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Improvements of present radioactive beam facilities and new projects

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Invited talk presented at the International Conference on Exotic Nuclei and Atomic Masses, ENAM 95, Arles, France, June 19-23, 1995

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IMPROVEMENTS OF PRESENT RADIOACTIVE BEAM FACILITIES AND NEW PROJECTS

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Abstract
A short overview is given over scheduled improvements of present radioactive beam facilities and of new projects. In order to put these into a coherent context the paper starts with a general section about the making of radioactive beams.

1. Introduction

The unique research opportunities in nuclear physics and nuclear astrophysics which are offered by radioactive beams have become most obvious during the last years (see, e.g., references [1,2]). The rapid progress of the field can be witnessed by consulting recent proceedings[3-5] of the two predecessor conference series (i.e. *Atomic Masses and Fundamental Constants* as well as *Nuclei far from Stability*), and, of course, in particular the many new results presented at this first ENAM conference at Arles. Concerning future experiments, many fascinating ideas are planned at the heavy-ion facilities of which several commit more than half of their available (primary) beam time to secondary beam experiments. Future radioactive beam facilities are under construction or planned in several countries (Belgium, France, Germany, Italy, Japan, Russia, United Kingdom, United States and at CERN). Of course, the present short article is not intended to be a complete or even representative description of all ongoing efforts, it is rather accented on projects which are started or financed. Thus I apologize to all those who feel that I have not covered what is close to their heart. My aim is two-fold: I shall make a few general remarks concerning (the difficulty of) the making of radioactive beams. From this basis I shall then somewhat synthetically overview the capabilities we are going to have in the near future either through improvements of "present" radioactive beam facilities or the construction of new ones.

2. Making Radioactive Beams

2.1. Fragment Separators and ISOL Systems

So far, energetic radioactive beams have mainly been made by the use of heavy-ion accelerators in connection with in-flight separation by recoil spectrometers. This technique relies on the forward focusing which is present in peripheral nuclear reactions (and also in inverse kinematics fusion-evaporation and transfer). The concept of "fragment-separators" has been pioneered with relativistic heavy ion-beams at Berkeley using beam-line elements, and later, at GANIL with the LISE spectrometer for intermediate-energy beams[6]. LISE was substantially upgraded[7] and new devices for fragment separation have been constructed and put into operation at GSI, MSU and RIKEN (*for a review see reference*[8] and *references therein*) and, *most recently the* SISSI device[9] at GANIL.

One has to note, however, that the optical quality of secondary projectile-like fragment beams is somewhat limited, in particular when one aims at a high transmission of the fragment separator, which means privileging its angular and momentum acceptance. In this respect the situation is best at high energy, where also contamination from fragments of incompletely-stripped charge states is minimal. However, the probability for "destroying" the wanted radioactive beam by nuclear reactions in the various materials it passes (production target, Z-selective degrader, detector systems) increases naturally with the amount of matter to be passed. Up to now, the experiments at the fragment separators have been made down to a minimum energy of, say 25 MeV/u, or, for identification and decay spectroscopy, at rest in suitably large detector systems.

Indeed, it is impossible to attain the energy band of 0-25 MeV/u by degrading the high-energy beam from a fragment separator through passage of matter and to simultaneously maintain reasonable optical properties and conserve the intensity. The very elegant technique of cooling/decelerating is also limited by transmission and, in particular for short-lived nuclei by the prohibitive cooling times.

The many exciting prospects for experiments with radioactive beams with energies around the Coulomb barrier have been extensively been discussed, see e.g. the NuPECC report[10]. The method which addresses the low-to-medium energy band has been pioneered at Louvain-la-Neuve[11]: The radioactive nuclei are produced at rest in a (thick) production target irradiated by means of a *first* accelerator. This target is connected to an ion-source. Suitable choice of the target nature, its operating temperature and of the "connection" allow to introduce, up to a certain degree, chemical selectivity in the transfer process to the ion source. After extraction (of the desired charge-state) and mass-separation, the wanted radioactive species are then *post-accelerated* by means of a *second* accelerator. The first part, prior to the injection in the postaccelerator is known as ISOL (Isotopic Separation On-Line). This method is successfully used at many laboratories in the world, of which the most well-known archetype is the ISOLDE facility at CERN[13]. Extensive expertise exists for designing the critical target/ion source combinations for which a variety of different schemes has been used (for a recent review, see, e.g. reference[14]). The progress of this technical challenging, but very active R&D subject can be followed up by consulting the proceedings of the EMIS conference series[15]. The performance of the post-accelerated radioactive beams at Louvain-la-Neuve has certainly contributed to encourage the new projects which are planned or under construction in many countries as discussed in section 3.

2.2. Nuclear Reactions used for Producing Radioactive Beams and Associated Luminosities

The available secondary radioactive beam *intensity*, is a critical factor for radioactive beam experiments. Furthermore, (in particular at high energy), numerous reactions channels may be populated. Thus, in addition to the wanted reaction product, a large amount of *contaminants* may be present and has to be filtered out by a carefully designed (fragment- or ISOL-) separator. Note that for short-lived isotopes, the *time* needed to perform the isotopic separation, may strongly reduce the final intensity.

The present radioactive beam "facilities" generally use charged-particle induced reactions, either in the Fermi-energy domain or at relativistic energies. Many kinds of nuclear reactions have found to be of interest, like fragmentation/spallation, nucleon transfer, deep-inelastic or fission. The (in-target) production rates for unstable nuclei are determined by the reaction cross-section, the target thickness and the primary beam intensity. As a generalization, one may say, that the luminosities are very high for proton-induced reactions (which may reach almost 10^{14} barn^{-1}s^{-1}, as at Louvain-la-Neuve[11]), other "representative" luminosities are given in table 1). This is because of the higher intensity of proton accelerators and the larger possible target thickness compared to heavy ion reactions of similar energies. For high-energy fragmentation the cross-sections are the "same" for proton-induced reactions on a given target nucleus or for the projectile-fragmentation of this nucleus because only the reference frame is interchanged. (Note, however, the basically "geometrical" gain in cross-section in target fragmentation induced by heavy ions). Thus (high-energy) heavy-ion reactions have basically lower *in-target* production rates and seem at disadvantage compared to proton-induced ones. Depending on its chemical and physical properties, however, the efficiency for subsequent stage of getting the wanted species out of the target, and separating it from contaminants, completely may negate this handicap.

Production Method	Typical Luminosities in [$barn^{-1} \times s^{-1}$]
High-Energy Fragmentation	
protons (e.g. CERN-ISOLDE)	10^{12} - 10^{13}
heavy ions (e.g. GSI)	10^{7}- 10^{8}
Intermediate-Energy Fragmentation (e.g. GANIL)	
heavy ions (LISE, SISSI, SPIRAL)	10^{9} - 10^{11}
light ions (e.g. ^{3}He for SPIRAL)	10^{13}
Transfer Reactions	
protons (e.g. Louvain-la-Neuve)	5×10^{13}
Fission	
heavy ions (e.g. GSI)	3×10^{3}
thermal neutrons (e.g. ILL)	2×10^{10}
fast neutrons (e.g. Argonne)	5×10^{14}

Table 1: "Typical" luminosities for selected production methods obtained at some facilities

Yet another method is of great potential for a particular region of the chart of the nuclei: The cross sections for producing very neutron-rich isotopes in the mass range, say $80 \leq A \leq 150$, by means of fission, induced by inverse-kinematics relativistic heavy-ion collisions[16)] or by slow neutrons are very large. In this respect, the high-flux reactor at ILL-Grenoble is believed to allow substantial luminosities for neutrons irradiating an uranium target[17)]. Yet another idea, recently proposed by Argonne, is to irradiate an extremely thick (380 g/cm^2) Uranium target by an intense secondary beam of fast (100MeV) neutrons[18)].

3. A Tour d'Horizon of Improvements to Radioactive Beam Facilities and new Projects

GSI Darmstadt, where the whole mass range of heavy ions is available with relativistic energies (up to 2 GeV/u) exploits very successfully the fragment separator FRS (see, e.g., the many results presented at this conference and note the possibilities of radioactive beam experiments with the storage ring ESR as shown by H.Wollnik). Thus the physics program with exotic nuclei and beams will considerably benefit by the substantial upgrade which is scheduled over the next years. Eventually, in particular due to a reconstruction[19)] of the injecting accelerator UNILAC, the heavy-ion synchrotron SIS will be filled up to its space charge limit. Consequently, the luminosities will be increased by several orders of magnitude as compared to table 1.

The NSCL at Michigan State University uses the superconducting cyclotron K1200 in connection with a superconducting ECR source to produce heavy-ion beams in the intermediate to pre-relativistic regimes with considerable intensities. The fragment separator A1200 is used for a very broad radioactive beam program. A substantial improvement which will be implemented over the next years consists in coupling the (first built) K500 superconducting cyclotron prior to the K1200[20]. As shown in figure 1, this will give rise to a substantial gain in energy, or, likewise, in intensity for a given energy.

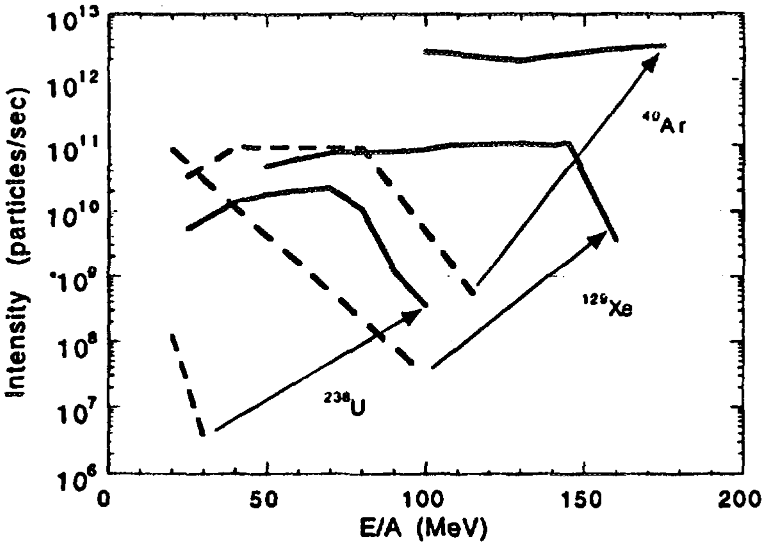
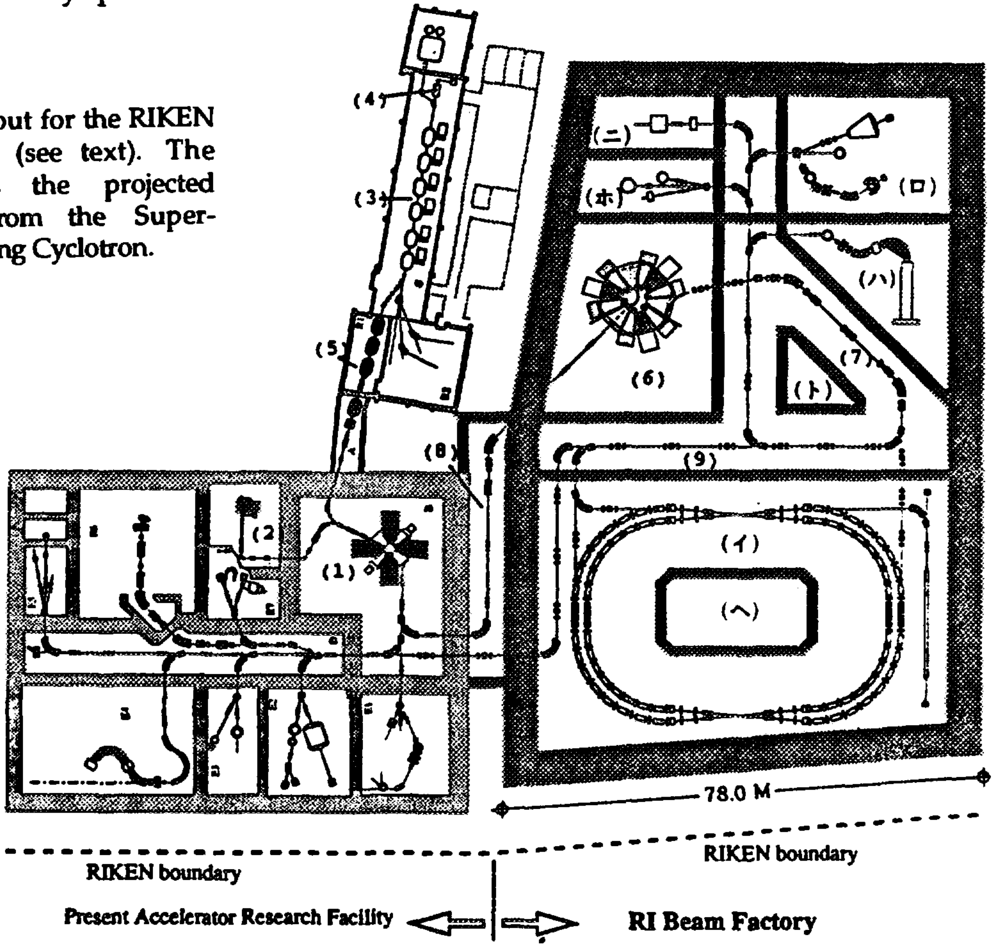


Figure 1: Performance gains from the MSU-upgrade (dashed lines convert to full drawn), see also text.

RIKEN in Japan provides intermediate energy radioactive beams from the fragment separator RIPS, the large experimental effort being accented in particular by physics with light neutron-rich nuclei. A very ambitious project is in preparation[21] which would completely reshape the facility: The present installation, upgraded in intensity, would serve as injector for a new machine: a superconducting separated sector cyclotron with a bending power of 30 Tm would provide very intense beams of energies of up to 500 MeV/u (see also the table included in figure 2). A fragment separator would deliver radioactive beams that could either be used directly or injected in the double intersecting storage rings MUSES. MUSES can be operated in the "classical" collider mode with the corresponding energy increase, or, in the "merging" mode, where both beams turn in the same direction. Finally, there would be a LINAC providing electron beams colliding with the radioactive beams in MUSES for electron scattering experiments (electron energy up to 2.5 GeV). Of course, the great challenge of the RIKEN project are the luminosities obtainable in the various collider modes.

As already mentioned, the radioactive beam facility at **Louvain-la-Neuve** has been pioneering the ISOL+postaccelerator method and is, as of today, still the only operational facility based on this principle. The target is connected to an ECR source. An important upgrade, called ARENAS[3] is presently under construction[14]: A K=44 cyclotron with 25% acceleration efficiency will deliver beams for the astrophysically interesting energy range 0.2-0.8 MeV/u. For the radioactive beam production one may use, in addition to the (presently used) driver-accelerator CYCLONE 30, the cyclotron CYCLONE presently operating as post-accelerator. CYCLONE 30 delivers up to 0.5 mA of 30 MeV protons, whereas the K=110 CYCLONE with its higher energy and diversity of particles may produce nuclei much further off stability, albeit at much lower intensity.

Figure 2: Layout for the RIKEN "RIB-Factory (see text). The table shows the projected intensities from the Superconducting Ring Cyclotron.



Element	Z	A	q	E/A (MeV)	Intensity (pμA)	Intensity (pps)
O	8	16	8	500	1.6×10^{2}	1×10^{15}
Ar	18	40	16	370	4.8×10^{1}	3×10^{14}
Kr	36	84	28	280	8.0×10^{0}	5×10^{13}
Xe	35	129	35	210	1.12×10^{0}	7×10^{12}
U	92	238	49	150	3.2×10^{-1}	2×10^{12}

Well advanced is also the **Holifield Radioactive Ion Beam Facility**[23)] at Oak Ridge. The existing ORIC cyclotron (60 MeV protons, 50 μA) will be used for production of the radioactive species. The ISOL system under construction will be optimized in particular for negative ions since the postacceleration will be made by the existing 26 MeV Tandem. Commissioning of this facility is expected in 1996.

Similarly combining existing equipment for production and post-acceleration, the **PIAFE** project in Grenoble would rely on the ILL high-flux reactor for production and on the SARA cyclotrons for post-acceleration[17)]. Exceptionally intense secondary beams of neutron-rich nuclei in the mass-range 75<A<160 are obtained (see section 2.2), provided that the technological challenges and safety issues can be addressed successfully. This is the aim of "PIAFE Phase I", were an a Studsvik-type ion-source will be placed in a beam tube of the ILL reactor (see J. Genevey these proceedings). Note that "Phase I" allows a strong physics program at low energy. The later "Phase II" consists in building a (400m long) transfer beam line to SARA, but other options for post-acceleration may of course also be envisaged.

The **ISOLDE** facility at CERN has been outstanding in developing over a quarter-century the thick target concept for the production of radioactive species of very many isotopes (about 600 species), generally available in the 1^+ or 1^- charge state. Since a few years the PS-Booster (2µA of 1GeV protons) acts as "driver"-accelerator for producing low-energy (60 keV total) mass-separated radioactive beams for a large user community. The post-acceleration (up to 2MeV/u for light ions) of these beams has been funded and the construction recently started[24]: Prior to injection into a linear structure (RFQ, interdigital H-type, linac) bunching and charge-state breeding is assured by a novel scheme based on a Penning trap and an EBIS source. Also underway at ISOLDE are preparatory and comparative tests of a high power target design that will be used in the **RIST** project of the Rutherford Appleton Laboratory (RAL). RIST (=Radioactive Ion Source Test) would use a Tantalum target irradiated by the 800 MeV from RAL at intensities up to 100 µA. If feasible and successful, these funded studies could become the starting point of a European "second generation facility" for the medium-term future.

Similarly, the meson factory TRIUMF in Vancouver constitutes a driver accelerator of great potential. Ultimately it is envisaged to use 100 µA of 500 MeV protons for an ISOL facility connected to an accelerator for energies between 0.2-1.5 MeV/u. This proposal, called **ISAC** may start using the beams from the present TISOL facility (1-10 µA), see J.M. D'Auria in these proceedings. Funding for this project was announced during the present conference.

Another intense driver accelerator would be the 1GeV linac (100 µA protons) of the Japanese Hadron Project. In order to advance the necessary R&D for this "exotic arena" radioactive beam facility[25], the **prototype E-Arena** at the INS in Tokyo is presently constructed[26]: The (40 MeV 10 µA proton or 90 MeV ^{3}He beams) from the existing SF cyclotron at INS will be used for an ISOL apparatus that is followed by an double linac system for postacceleration of light beams (A<30) up to an energy of 1.05 MeV/u.

Wheras the projects mentioned above rely on the existence of a driver accelerator, it might actually also be very attractive to build a new one and use the existing facility for postacceleration (historically that is the way the Louvain-la-Neuve facility started). Thus the **Argonne project** relies on the present ATLAS facility[18]. The proposed driver linac is able to produce 100 MeV/u beams ranging from protons to ^{36}Ar with a beam power of up to 100kW feeding the ISOL part. A variety of production mechanisms are possible (see section 2.2), and in particular fission induced by fast neutrons is planned. Certainly, much R&D is required for this ambitious project (the price tag, e.g. is in the order of 100 M$), but, at least to my opinion, the potential is there for a true "second generation" facility.

This short overview will finish by the presentation three of the "first generation" facilities" which have the special feature of providing radioactive beams by both in-flight fragment separation as well as ISOL+postacceleration. Thus very different production methods may be used and radioactive beams over a wide energy range will be available at these places.

The recently commissioned superconducting cyclotron of the Catania National Laboratory (K=800) delivers intermediate-energy heavy-ion beams which can be used in connection with the fragment separator **ETNA** or with the **EXCYT** facility (see D. Vinciguerra et al. these proceedings). This latter project, recently funded, connects an ISOL system to the existing 15MV tandem. Vital for the project are the most efficient injection and ejection for the cyclotron: The high-current high charge-state super conducting source SERSE is under construction and special care is taken for the critical electrostatic deflector in the ejection system.

The **Flerov Laboratory** at Dubna operates two cyclotrons, U400 (K=400-540) and U400M (K=450-630), reputed for their high intensity. The fragment separator **COMBAS**, to be installed behind U400M is under construction[27)], and it is projected to use U400M also as a driver accelerator for an ISOL-system based on an ECR target-ion source technique for the secondary beam production followed by U400 for the post-acceleration. Furthermore, a cooler/storage ring is planned after the U400.

Also the **SPIRAL** project at GANIL[28)] relies on ECR techniques to inject highly-charge secondary beams into the cyclotron CIME for postacceleration to energies between 1.8-25 MeV/u (see figure 3). The production targets can be irradiated by a wide range of heavy ions of energies up to 95 MeV/u and beam powers of up to 6kW. This ten-fold increase of the present intensity, available in 1996, is of course also very beneficial for the high-energy radioactive beams prepared in-flight through projectile fragmentation by means of LISE and SISSI (see also section 2.1). Concerning the ISOL production scheme a vigorous R&D effort is under the way. Production targets located in the "D2"-vault (see also figure 3) have been connected on-line to different ECR-sources. For radioactive isotopes of several gaseous elements produced in a "universal" projectile fragmentation (carbon) target, an originality of a heavy-ion driver accelerator, encouraging production rates for short-lived species, extracted in high charge states, have been observed[29)]. The future beam power increase has been "simulated" in irradiations at Louvain-la-Neuve with the intense 30 MeV proton beam, which has an energy-loss comparable to typical GANIL heavy-ion beams. The "CHILOU" carbon targets, especially designed for high power density (collaboration CIRIL-GANIL-IPN&CSNSM Orsay-Louvain la Neuve) were successfully tested beam powers of above 6kW). In the future, other targets will be investigated (some early results for MgO and Al_3SiO_2 can be found in ref.[28]) in particular in view of the production of neutron-rich isotopes by target fragmentation/fission induced by light ion beams (^{12}C, ^3He). The design and construction of the post-accelerating cyclotron CIME (K=265) is assured by a collaboration between GANIL and IPN Orsay. The progress made for the various subsystems during the last months[30]) has been according to the planning which projects first beams for 1998.

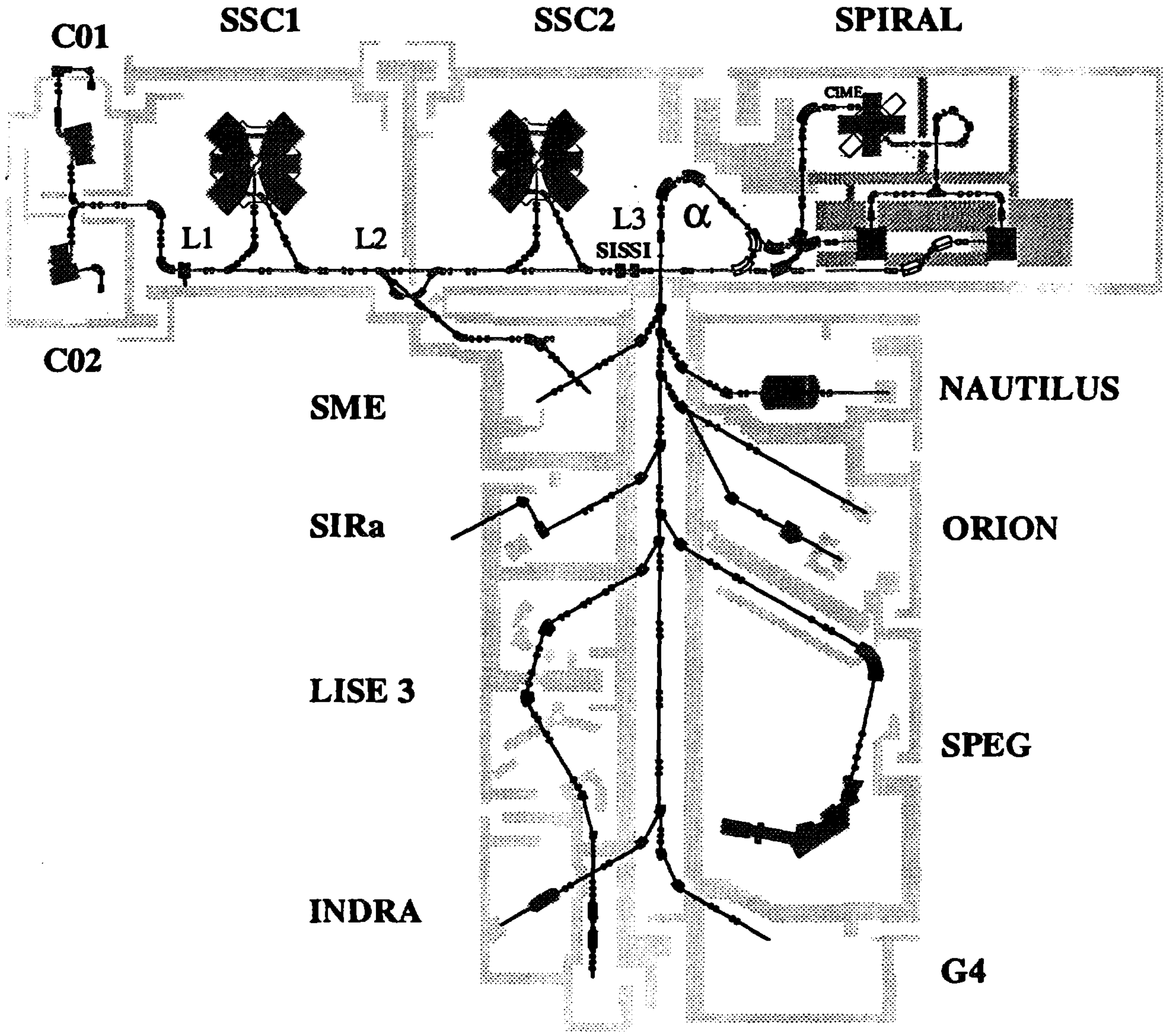


Figure 3: Layout of the future installation of SPIRAL at GANIL: The primary beam from SSC2 may be directed either to the present experimental area or to SPIRAL. After production, ionization and magnetic separation, the secondary beam is injected into the CIME cyclotron. The accelerated beam is then transported to the experimental area via a "S"-shaped spectrometer, re-using the second half of the α-spectrometer. Note that one special use of this instrument may be beam purification through energy-loss analysis [28]).

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