Letter of Intent for

Exotic nuclei studied in light-ion induced reactions at the NESR storage ring

EXL Collaboration

April 06, 2004

Abstract

We propose to study the structure of unstable exotic nuclei in light-ion scattering experiments at intermediate energies. The EXL objective is to capitalize on light-ion reactions in inverse kinematics by using novel storage-ring techniques and a universal detector system providing high resolution and large solid angle coverage in kinematically complete measurements. The apparatus is foreseen being installed at the internal target at the NESR storage-cooler ring of the international Facility for Antiproton and Ion Research (FAIR).

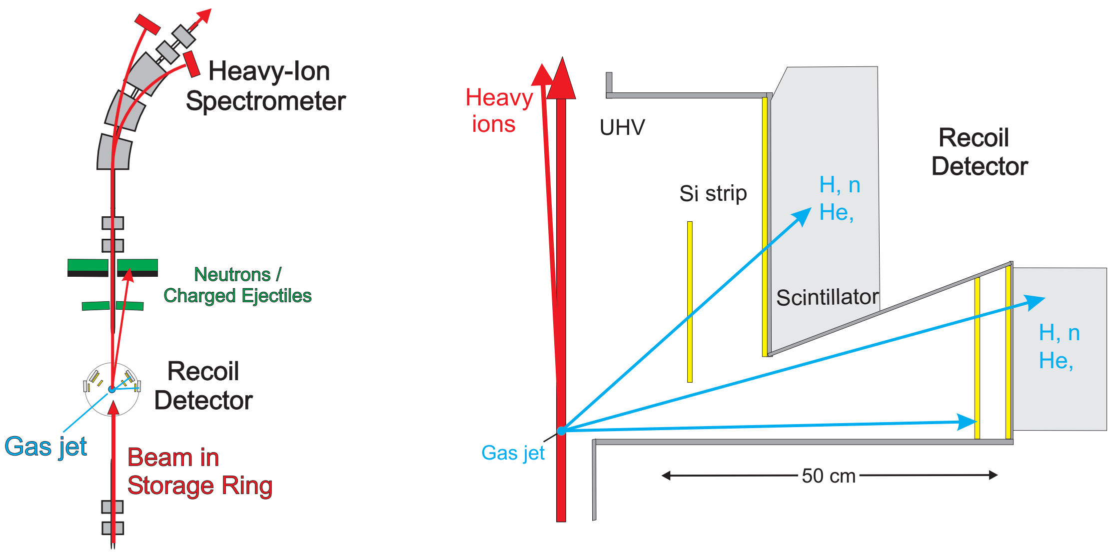

Fig. 1: Schematic view (cross section) of the EXL detector system.
Left: Setup built into the NESR storage ring. Right: target-recoil detector.

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1. Physics case

1.1 Research objectives

Light-hadron scattering has provided a wealth of nuclear structure information for stable nuclei. Usually, such reactions are performed in ‘normal kinematics’, i.e., where intermediate-energy light ions are scattered from a fixed target consisting of stable nuclei. Secondary beams of exotic nuclei produced by in-flight fragmentation of primary heavy ion beams can be scattered from stable light target nuclei using the so-called ‘inverse kinematics’. Because of luminosity constraints and the specific circumstances of inverse kinematics, these scattering experiments could not be applied to a similar extent as the normal scattering experiments. Up to present, such investigations are restricted to light exotic nuclei and only with limited applications even there. A wide and unique discovery potential would emerge if such reactions can be studied using exotic nuclei far from the valley of stability.

Using inverse kinematics on light stable target nuclei, essential contributions can be made to most important nuclear structure and nuclear astrophysics issues discussed in the context of exotic nuclei, in particular for neutron-rich nuclei, towards which the current thrust is being directed. Here, we just name a few interesting topics:

- The unusual matter distributions in neutron-rich nuclei near the neutron drip line, exhibiting neutron halos and skins;
- the shell structure in nuclei of extreme proton-to-neutron asymmetry leading to a disappearance of the known magic numbers and, in turn, to the appearance of new shell gaps;
- deformations different for the proton and neutron distributions giving rise, as a consequence, to new collective modes;
- electric and magnetic giant resonances with strength distributions totally different from those known in stable nuclei;
- in-medium interactions in proton-neutron asymmetric and low-density nuclear matter.

Light-hadron scattering in the intermediate-to-high energy regime (here, typically bombarding energies of 100 – 700 MeV/nucleon are considered) is a well-established method in nuclear-structure physics; its application to beams of exotic nuclei is indispensable. The great nuclear structure potential of light-hadron scattering arises from the fact that, by means of a proper choice of the probe, transitions can selectively be induced (e.g. emphasizing or excluding spin and/or isospin transitions), and the form factors are sensitive to the transition multipolarity. Polarized targets allow to be selective not only on the orbital angular momentum, l, but also on the total angular momentum, j, and therefore gives extra sensitivity on the spin-orbit part of the potential.

A survey of the nuclear structure information, which can be gained from the type of measurements as described here, and as far as relevant with regard to unstable nuclei, is provided in tabular form (Table 1); details on specific reactions are outlined subsequently.

The physics case and the basic experimental scheme addressed in this Letter of Intent was already outlined in the Conceptual Design Report for the International Accelerator Facility for Beams and Antiprotons [CDR01] to which refer including the references cited therein.

Table 1: Nuclear structure information from intermediate-energy scattering off light nuclei.

Method (reactions)	**Physical observables**	**Related effects in exotic nuclei**
elastic scattering (p,p); (^{4}He,^{4}He);	nuclear matter radii and distributions	halo; neutron skin; central density; optical potential
inelastic scattering (p,p');($\bar{p}$,p'); (^{4}He,^{4}He')	surface collective states; electric giant resonances; isovector magnetic excitation for (p,p'); analyzing powers	bulk properties in N-Z asymmetric matter; proton/neutron deformation; nuclear compressibility; threshold strength; soft modes
charge exchange (p,n); (d,^{2}He); (^{3}He,t)	spin-isospin excitations; Gamow-Teller; spin-dipole resonance	(stellar) weak interaction rates; spin excitations; neutron skin
transfer reaction (p,d); (d,^{3}He); (p,t); (d,p)	Spectroscopic factors; Single particle (hole) states; pair transfer	single-particle structure; spin-orbit; pairing interaction
quasi-free scattering (p,2p);(p,np); (p,p ^{4}He)	single-particle spectral function; cluster knockout	single-particle structure; nucleon-nucleon and cluster correlations; in-medium interactions

1.1.1 Elastic scattering

Elastic scattering, such as (p,p), (α,α), etc. gives access to nuclear potentials and to the size and radial shape of nuclei. Intermediate-energy elastic proton scattering is a standard tool in measuring nuclear matter distributions in stable nuclei and it was already used to determine the nuclear matter density distributions of light exotic nuclei [Alk02]. It will serve in future investigations of skin and halo structures in heavier nuclei far off stability. Fig. 2 demonstrates the high sensitivity of the method as proposed here. The simulation calculation was performed adopting predicted nuclear matter distributions for Sn isotopes [Hof01], applying the Glauber multiple scattering theory, and adopting experimental conditions as expected for the proposed scheme. Keeping in mind that the matter radii of the two ^{120,132}Sn nuclei differ only by 0.13 fm, the precision that can be achieved for r.m.s radii is evident. Obviously, higher moments of the matter distribution such as related to the surface diffuseness, the central density, etc. can be deduced from the analysis of the measured differential cross section.

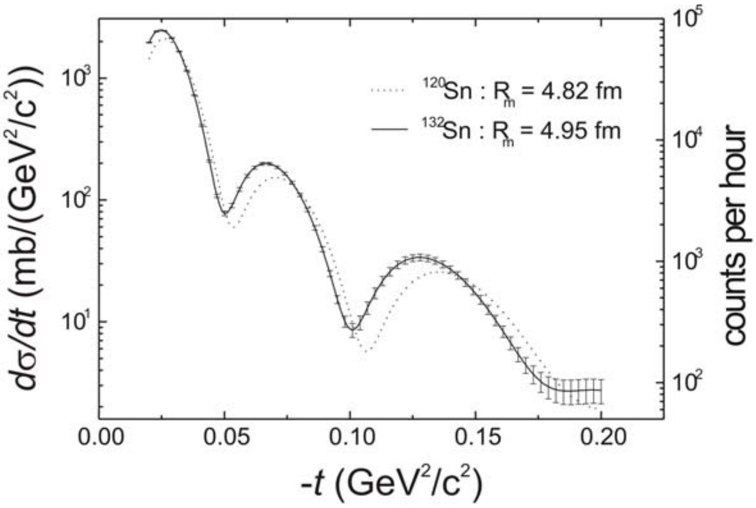

Fig. 2: Differential cross sections dσ/dt versus the four momentum transfer squared -t for proton elastic scattering on ^{120}Sn (dotted line) and ^{132}Sn (solid line) at E = 740 MeV per nucleon resulting from a simulation calculation. The scale displayed on the right-hand axis of the figure and statistical error bars in case of ^{132}Sn correspond to typical experimental conditions as expected at the NESR and a luminosity of 10^{28} cm^{-2} s^{-1}.

1.1.2 Inelastic scattering

Light-ion inelastic scattering allows to trace the evolution of nuclear shape and collective motion over the chart of nuclei. The excitation of low-lying collective states by proton or α-particle scattering probes essentially the isoscalar transition density. By combining with electromagnetic excitation, the proton/neutron content of the transition density can be deduced and thus proton and neutron deformations be separated which may differ substantially from each other in exotic nuclei.

A large proton-neutron asymmetry in a nucleus as well has significant influence on bulk collective motions, i.e., on the strength distributions of giant resonances, and may lead, for instance, to a vibration of loosely bound valence neutrons forming a neutron halo against the remaining core nucleons. Proton inelastic scattering played an essential role in the discovery of spin-excited giant resonances, like the M1 mode, while α-scattering is widely used to study isoscalar modes, such as giant monopole (GMR) or quadrupole resonances [Har01]. A study of the GMR in neutron-rich unstable nuclei will give access to the compressibility of proton-neutron asymmetric nuclear matter. The angular distribution of the GMR in inelastic α scattering is centered at zero degree center-of-mass angle; it is an essential feature of measurements in inverse kinematics, in conjunction with gas jet targets in a storage ring, that these very small center-of-mass angles can be covered.

1.1.3 Transfer reactions

One- or few-nucleon transfer reactions such as (p,d), (p,t), (d,^{3}He), (p,^{3}He), (d,p), etc. provide information on the single-particle neutron and proton structure in nuclei far off stability. Occupation numbers and spectroscopic factors can be deduced. The investigation of single-particle (hole) states and two-particle (hole) states, in particular in the vicinity of unstable doubly magic nuclei, delivers information on effective interactions in these off-stability nuclei. A comparison of cross sections for one- and two-nucleon pickup reactions allows studying nucleon pair correlations. Spectroscopic data and capture cross sections via indirect methods (such as (d,p) neutron transfer reactions) for nuclei participating in the astrophysical r- and rp-processes are essential in understanding the nucleosynthesis pathways. Due to momentum matching criteria for the transferred particle(s) such investigations are most favourably performed at incident energies of about 10-30 MeV per nucleon. In consequence, such measurements require decelerating the ion beams stored in the rings [Ege97]. Present or future ISOL facilities with re-accelerated beams of unstable isotopes may provide higher luminosities, in particular for neutron-rich fission fragments; the proposed scheme here may have advantages in case of shorter-lived isotopes and for neutron-deficient isotopes.

1.1.4 Charge-exchange reactions

The Gamow-Teller (GT) transition is the most basic spin-isopin excitation without angular momentum transfer and plays as an important role in the allowed β-decay caused by the weak interaction. The initial step of the hydrogen fusion reaction leading to nucleosynthesis in stars, the electron-capture reactions leading to stellar collapse, and supernova formation are mediated by the GT transition. A basic understanding for all these processes requires reliable knowledge of the GT strength distribution in nuclei far from the stability line within a large excitation energy range.

Spin-isospin transitions with higher multipolarities are equally important in nuclear processes that happen under extreme conditions, like in a supernova. A study of these excitations in the unstable nuclei involved in such nuclear processes is indispensable. Furthermore, there is a correlation between the cross section of the spin dipole resonance and the neutron-skin thickness of nuclei [Kra99]; this latter quantity is important for constraining the density dependence of the symmetry energy of nuclear matter. Intermediate-energy secondary beams allow studying spin-isospin excitations in unstable nuclei using charge-exchange reactions, such as (p,n), (d,^{2}He), and (^{3}He,t) in inverse kinematics. The kinematically complete experiments (see below) should even enable a substantial suppression of competing background reaction channels, prohibited in the earlier inclusive-type of investigations on stable nuclei.

The use of polarized targets in (^{3}He,t) reactions can be of great help to disentangle the information on different spin-dipole excitations, as well as for the identification of the isovector M1 and ΔL=1 spin-flip modes in sd- and fp-shell nuclei, relevant in the astrophysical context.

1.1.5 Quasi-free scattering

Quasi-free scattering has proven to be one of the most direct and powerful ways of investigating the single-particle properties of a nucleus, such as the separation energies and momentum distributions of nucleons inside the nucleus, in particular for inner-shell orbits [Kit85]. Quasi-free scattering data are also employed to study the effect of the medium on the underlying nucleon-nucleon interaction; in case of exotic nuclei, the environment of proton-neutron asymmetric matter and of low density in extended nuclear surfaces are of particular interest. The quasi-free scattering physics program at the NESR storage ring will focus on several distinct, but related, key experiments:

The single-particle structure of light and medium-mass neutron-rich nuclei is investigated using (p,2p) and (p,pn) reactions. Key nuclei will be nuclei near neutron (sub-)shell closures such as ^{56}Ni (N=28), ^{68}Ni (N=40), and towards ^{78}Ni (N=50); the chains of argon and tin isotopes are also of particular interest. Other investigations focus on the effects in low-density matter, i.e., in neutron halo nuclei and in nuclei exhibiting extended neutron skins.

Clustered structures in exotic nuclei are studied using cluster knockout reactions. Close to the neutron drip line it is predicted that the ground-state structure of nuclei may adopt a highly clustered state. (p,pCluster) knockout reactions may provide a method for the determination of the cluster spectroscopic factor. The evolution of clustering from stability to the drip line is a key test of the theoretical predictions.

1.2 Competitiveness

Until now and presently, a number of experimental attempts were and are undertaken at various laboratories to utilize light hadron scattering with rare-isotope beams. Proton elastic and inelastic scattering, knockout and transfer reactions at low-to-intermediate energies were performed at GANIL (France), GSI (Germany), JINR (Russia), MSU (USA) and RIKEN (Japan). Elastic scattering experiments have been used for matter radii and distribution measurements of light halo nuclei such as ^{6,8}He or ^{11}Li, inelastic scattering experiments provided data on the excitation of bound excited states. Heavy-ion induced knockout reactions have been used to measure spectroscopic factors. In contrast to quasi-free proton scattering, such knockout reactions probe, however, only the asymptotic part of the (valence) nucleon wave function. As far as giant resonances in exotic nuclei are concerned, the present-day technique relies on heavy-ion induced Coulomb excitation, which is restricted, however, to the nuclear dipole response. Light-hadron scattering, together with electron scattering, the standard tools in that respect, could not yet be used.

So far, light-ion scattering measurements were performed for light unstable nuclei only and were of more inclusive type. For heavy exotic nuclei, measurements at low momentum transfer require a different experimental technique. The originality of the present project arises, in essence, from the following aspects:

- The project represents, worldwide, a first attempt to implement nuclear reaction studies with unstable exotic nuclei utilizing heavy-ion storage rings. Windowless thin internal targets are a key prerequisite for studies at low momentum transfer.
- The detector system under consideration (see below) is universal in the sense that it allows to handle a wide class of different nuclear reactions and thus to address numerous physics questions. Technologically, the required Ultra-High-Vacuum compatibility is most demanding and requires non-standard solutions of the detector design.

- The detector system provides the capability of fully exclusive kinematical measurements. This is of interest not only in experiments with exotic nuclei, but also with stable beams. Conventional techniques in the context of light-hadron scattering are of inclusive type to a large extent.

The EXL physics program has some overlap with that proposed in the R3B Letter of Intent as far as light ion scattering is considered there, in particular with regard to quasi-free scattering. For nuclear lifetimes around or below one second, where beam cooling (see below) is not fast enough, measurements at the external target are of preference. For longer lifetimes, cooling and beam accumulation in the storage ring should provide superior conditions.

2. The EXL Detector

2.1 Experimental concept and requirements

For the studies listed in Table 1, exotic nuclei are provided as a secondary beam to be scattered off the light target nuclei (e.g., p, d, ^{3}He, ^{4}He). For a number of studies, e.g., that of the GMR or GT strength, the relevant nuclear structure information is obtained from form factors measured at rather moderate or even small momentum transfer, i.e., at c.m. angles around zero degree. Inverse kinematics implies that the light target nuclei emerge from the reaction with extraordinarily low kinetic energies, around and even below 1 MeV (see Fig. 3). Momentum and energy transfer need to be extracted from the kinematical quantities of the light target recoil, because of the high projectile energy and because of the fact that the heavy projectile-like fragment often disintegrates. In order to extract reliable information on excitation energy (required resolution ~ 0.1 MeV) and on center-of-mass scattering angle (required resolution: a few mrad), kinetic energy and scattering angle of the target recoil in the laboratory frame need to be measured down to a resolution of 100 keV and 1 mrad, respectively.

Additional mandatory prerequisites are a) a small spread in kinetic energy (T_b) of the secondary ion beams ($\delta T_b/T_b \sim 10^{-4}$) and b) a low target thickness in order to let the target recoils escape and to keep small-angle multiple scattering on a tolerable level (typically, the effective target thickness, including windows, needs to be below 1 mg/cm^2). Low target thickness yields low reaction luminosities; transferring the beam into a storage ring and thus benefiting from its re-circulation can overcome this problem.

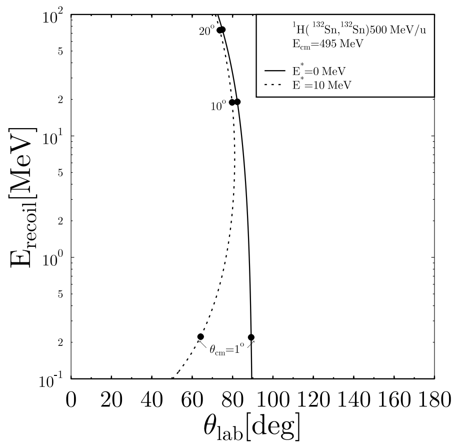

Fig. 3: Kinetic energy of recoiling ^{1}H target nuclei versus laboratory scattering angle for (in)elastic scattering of a ^{132}Sn beam of an energy of 500 MeV per nucleon. Respective center-of-mass angles are indicated.

The CR-RESR-NESR storage-ring complex planned at the Facility for Antiproton and Ion Research (FAIR) provides optimal conditions for inverse light-ion scattering experiments, the most relevant features are:

- Luminosities even above 10^{28} cm^{-2} s^{-1} can be achieved, see Table 2; further developments on internal targets may even yield improved values. Cross sections of 0.1 – 100 mb/sr are typical for reactions as listed in Table 1 and thus very reasonable reaction rates are expected. The windowless internal target avoids background reactions.
- Stochastic pre-cooling in the CR combined with electron cooling in the NESR provides stored beams of excellent quality with regard to emittance and momentum spread, matching the requirements (see above) for kinematical measurements of the target recoils.
- The energy of the stored beam is variable within a wide range up to 740 (depending on magnetic rigidity even up to 820) MeV per nucleon. For isotopes with a lifetime of at least seconds deceleration down to tens of MeV per nucleon becomes feasible without substantial deterioration of beam intensity and quality. This wide range in beam energy suits well to the experiments under discussion.
- Secondary beams produced in fragmentation or fission reactions may have sizeable contaminants of nuclei in long-lived isomeric states. Measuring during distinct time intervals after injection into the ring allows disentangling such beam components (an interesting scheme of separating isomeric beams by a beam-scraping technique is proposed in another Letter of Intent to FAIR).

The main objectives of the experimental scheme as proposed in this Letter of Intent are a) optimizing the luminosity, b) providing a high-resolution detection system with nearly full solid-angle coverage and detection efficiency, c) providing a detector setup for kinematically complete measurements, thus covering simultaneously all reaction channels of interest.
At present, only a first concept of the detection system can be given; the participating groups will work out the final conceptual and technical design subsequently, see section 3.4 .

Table 2 Expected luminosities in the NESR storage ring adopting an internal target density of 10^{14} hydrogen atoms/cm^2 and for a beam energy of 740 MeV per nucleon.

Nucleus	Rate after production target [1/s]	Lifetime including losses in NESR [s]	Luminosity [cm^{-2} s^{-1}]
^{11}Be	2×10^9	36	$> 10^{28}$
^{46}Ar	6×10^8	20	$> 10^{28}$
^{52}Ca	4×10^5	12	2×10^{26}
^{55}Ni	8×10^7	0.5	5×10^{26}
^{56}Ni	1×10^9	3800	$> 10^{28}$
^{72}Ni	9×10^6	4.1	1×10^{27}
^{104}Sn	1×10^6	51	2×10^{27}
^{132}Sn	1×10^8	93	$> 10^{28}$
^{134}Sn	8×10^5	2.7	3×10^{25}
^{187}Pb	1×10^7	34	2×10^{28}

2.2 Detector components and environment

The main ingredients of the experimental scheme are briefly described as follows.

2.2.1 Stored and cooled beams

Secondary beams are transferred from the fragment separator (Super-FRS) to the collector ring (CR) at a fixed energy of 740 MeV per nucleon. The main task of the CR is the efficient collection and stochastic pre-cooling to a relative momentum spread around 10^{-4} and an emittance of 1 mm mrad within a cooling time of a few hundreds of milliseconds. The beam

quality can be further improved by means of electron cooling in the new experimental storage ring (NESR). Electron cooling serves as well to compensate the beam heating due to its interaction with the internal target. Using rf cavities inside the RESR, a third storage ring in between the CR and NESR, the beam can be decelerated thus providing a variable energy (rf cavities are also installed at the NESR). For example, only about 1 second is needed to decelerate from 740 to 100 MeV per nucleon. This procedure results in an increase in emittance that needs to be counteracted by electron cooling.
Luminosity at the internal target is gained due to the circulation frequency (~ 1 MHz) of the stored beam. An important option to achieve optimum luminosity is fast beam stacking. The limitation for this scheme is given by the beam lifetime that is determined by the nuclear lifetime and losses due to atomic charge exchange processes in the internal target, in the residual gas in the ring, and in the electron cooler. Some representative examples are given in Table 2. Multi-charge state operation of the NESR may increase the effective beam lifetime.

2.2.2 Internal target
Gas/cluster-jet or pellet targets with densities of 10^{14} - 10^{15} hydrogen or helium atoms/cm^2 are envisaged (targets of heavier elements can be provided as well). Such densities are within reach on the basis of present-days knowledge and may still be improved. Cluster-jet targets, for instance, exist at the ESR (GSI) and at the CELSIUS (TSL) storage rings; a pellet target was developed at the CELSIUS ring. Using thin-foil or fiber targets can reach higher densities; it needs to be explored, however, if higher densities are compatible with the demands on beam quality (deteriorated by multiple passage through the internal target). The energy loss in passing a thin-foil target could be compensated by rf cavities; the NESR rf cavities would allow to eliminate a few keV energy loss per nucleon per single passage. Whether the degradation of beam momentum spread can be tolerated depends on the specific experiment and the optimum target thickness has to be found from simulation studies. At low momentum transfer, the low target recoil energies prohibit a vertex reconstruction. The interaction point is sufficiently defined transversally by the beam diameter; longitudinally along the beam direction, however, the extension of the jet target determines the spatial accuracy of the interaction point. Developments are required to minimize the jet diameter to about 1 mm. Alternatively, a diaphragm narrowing down the effective interaction zone along longitudinal direction could be used, but reduces the effective luminosity. It will also be considered if polarized targets can be implemented. Polarized ^{3}He-targets with polarizations of up to 75% are available today (W.Heil, Mainz) and internal polarized ^{3}He targets have been used at several laboratories in the past (NIKHEF, Bates, Hermes).

2.2.3 Target recoil detector
The main requirements are high resolutions for momentum and energy of the recoiling target nuclei and a low detection threshold. A very schematic view of the target recoil detector is shown in Fig. 1. At high momentum transfer (forward angles), tracking of the target recoil is feasible, but prohibited at small momentum transfer.
Two layers of radiation-hard (double-sided) Si strip detectors measure position and kinetic energy and time of flight. For low recoil energies not allowing for tracking, the accuracy of the measured scattering angle depends on the extension of the gas-jet target along beam direction (see above) and the distance between target and detector. In that case, i.e., at recoil angles near 90^o, the target-detector distance will range in between 0.5 m to 1 m; detection thresholds around 100 keV are required. At more forward angles, the target recoils can be tracked in two layers of Si detectors that can gradually be placed closer to the jet target. The position resolution of the Si detectors has to be adjusted to the required angular resolution of about 1 mrad requiring 100 - 200 μm pitch. Eventually, the recoil ions will be stopped in organic scintillation detectors, e.g. (cooled) CsI crystals, serving also other purposes (see below). The target recoil detectors are thus operated as (Δ)E-(Δ)E-E telescopes. The optimum thickness of each of the three detectors varies with recoil angle and more detailed simulations for different reaction scenarios are required for a final design. At least the first layer of the target recoil detector needs to be operated under the ultra-high vacuum (UHV) conditions of

the storage ring, imposing severe requirements upon the detector material. Groups working at CELSIUS gained experience with an UHV compatible Si detector array [CHICSI]. Tests with UHV compatible Si detectors are currently also performed at the ESR at GSI. The Saclay group has built a large array of Si-Si(Li)-CsI telescopes with integrated signal processing, with characteristics rather similar to the recoil detector here [MUST]. The UK groups have built a Si strip detector system for direct reaction studies [TIARA]. Energy resolutions of about 50 keV, time-of-flight resolutions of 200 ps, and a detection treshold of 100 keV seem achievable.

It is intended to subtend the forward hemisphere in a cylindrically symmetric (except for provisions for the internal target) geometry. It is still under discussion to which extend the backward hemisphere should be covered as would be required if transfer reactions of type (d,p) are considered. Detailed simulation studies will be performed in order to find the optimum detector characteristics and geometry, taking economical aspects into consideration.

Electrons released (with energies up to MeV's) from the gas target will be by orders of magnitude more abundant than recoil ions and need to be transported out of the recoil-detector area by a magnetic field along beam direction.

2.2.4 Gamma-rays and slow neutrons

The inorganic scintillation detectors (see above) serve as well for detection of gamma-rays emitted from the excited projectile residue. A rather high granularity is required in order to cope with gamma-ray Doppler broadening effects; an energy resolution of about 2 % is envisaged. A CsI barrel of 144 elements with a geometry similar to the one considered here is is existing at GSI. For some experiments, it is under discussion to install Ge detectors with better resolution such as an array composed out of AGATA detector modules, see [LEB04]. Likewise, a dedicated fast organic scintillation detector for precision neutron measurements in (p,n) reactions is proposed, prototype detectors are already tested.

2.2.5 Forward spectrometer

Mass and charge of the heavy projectile fragment needs to be identified and its momentum measured. For that purpose, it is foreseen to utilize bending magnets of the storage ring for the analysis of the fragment magnetic rigidity in combination with energy loss, time-of-flight, and position measurements; see Fig. 1 for a schematic view. It is envisaged to achieve a (transversal and longitudinal) momentum resolution of the order of 10 – 50 MeV/c. Preliminary considerations indicate that a corresponding value of $\Delta p/p \sim 10^{-4}$ can be achieved, but detailed ion-optical studies need to be performed. Excitation of the projectiles into the continuum leads to particle emission, i.e., essentially neutrons and light charged particles around beam rapidity. The envisaged detector scheme comprises their position and time-of-flight measurements using fast scintillators, in case of neutron detection involving converter material or, alternatively, appropriate inorganic scintillation material. Accurate position measurements for charged particles are achieved in drift chambers. It is intended to exploit recent developments towards ultra-fast phototubes and fast scintillating material for time-of-flight resolutions below 100 picoseconds; depending on the achievements, a flight path of 5 – 10 meter will be needed in order to gain a momentum resolution below $\Delta p/p \sim 10^{-2}$ with a detector compact array. This would allow reconstructing the excitation energy of the projectile residue to an accuracy of about 1 MeV by means of the invariant-mass method, thus delivering information redundant, although less accurate, to that obtained from the target-recoil kinematical measurement.

2.2.6 Trigger and data acquisition

Electronic detector readout schemes, trigger systems, and data-processing procedures need to be developed hand-in-hand. The high granularity of the position-sensitive detectors for the target recoils demands on-board signal processing; it is explored whether customized wafers are available, but the demand of operation under UHV condition may require dedicated developments. The fast timing measurements for the projectile and its ejectiles demand the design of high-resolution timing circuits.

Given the luminosities and total interaction cross sections, nuclear reaction rates hardly exceed 10^5 per second; fast coincidence requirements among the various detector components reduce the trigger rate down to 10^4 s^{-1} or less. Thus a conventional scheme of transferring pre-selected data to a higher-level hierarchy or directly to storage could be implemented. More advanced schemes, nevertheless, are considered where signals from all detectors are autonomously detected, pre-processed, and buffered by FPGA, DSP and CPU based computation boards. Higher-level trigger selections may thus be made on-line in the cross-linked boards. Finally, only relevant and preprocessed information, synchronized by timestamps, is transferred. In such developments, one may benefit from the developments that are currently started within the FutureDAQ Joint Research Activity from the I3HP Initiative of the 6th EU framework (2004-2006) for the CBM, PANDA and COMPASS experiments. As indicated in the introduction to the NUSTAR letter of intents, it is envisaged to develop a common basic DAQ scheme at the SUPER-FRS facility.

2.2.7 Physics performance

A simulation software will be developed on the basis of which feasibility demonstrations for the specific reaction studies of interest can be provided in a conceptual design report. In parallel, prototype detectors will be built and tested and the electronic read-out techniques will be developed. An experimental storage/cooler ring (ESR) for heavy ions is at this moment operational at GSI which is linked to the FRS radioactive-beam facility. The ESR will be instrumental in developing the EXL detector, in performing feasibility studies and first experiments. It should be noticed that the EXL concept provides the means for kinematical fully complete measurements, under most circumstances not achieved in conventional light-ion scattering experiments with stable target nuclei. It may thus add substantially to the physics information derived from light-hadron scattering experiments applied to *stable* isotopes and scientifically valuable experiments can already be performed at the ESR.

2.2.8 Synergy with other Letter of Intent

The NUSTAR Letter of Intent (LoI), aside from EXL, comprises LoI on external target (R3B LoI [R3B04]) and on electron scattering experiments (ELISe LoI [ELI04]). Evidently, there are common interests as far as the physics goals are concerned. The R3B LoI includes light-ion scattering complementing the storage ring experiments discussed here, covering the part of large momentum transfer. A target recoil detector, although of different specification, is required as well and it is envisaged to develop a common electronic read-out scheme. In case of electron scattering at the electron ring intersecting the NESR [ELI04] and for the proposed antiproton-ion collider [PBAR04], a forward spectrometer for the projectile fragments built into the NESR lattice is required, similar to the one discussed here. Both, from the common physics goals and similar development lines for subsets of the setups, a close collaboration among the participants of R3B, EXL and ELISe is most natural, and is manifested in the partial overlap in personnel.
Synergy with LoI's outside NUSTAR is evident as well: The internal target will be used by atomic physics groups (AP), these groups are in part also planning for a (UHV) detector system similar to the recoil detector and as well will use a fragment forward spectrometer; a close collaboration is envisaged and discussions were already started. To our knowledge, silicon tracker devices (here, the target recoil detector) are substantial devices in both the PANDA and the CBM LoI; PANDA is also aiming at high-density internal targets. a collaboration in particular on the read-out schemes should be achieved.

3. Implementation

3.1 Experimental area and radiation environment.

The EXL apparatus needs to be installed at one of the four straight sections of the NESR. Since reaction rates are low, no specific demands on radiation shielding beyond that needed for NESR operation seem to appear. Around the cluster-jet (or other) target, an area of 150 m^2 is requested , i.e., 5 m wide on each side of the beam line, 10 m downstream the beam, and 5 m upstream the beam. The height of the beam line above ground should be 2.5 m. Other groups will use the same NESR straight section as seen from the submitted LoI's. A first discussion with representatives of such groups resulted in the suggestion that only one target station together with a scheme of replacing the various setups including the internal target would be preferable over solutions with multi-target stations. In consequence, parking room for the detection systems in immediate neighborhood to the experimental area is needed, in the case of EXL about 100 m^2. This storage area should moreover serve for off-line detector testing and maintenance etc., and should have access independent from operation of the NESR (or other accelerator components) and thus sufficient radiation shielding. Space for on-line data taking (~ 150 m^2) and additional office space (~ 200 m^2) to host the collaboration during experiment should be provided; to some extent, it might be shared with other collaborations.

3.2 Cost estimate

Only a rough cost estimate can be provided (Table 3), based on a tentative design involving a target recoil detector of 3 x 10^5 Si strip readout channels and 0.2 m^3 CsI scintillation material (1200 photodiodes), a forward ejectile detector of inorganic scintillation material (0.4 m^3) plus charged particle detection, a forward heavy-ion spectrometer, and a jet target and UHV chamber.

Table 3. Preliminary cost estimate

Task	**Cost estimate** (kEuro)
Target recoil detector	
Si micro strip	1,600
CsI	850
Forward spectrometer	
Light charged particles	150
Inorganic scintillator (neutron)	1,100
Heavy ion detectors	100
Trigger electronics, slow control, data acquisition	200
Jet target, pumping units, vacuum chamber	1,200
Overhead (10%)	600
Total:	**5,800**

3.3 Organisation and responsibilities

All participating research teams have experience with regard to scientific or technological aspects addressed in this LoI and will participate according to their expertise and physics interests. Three of the participating institutes operate storage-cooler rings for hadrons or heavy ions (COSY at FZ- Jülich; CELSIUS at TSL, Uppsala; ESR at GSI, Darmstadt).

A Coordination Board (CB) will be formed out of representatives of the participating groups. At its next meeting, the CB will name the spokesperson and deputy of the EXL collaboration. The main duties of the CB are to monitor the progress of the project and the quality of the developments, to ensure the reporting procedure according to the demands of FAIR as well as publication of results, and to guarantee optimal communication between the participants and thus economical usage of the provided funding. For the monitoring purpose, the CB will request internal reports from the participants at regular intervals.

To guarantee that various components of the project are properly dealt with, working groups are formed, which are responsible for the different parts and report to the CB. Responsibilities for the various tasks are given in Table 4 as agreed upon in collaboration meetings so far, but should be considered as tentative, a final decision will be taken after the CB has been formed. External expert advice will be asked for when deemed necessary by the CB.

Table 4: Tasks and responsibilities.

Task	Group
Realistic physics scenarios and key experiments: - nuclear structure - nuclear (astroph.) reactions	 Madrid, Milano, GSI UK, UNIBAS
Physics/detector requirements	UK, Mainz, GSI
Storage Ring	GSI
Internal target	TSL , FZJ, GSI
Target recoil detector and UHV	CEA, UK, Mainz, FZJ, IPN, TSL, Lund, GSI
Gamma detector Low-energy neutrons	UK, TUM, GSI ATOMKI
Fragment spectrometer	GSI, TUM, Dubna
Forward ejectiles	GSI, Gatchina
Readout electronics, DAQ	CEA, UK, TUM, GSI

3.4 Time schedule

The implementation of the EXL detector and ancillary components involves various steps, the general time line of the project is as follows: the implementation phase covers a period of 6 years (2004 – 2009). The conceptual design of the detector system will be finalized end of 2004. The technical developments of the subtasks (e.g. improvement of internal targets, detector prototypes, electronics and read-out schemes) and test measurements will be performed until end of 2006 and a technical report is delivered. It is intended to show the proof of principle of all subunits until 2007 and subsequently realize the full system. According to present planning for FAIR, the ESR at SIS18 should remain operational until 2009. Thus, for a period of about two years, the EXL detector system (or major components of it) can be utilized for first experiments at the already existing storage ring. For such purposes, stable or near-stability beams will be used, in the latter case one benefits already from the SIS18 intensity upgrade by about one order of magnitude as planned for 2006/2007. At the new facility, the instrument proposed here can be fully exploited in experiments with stored beams of exotic nuclei much further away from the valley of stability.

3.5 Beam time considerations

A typical experiment requires about two weeks of beam; it may be estimated that the requests for EXL experiments add up to about two month per year. Storage and accumulation of ions followed by measurement phase allows sharing the beam with other experiments to some extent, and the effective beam request may thus reduce. A parallel antiproton program, however, is prohibited since for most of the experiments the full storage ring complex is needed. Only for experiments with long-lived isotopes (allowing for the longer period of electron cooling without stochastic pre-cooling), the secondary beam can be transported from the Super-FRS directly into the NESR.

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