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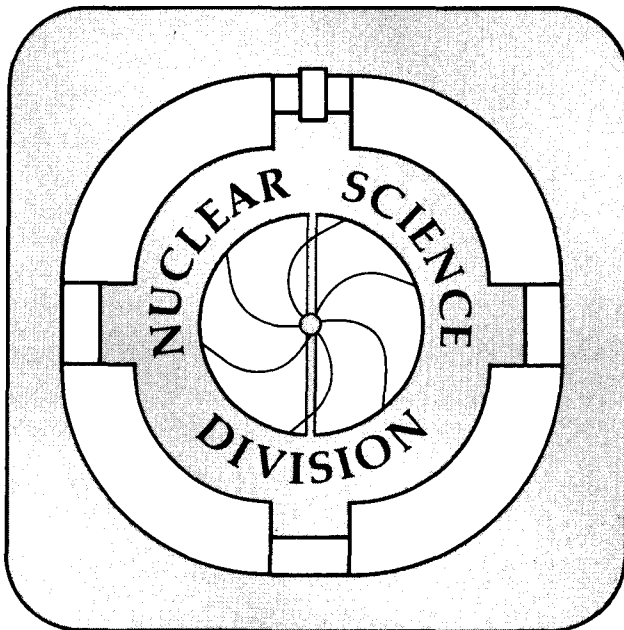
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Invited talk presented at the Workshop on
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September 1985



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Secondary Beams and the Synthesis of Exotic Nuclei

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Secondary Beams and the Synthesis of Exotic Nuclei

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With the advent of modern fast cycling synchrotrons [KI 85] capable of delivering high intensity heavy ion beams up to uranium, the production of secondary radioactive ion beams (RIBs) with sufficient intensity has become feasible. The basic production mechanism is the fragmentation of near relativistic heavy ion beams on light targets. The physical facts underlying the efficient conversion of stable beams into RIBs are: (1) at beam energies of several 100 MeV/A thick conversion targets ($1-10 \text{ g/cm}^2$) can be used, which, for nuclei near stability, convert on the order of .1 to 1% of the primary beam into secondary beams, (2) the secondary beams are emitted into a narrow phase space (small transverse and longitudinal emittances), and (3) these emittances are of the correct magnitude to match the acceptances of suitably designed storage and accumulator rings.

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A second generation medium energy heavy ion facility designed for the incidental production of secondary beams would therefore consist of a high intensity synchrotron coupled with a universal storage and accumulator ring (USAR) [NI 84]. The USAR should be able to accept the full rigidity primary beam (stripped) and be able to cool and decelerate the beam. Since secondary beams produced in thick targets are quite hot but have relatively low intensity, stochastic precooling is the most effective method to reduce the large transversal and longitudinal spreads in momenta. Further cooling in the USAR down to $\Delta p/P \approx 10^{-5}$ is possible with electrons. Assuming that primary beams of $10^{11} s^{-1}$ for the heaviest, and $10^{12} s^{-1}$ for light ions can be obtained from the synchrotron the following secondary beams can be expected [CR 84]: (1) neutrons ($\sim 10^{11} s^{-1}$), (2) light RIBs near stability ($\sim 10^{11} s^{-1}$ (for each additional neutron removed or added the yield drops about an order of magnitude)), (3) fission fragments ($\sim 10^8 - 10^9 s^{-1}$ per percent fission yield), and (4) neutrals leaving the electron cooling section ($\sim 10^4 s^{-1}$).

Secondary beams as they emerge from the converter target cover a wide range of A and Z values, and for direct experiments as well as for injection into the USAR it is in general necessary to provide some form of beam analysis and purification [GE 85]. This is a difficult task in particular for heavier RIBs since they do not differ much in magnetic or electric rigidity or velocity from the primary beam, and many secondary beams overlap in charge to mass ratios. Position dependent degraders coupled with dispersive elements will have to be employed. After analysis the secondary beam can be injected into the USAR. The storage ring should be designed with the following characteristics: (1) large acceptance in transverse and longitudinal momentum space, (2) multiple charge state operation, (3) stochastic and electron

cooling (provisions for future collinear laser cooling and/or experiments), (4) RF section for deceleration to ~ 5 MeV/A, acceleration to compensate for energy losses in internal targets, and bunching to obtain a sub-nanosecond time structure or quasi-DC beams, (5) slow extraction, and fast extraction for reinjection into the synchrotron, and (6) provisions for internal targets and polarized beams.

The design of suitable internal targets [ME 85] [TC 84] is difficult, and characterized by the following dilemma: To obtain the highest possible luminosity, say $10^{32} \text{ s}^{-1} \text{ cm}^{-2}$, and still retain a reasonable "life time" for the internal beam the target thickness should be in the range of 10-100 ng/cm^2 ($\sim 10^{15} - 10^{16}$ atoms/ cm^2); such targets can, however, no longer be made self supporting. Conversely, most other internal targets like molecular jets, storage cells etc. provide only target thicknesses of 10^{11} to 10^{13} atoms/ cm^2 and, therefore, make inefficient use of the beam. Much creative development in this area will be necessary.

From a primarily experimental point of view experiments with RIBs [SC 85] can be divided into three categories: (1) Experiments that measure properties of the secondary beams as such, like masses, Q-values, and magnetic moments [SU 84], β -decay studies of implanted exotic nuclei, and Mössbauer spectroscopy. (2) Experiments that use external targets. This includes the synthesis of exotic nuclei with neutron- or proton-rich beams, implantation of RIBs for tracer studies in solid state physics, and biomedical applications. Many well established experimental techniques can be used in these two categories, while (3), the use of internal targets, represents in many ways new challenges to experimenters in nuclear and atomic physics [ME 84]. Several properties of stored, cooled secondary beams provide unique

experimental possibilities: (a) small momentum spread ($\Delta p/p \approx 10^{-5}$), (b) small emittance ($\sim 10^{-6}$ m), and (c) RF acceleration to compensate for energy losses in the internal target thus facilitating multiple traversals. Coupled with thin, light targets--for example, cooled molecular jets of hydrogen or deuterium--these properties allow high resolution experiments and the precise determination of Q-values for exotic nuclei via the inelastic scattering of the light target nucleus in reactions based on inverse kinematics. Other applications include coulomb excitation and dissociation with internal atomic beam targets of lead for instance. Weak interaction studies would find experimental conditions that exist only in intergalactic space: beta decay of fully stripped ions could be observed as well as beta decay into coulomb bound states. Radioactive ions other than tritium would be available for the measurement of the neutrino mass. For the first time it will be possible to study reactions with beams of nuclei in excited states (isomers) and it may also be possible to produce polarized stable beams as well as RIBs via the strong hyperfine interactions of hydrogen-like heavy ions. Even if the latter proves to be difficult the electric and the magnetic hyperfine interactions can be used to determine electric and magnetic moments, and lifetimes of short lived states as well as perturbed angular correlations in beta- and gamma decay. Collinear laser experiments are particularly well suited for the storage ring because of its good emittance. Laser cooling can reduce the ion energy spread to a few tens of meV (!). One could even speculate about the collision of sub-nanosecond laser and RIB pulses interacting with each other to study low cross section phenomena, and make use of time of flight and other time correlation techniques. The low duty factor of present day lasers presents, however, a problem.

Many applications of stored RIBs can be envisioned for the study of strong interactions [TA 85a,b,c]; one of particular interest to the present author is the possibility of synthesizing superheavy elements (SHE) [LO 78]. It is thought that one of the reasons why SHE have not been observed in nuclear reactions is that an insufficient number of neutrons have been combined in the compound nucleus. In the "famous" $^{48}\text{Ca} + ^{248}\text{Cm}$ reaction only 177 neutrons were left after a hypothetical $3n$ evaporation process, while the island of stability is predicted to be located at $N = 184$. This could have caused a reduction in the SHE half-life of four to ten orders of magnitude. The use of RIBs of ^{50}Ca or perhaps even ^{52}Ca combined with very neutron rich targets like ^{250}Cm would allow a significant advance in "the art of making superheavys." The fact that ^{250}Cm exists only in small quantities ($\sim 4 \times 10^{12}$ atoms) is not necessarily a serious handicap since thin targets are a requirement for targets inside the storage ring. The multiple traversal of the $^{50/52}\text{Ca}$ beam with subsequent energy compensation and cooling makes up a factor of about 10^6 for the greatly reduced target thickness. Ultimately it is thinkable that one could have thin fiber targets even of ^{257}Fm , a rare isotope of which there exist only about 1 to 4×10^9 atoms.

In conclusion, secondary beams of radioactive ions will open up new, exciting dimensions in experimental physics not only for the study of nuclear properties but also in atomic-and solid state physics [IS 84], and for biomedical applications.

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