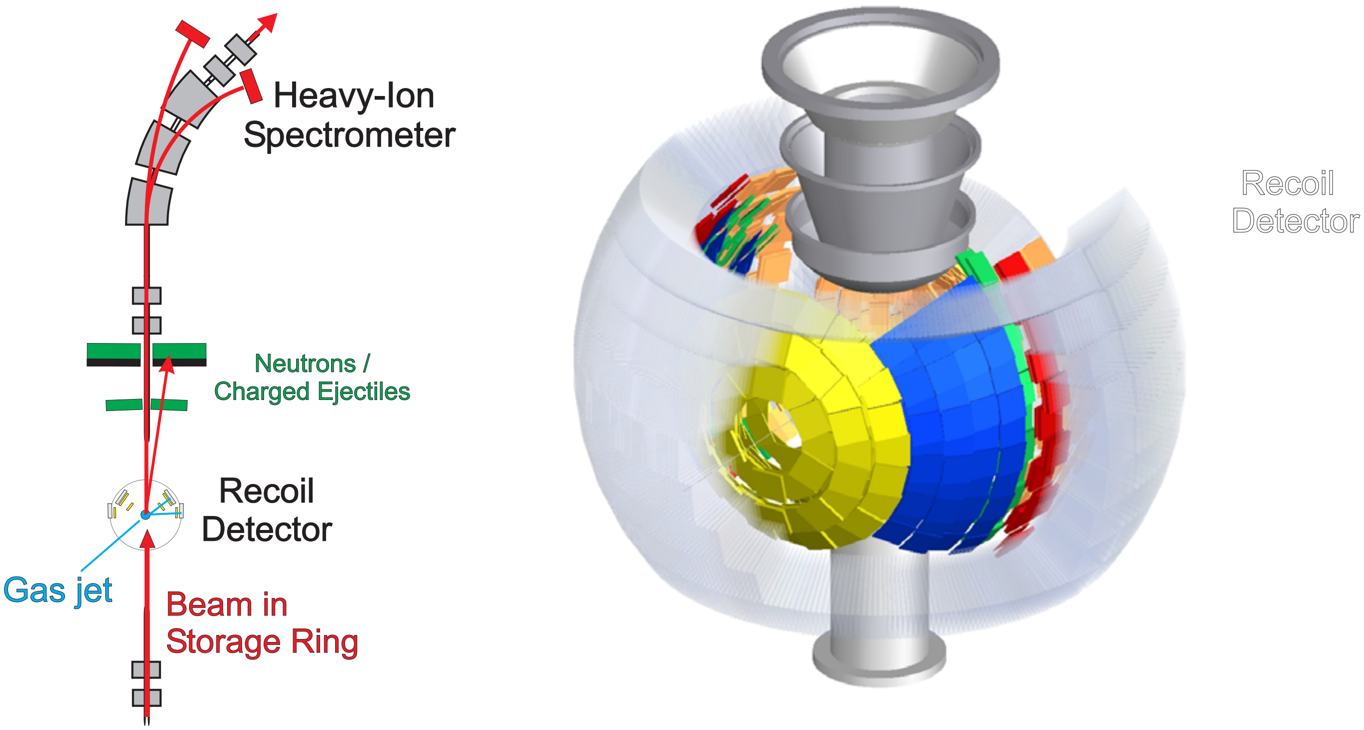

Figure EX.2: *Schematic view of the EXL detection systems. Left: Set-up built into the NESR storage ring. Right: Target-recoil detector surrounding the gas-jet target.*

An international collaboration was formed with more than 100 members and 30 institutions. The collaboration is structured in a number of boards and work groups. Several collaboration, work group, and board meetings were held. Early in 2005, a technical proposal was submitted to the FAIR NUSTAR-PAC. On the basis of the PAC recommendations, the FAIR-STI qualified the EXL proposal as 'part of the basic research program as defined by the CDR' and as 'part of the core experimental facility of FAIR'. The implementation of the EXL project is subdivided into two phases which coincide with the first two phases of the FAIR stage plan. The EXL detector setup will be ready for first measurements as soon as the Super-FRS and the CR and NESR storage rings are in operation at FAIR.