RFQ injector A/Q = 7 for the production of exotic nuclei using fusion-evaporation and multinucleon transfer reactions

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Summary: Having a Q/A = 1/7 or 1/6 injector available as soon as possible is essential for S^3 to be competitive for heavy and super-heavy nuclei studies. A higher intensity can be obtained for the heaviest beams with an injector Q/A = 1/7 compared to 1/6, but will not benefit to S^3 in the medium term due to the limitations of the S^3 electric dipole. In the longer term, it is imperative to increase the variety of beams on offer for the long-term future of GANIL and SPIRAL2: radioactive beam production method different from fission, alternative to the CSS cyclotrons, and new associated instruments. An energy limitation of the injector Q/A = 1/7 compared to 1/6 is not prejudicial in this perspective, whereas the highest intensities of the heaviest beams are an advantage in the 1/7 case. This is illustrated with the case of multinucleon transfer reactions produced using a target-ion source followed by a post-acceleration. Such an experimental complex would make it possible to have competitive beams for a unique physics.

Fusion evaporation reactions

The interest for having an RFQ injector Q/A = 1/6 or 1/7 for the physics of rare events such as super-heavy nuclei has been pointed-out many times since the birth of the Spiral2 project. The main obstacle to the synthesis of super-heavy nuclei is **the exponentially decreasing production cross sections with the atomic number**; hence the need for the highest possible beam intensity. ^{48}Ca and ^{50}Ti beams are of paramount importance to produce SHE for Z>112. **In that case, the gain compared to a Q/A injector = 1/3 is of the order of a factor of 5 to 6[1].** Having a Q/A = 1/6 or 1/7 injector is imperative in order to be competitive with JINR/FLNR Dubna's SHE-Factory which will be in the short term the most performing complex in the world [SHEF]. The synthesis using the so-called « cold fusion » reactions from Z = 104 to Z = 113, which is realized by the collision of ions impinging on lead or bismuth targets, requires beams heavier than Ca-Ti, for which the gain in intensity is especially large when switching from Q/A =1/3 to Q/A=1/6 or 1/7. As well, such beams are very important to reach neutron-deficient nuclei in the ^{100}Sn region or heavier.

It is therefore essential that the new RFQ injector is available as soon as possible. It is also planned that exotic beams produced with S^3 will feed the low energy branch (LEB) and later in the medium term the DESIR experimental area. In this case, having the highest beam intensities is a considerable advantage in order to study the rarest nuclei.

Concerning the **fusion-evaporation reactions**, the heaviest beams (Xenon and beyond) are relevant only in inverse kinematics. This should be however considered with care since (i) the required S^3 beam rejection is not proven to be achievable in this regime (ii) the rigidity of the fusion-evaporation residues is too high for the S^3 electric dipole (currently limited to 12 MV).

[1] It should be noted that the performances quoted in this document are provided using a last-generation superconducting high-current ion source (e.g. VENUS or SECRAL type)

Multinucleon transfer reactions

Multinucleon transfer reactions were widely exploited in the 1980s using radiochemistry techniques for the study of transactinide nuclei [Kra15]. The technique was abandoned because it was not applicable for decay or in-beam spectroscopy (since the products were stopped in the thick target). There was a renewal of interest for multinucleon transfer reactions with the work of Zagrebaev and Greiner, predicting very attractive production cross sections **using the heaviest beam on the heaviest target**, and at angles close to zero degree [Zag11+13]. Indeed, compared to few nucleon transfer reaction studies that are traditionally performed at the grazing angle, this allows the interception of a much larger fraction of the products in a spectrometer or separator, which is the only way to make spectroscopy realistic. On the other hand, these reactions make it possible to synthesize neutron-rich nuclei, precisely those approaching the super-heavy island of stability, whereas they cannot be populated by fusion-evaporation reactions.

The feasibility of these experiments at small angles has only recently been proven with experiments at GSI SHIP [Dev19] and TASCA [Din18]. A new exploratory program lead by Irfu/DPhN is also on-going at the Argonne National Laboratory (ANL) [Fav19]. At GANIL, fairly intense U-beams are already available. The study of the multinucleon transfer reactions is envisaged using the large acceptance VAMOS spectrometer in its standard vacuum configuration [Ack17]. The gas-filled operation of VAMOS has been implemented and tested [Sch10] and could be used to perform similar studies as at GSI and the ANL gas-filled separators. **Definitely, these reactions must be considered as very promising, even the future for the synthesis and spectroscopy of heavy and super-heavy nuclei.**

Recent experimental studies using LISE [Ste18] showed that deep-inelastic reaction mechanism is also an effective mechanism to produce light neutron-rich nuclei not only at grazing angle but also at forward angles. It is a complementary way to the fusion evaporation reaction mechanism which can give access to proton-rich nuclei. In addition, multinucleon transfer reactions can be used to create neutron-rich isotopes of very heavy elements with $N \approx 126$ for studies of interest to the formation of the $A \approx 195$ abundance peak in the r-process, a region that can be hardly produced by other reactions: see e.g. [Sav20][Wat15].

Then the question of the respective performances of an injector Q/A = 1/6 compared to 1/7 can be raised. Both options have consequences in terms of maximum beam intensity and energy. As far as intensity is concerned, **there is a significant difference only for heavy beams such as Au, Pb, Bi, U. It is precisely these beams that are the most relevant to perform multinucleon transfer reactions. For U, the gain is very significant, by a factor of about 6 in favour of Q/A = 1/7** (Figure 1).

As far as beam energies are concerned, there will be a limitation of E_{max} of 6.3 - 7 MeV/u for an injector Q/A = 1/7 compared to E_{max} ~ 8.5 MeV/u for 1/6 (these number have to be consolidated during the study phase). This is not a limitation for fusion-evaporation reactions which are at the heart of the S^3 programme: these reactions are performed, whatever the mass of the beam is, around 5 MeV/u. On the other hand, there is a potential limitation for heavier systems using a heavy beam on heavy targets, for which the Coulomb barrier is higher. The energy has to be around 6 MeV/u to be in the quasi-elastic regime (0-10% above the Coulomb Barrier) or higher energy to be in the deep-inelastic regime. The beam can still be produced at the required energy by changing the charge state, but at the price of a lower intensity.

However, the electric rigidity of S^3 is again a problem: to take the example of the $^{238}U+^{248}Cm$ reaction at 7 MeV/u, the quasi-target nuclei have an electrical rigidity of about 34 MV, well above the 12 MV S^3 limitation. Also, the S^3 angular acceptance is limited to 50-70 mrad around zero degree, preventing the observation of the nuclei produced at large angles. Therefore, S^3 is not the best device to study such kinematics, and we think that they could largely benefit from a dedicated setup.

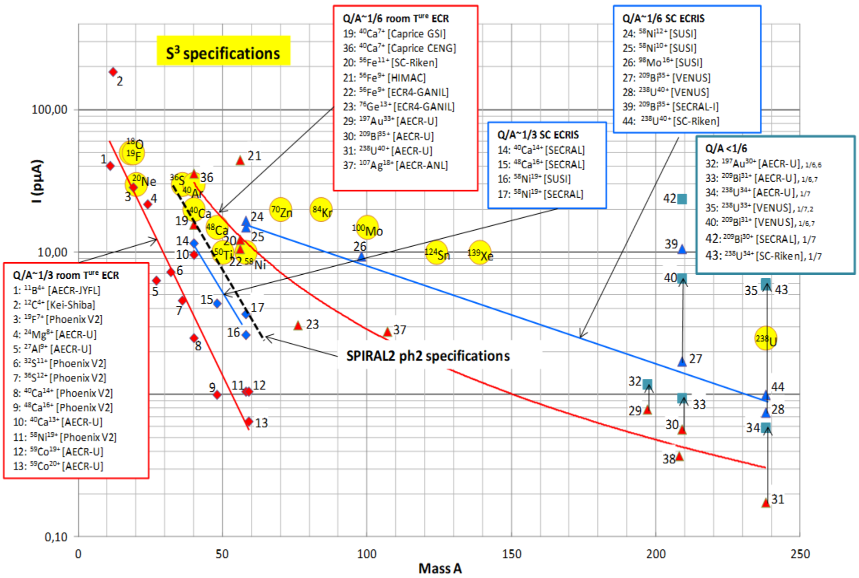

Figure 1: Injectors and ECR sources state of the art. The rightmost box "Q/A < 1/6"corresponds to an injector Q/A = 1/7. The upward arrows for the heavy beams Au, Bi and U indicate the gain between an injector 1/6 and 1/7. Figure after [Baru16].

A new target-ion source based on multinucleon transfer reactions

We therefore propose to build a new target-ion source that would produce exotic heavy nuclei using multinucleon transfer reactions (and possibly fusion-evaporation reactions)**. This setup will benefit from the highest intense heavy beam from the injector Q/A = 7.** Such a set-up does not exist yet for very high intensity, but would be based on gas catchers with large angular acceptance see e.g. [Sav20].

The produced ions could benefit from the S^3 low-energy-branch instrumentation (RFQ buncher, laser spectroscopy $REGLIS^3$ and multireflection time-of-flight spectrometer PILGRIM) and could be sent to the DESIR hall, in the same way as it is already planned for the S^3 products. **Alternatively, one could consider a target-ion source independent from S^3 in a future production building.** It would require its own selection/purification line, but this could also be shared with an ISOL facility for neutron-rich nuclei produced by fission.

One also could perform their re-acceleration (see also the contribution "Reacceleration of radioactive ions beams up to 60 A MeV"). The reacceleration of primary-reaction products is moreover an efficient process to purify the beam. Indeed, in the case of multinucleon or few-nucleon transfer reactions, a cocktail beam is produced. The reacceleration then acts as a purification stage. After this purification one could therefore perform the spectroscopy (in-beam or after implantation) of a well-identified isotope. If the beam intensity is above 10^4 pps, it is possible to perform secondary reactions like e.g. Coulex, elastic and inelastic scattering, transfer reactions, or to populate even more exotic actinides, study their fission barriers or their structure, perform electron-ion collisions (as proposed in the contribution "Nuclear structure from electron-ion collisions"), etc. **Besides the quest for the unknown in basic research studies, there is also a large demand for nuclear data in the actinide region that could be addressed with the proposed facility** among which fission barrier measurement, fission fragment yields, etc.

The re-acceleration of actinide nuclei was already proposed in frame of the GANIL2025 think tank [Far15] (but at that time limited to S^3). It was largely based on existing or planned infrastructures. As shown in Figure 2, it consists first in a gas-cell and quadrupole mass filter (QMF) both located in the S^3 cave. The S^3 low-energy branch (or a similar device) acts as the selection step and provides low-energy (≈30 keV) pure beams in a 1+ charge state. They are then transported to the existing GANIL building into an EBIS source (to increase the charge state) before injection in the CIME cyclotron. The efficiency from the gas cell to the CIME acceleration is estimated to 0.2-0.5 %. Obviously, this scheme also applies to any reaction products from S^3.

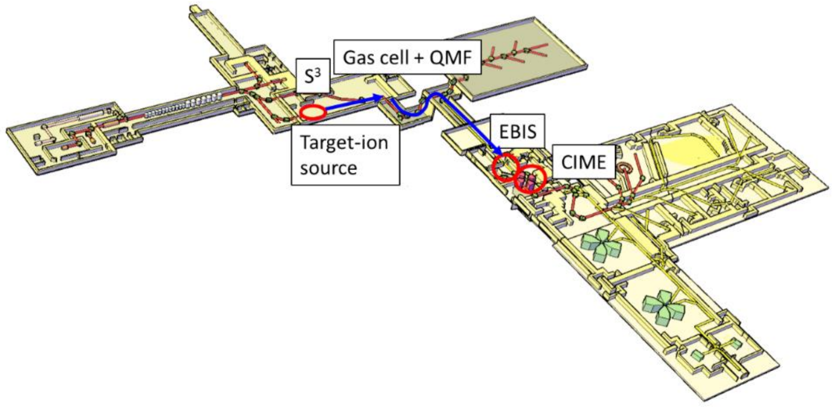

Figure 2: possible implementation of a target-ions source with a post-acceleration scheme.

An alternative to CIME would benefit from a new accelerator, as already proposed in the framework of the GANIL2025 think tank, or within the present "future of GANIL" initiative. With this solution, a gain of a factor ≈ 10 in transmission can be expected. This post-accelerator could obviously be used to accelerate any ions produced by various techniques (*e.g.* neutron-rich nuclei from fission).

This would allow to broaden the physics program of SPIRAL2 well beyond the heavy and superheavy nuclei, and thus address a community that is currently not concerned by S^3. In the more distant future, the question of the durability of the GANIL cyclotrons will also arise, as well as the possible alternative to SPIRAL2 phase2 based on fusion-evaporation and/or multinucleon transfer reactions. The new target-ions source and post-accelerator therefore are a valid answer to these issues.

Conclusion

To conclude, the superiority of an injector Q/A = 1/7 compared to 1/6 essentially concerns the heaviest beams: Au, Pb, Bi, U, etc. We recommend the construction of an RFQ injector Q/A = 1/7 as soon as possible. At the start of operation, the option Q/A = 1/7 over Q/A=1/6 will not be a decisive advantage for S^3 in its nominal configuration. On the other hand, in the longer term and in the perspective of the **construction of a new target-ion source for the production of heavy nuclei using multinucleon transfer reactions, an injector Q/A = 1/7 would open up new opportunities**. **Finally, in the even longer term, we believe it is essential to anticipate a cyclotron shutdown. A new post-acceleration stage is envisaged in order to reach energies of a few tens of MeV/u. Such an experimental complex would make it possible to have competitive beams for a unique physics.**

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