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LETTER OF INTENTION

A POST-ACCELERATOR FOR ISOLDE

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1 Introduction

In contrast to the situation which pertains at the neighbouring atomic and subnuclear levels of matter, there is as yet no fundamental theory of the bound nucleus: our knowledge of the structure and properties of nuclei is largely phenomenological. The dominant influence on this structure is contained in the details of the quantal states occupied by a finite number of valence nucleons and their mutual, state-dependent interactions. The data reveal that these interactions frequently lead to a rich variety of collective modes, involving the cooperative motion of the ensemble of nucleons. This observation supports the relevance of the mean field concept which underpins our current theoretical understanding of nuclear structure and also suggests the presence of underlying symmetries. If our goal is a basic unified theory of atomic nuclei, then the capability to produce beams of unstable nuclei at energies which permit the study of nuclear reactions is vitally needed.

Such beams offer the chance to study and create exotic nuclear configurations and phenomena which cannot exist in stable matter, nor be accessed by reactions between stable species. They will also provide a wealth of new opportunities to investigate the processes taking place in the explosive stellar events which lead to nucleosynthesis.

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The idea of post-accelerating beams of radioactive nuclei produced at an on-line separator arose as long ago as 1966, at the start of the ISOLDE programme of research. In the last few years, this concept has reemerged and gathered considerable momentum, with the result that it has now become a topic of worldwide interest and, indeed, a primary goal for many nuclear physics communities. In the European context, this commitment is reflected by NuPECC in its report, **Nuclear Physics in Europe - Opportunities and Perspectives**, where it concludes that physics with radioactive beams represents one of the foremost frontiers of nuclear physics. It went on to establish a Study Group to advise it on this subject, and the report of this body has recently been completed. Its conclusions and recommendations, included in Appendix 1, strongly endorse both the strength of the physics case and the need for a network of 'first generation' facilities in Europe, with a view to the eventual development of a large-scale European facility of this type.

The purpose of this letter is to signal the intention to submit a proposal for a post-accelerator to be built at the ISOLDE facility. The proposal recognizes the existing facilities and expertise which are unique to ISOLDE and uses those assets as the basis of a radioactive beam accelerator which involves no major extrapolation of existing technology, but nevertheless offers a facility which would be unique and capable of addressing a range of new physics problems well beyond the scope of existing or approved facilities elsewhere in the world. Indeed, it is the ISOLDE technology which is being used as the model for the majority of other proposed facilities in the U.S.A. and elsewhere. The other major advantage is, of course, the location and the prior existence of the ISOLDE scientific community. CERN offers the ready-made infrastructure of a European laboratory. CERN and the ISOLDE collaboration have built up a complex of specialised radioactivity laboratories with off- and on-line low energy mass separators around which a lively field of nuclear physics, solid state physics and astrophysics already exists.

The project has the support of the ISOLDE Collaboration Committee. In addition, physicists from 8 different countries have already made contributions to the proposal, which is currently being written. A full list of the main contributors and an indication of the contents is given in Appendix 2. Additional collaborators/consultants will have to be found with the necessary expertise to address some of the R&D problems which remain and will be discussed in more detail below. In particular, it is hoped that some of the expertise of the CERN Accelerator Division will be made available to assist with the design and costing of the proposed accelerator.

2 Science with Radioactive Beams

The rationale behind the global enthusiasm for the development of radioactive beam accelerators is clear. The steady advance over the past decades in accelerator design has resulted in a capability to accelerate the entire range of stable nuclear species to energies well beyond those at which the mean field of individual nuclei plays any significant role in the outcome of nuclear collisions. The major constraint which remains and which severely limits our view of the nuclear landscape is the confinement of both beam and target species to the line of stability. This restriction has been a fundamental one, in that it precludes access to a large fraction of the nuclear chart and, more importantly, to the type and extent of information which can be obtained. Many crucial properties of nuclei can only currently be studied in the stable isotopes, while other experimental techniques access only limited regions of nuclei. For instance, studies of the extremes of angular momentum in the nuclear system have so far been limited to neutron deficient nuclei. Conversely, it is only for the narrow band of stable nuclei that we have detailed experimental information on single-particle structure, on giant resonance phenomena, on the entire field of scattering processes, on electromagnetic matrix elements, and so on. The advent of radioactive beam accelerators will remedy this situation and provide access to new phenomena in new regions, regions in which the orbits occupied by the valence nucleons are radically altered, enabling our understanding of residual interactions and nucleonic correlations to be greatly enhanced.

A radioactive beam facility will also have important applications in several other fields of science. Atomic physics, solid state physics and nuclear chemistry are all examples which will benefit from this new capability, but the greatest impact outside of nuclear structure will be in the realm of nuclear astrophysics. Accelerated radioactive beams offer the chance to study structure at one of the extremes of nuclear matter, namely, the limits of particle stability, and the properties of many such nuclei are of crucial importance in the study of stellar nucleosynthesis, particularly when explosive events are involved. After the first three minutes, the universe had cooled sufficiently to allow protons and neutrons to bind together. In essence, the remaining history of the universe is governed by nuclear reactions and nuclear structure and, because of the high temperatures and densities involved,the information which is lacking involves reactions on unstable nuclei. Specifically, the rp-, r- and p-processes are all fundamental nucleosynthetic processes that require global nuclear structure information and nuclear reaction rates for nuclei on both the proton and neutron-rich sides of the valley of beta stability. Each takes place along a path which lies far off the line of stability so that most of the information required can only be obtained with radioactive beams.

There are a host of topics which can be addressed with radioactive beams and many of these will be dealt with in detail in the full proposal. Here, it will only be possible to summarise briefly some examples of the general class of problems which could be explored in each field. Full discussions of the Physics case have already been presented in other proposals for radioactive beam facilities and in the proceedings of recent conferences on this subject.

2.1 Nuclear Structure

As pointed out in the Introduction, the characteristic feature of the nuclear many-body problem is the finite number of constituents involved and the sensitivity of the overall mean field to the details of the last few (valence) nucleons. This sensitivity implies that the shape and symmetry of the nuclear potential can change radically over the space of just a few nucleons. These properties are also strongly dependent on the angular momentum and temperature of the nuclear system. The resulting range of empirical structures observed in nuclei near the stability line have been described by means of wide variety of nuclear models which, in the microscopic domain, have attempted to track the changing properties by means of a self-consistent Hartree-Fock approach with an appropriate choice of effective interaction while, in a macroscopic framework, they have relied on the assumption of a geometrical shape for the nuclear core and a corresponding single particle potential for the valence nucleons. The advent of radioactive beams will allow these mean field properties to be probed in regions where the neutron and proton numbers, and the corresponding single-particle states, occur in hitherto unencountered combinations. Some examples of the potential areas of study are given below. The list is by no means complete, and no order of preference is intended.

- Nuclear structure at and near the N=Z line; the role of isospin in collective nuclear structure; isospin mixing; T=0 pairing; study of mirror nuclei at high mass and high spin.

- High spin spectroscopy; search for new regions of extreme deformation, predicted by mean field calculations.

- New collective modes; search for examples of stable octupole, oblate or triaxial nuclear shapes.

- Complete spectroscopy; the study of both the low lying intrinsic structure and the yrast states to high spin will be possible in a single nucleus.

- Single and di-proton radioactivity; order-of-magnitude enhancements in the yields of proton drip-line nuclei, offering the prospect of fully mapping out the limit of proton instability up to $Z \sim 82$.

- Exotic matter distributions; Several of the light nuclei at the neutron drip-line have been shown to exhibit anomalously large matter radii which is now associated with a highly extended tail in the neutron density distribution -- the neutron halo. Such weakly-bound systems have a very high electric dipole polarizability which in turn is expected to give rise to dramatic changes in the general behaviour of transfer and fusion reactions.

- Use of polarized beams, via the tilted foil technique, and the ability to tag individual incoming nuclei will have particular advantages in both nuclear structure and fundamental aspects of ß-decay studies.

- Extension of studies in the actinide and transuranic regions; fusion evaporation reactions using neutron-rich beams may offer the most promising way to explore the shell structure beyond uranium, due to predicted enhancement of the sub-barrier fusion cross-section.

- Reactions with radioactive beams; new phenomena may be observed, particularly with neutron-rich beams due to the high positive Q-values involved. Examples are tunneling and neck formation in fusion, and highly enhanced pair transfer of weakly-bound pairs. The field of nuclear reaction studies has, of course, been limited up to now to participants on the line of stability.

- Giant resonance studies with radioactive beams; Measurement of the photon emission from Giant Dipole Resonances (GDR) built on excited states is a new and powerful tool to study nuclei at high temperature. Isospin purity can be tested by comparing GDR spectra from nuclei produced with T=0 and T≠0, using N=Z projectile and target nuclei.

2.2 Nuclear Astrophysics

In explosive astrophysical events, and also in the early universe, the temperature and pressure become very high, so that nuclear reaction rates are increased enormously relative to the situation which pertains in normal stellar burning. The thermal energy in fact approaches the height of the Coulomb barrier for charged particle reactions. Under such circumstances, radioactive nuclei which form frequently do not have time to decay, but are instead involved in further reactions. It is thus possible for chains of rapid reactions to occur that involve only unstable nuclei, which eventually decay back to stability after the explosive force has passed. To understand these processes and the parameters of the stellar environments in which they took place, it is necessary to measure the cross sections of the reactions and the properties of the nuclei involved via experiments with radioactive beams. Such experiments are focussed principally on two different nucleosynthesis processes, the r- process, which is thought to occur in supernova explosions, and the hot CNO-cycles and rp/αp processes which determine the nucleosynthesis in explosive hydrogen burning, and lead up the proton rich side of stability to the Fe region.

The r-process is a rapid neutron capture process where the reaction path runs up the neutron rich side of stability and is mainly determined by the (n,γ) - (γ,n) equilibrium under the prevailing stellar conditions of temperature and density. Its understanding requires knowledge of the nuclear physics properties of the nuclides along the path, such as masses, lifetimes and level structure up to the neutron threshold, in particular for the so-called "waiting point" nuclei which occur at magic neutron numbers.

Explosive hydrogen burning in stars is determined by the hot CNO cycles and by the rapid proton capture, (p,α) and (α,p) reactions. Reaction path, energy production, timescales and nucleosynthesis in such scenarios depend on the reaction rates involved. In general, the reaction path is close to the proton drip line and the reaction rates used to date for these calculations are based on statistical models, with insufficient nuclear structure data being available for the nuclei involved. An experimental determination is therefore highly desirable. Recent studies point to proton capture on $T_z = -1/2$ nuclei such as ^{19}Ne, ^{27}Si, ^{31}S, and ^{39}Ca, and T=0 nuclei such as ^{56}Ni, ^{60}Zn and ^{64}Ge as key reactions in this regard. The installation of a post-accelerator at ISOLDE would allow the cross sections to be measured in inverse kinematics by bombarding a hydrogen target with the radioactive nuclei produced and thus provide a unique opportunity in experimental nuclear astrophysics.

3 The Facility

The on-line separator ISOLDE was originally constructed at the CERN 600 MeV synchro-cyclotron and came into operation in 1967 as one of the first machines of its kind. A continuing programme of improvement and extensive work on ion source and target techniques has led to a wealth of experimental results in many areas of science, culminating in the recent re-location of the facility to the PS-Booster. A few years ago, the concept of re-accelerating the beams of exotic nuclei produced at ISOLDE was discussed in the PRIMA proposal. The prime scientific motivation at this time was the study of nuclear reactions occurring infast-burning astrophysical environments, and the energy and mass ranges were to be limited to ~ 1.4 MeV/A and A≤ 27, respectively. The accelerator design envisaged was a linac consisting of a radiofrequency quadrupole (RFQ) stage followed by several interdigital-H structures and single resonators.

Since this time, the majority of nuclear physics communities throughout the world have reached a clear concensus that the next major step forward in both nuclear structure physics and nuclear astrophysics will come from the acceleration of nuclei far from stability. The focus of interest has thus broadened to encompass energies up to, and eventually exceeding, the Coulomb barrier, with a concomitant increase in the size of the community supporting the proposal.

The design of a post-accelerator for ISOLDE is still under discussion. Currently, a RFQ (radio frequency quadrupole) plus superconducting linac arrangement is favoured. The accelerator would accept $q=1^+$ ions from the ISOLDE High Resolution Separator and have a continuously variable energy range up to 5 MeV/A for A≤ 80. These limits in mass and energy are effectively dictated by the fact that ISOLDE produces only singly-charged ions with any reasonable intensity and that the maximum extraction voltage which can currently be used is 60 kV. An increase in either the initial charge state or extraction voltage would relax these limitations or, perhaps more importantly, could greatly reduce the complexity and cost of the subsequent accelerator.

A schematic indication of the design envisaged and of the interdependence of the features mentioned above is given in Figure 1.

For $q = 1$ and a maximum extraction voltage of 80 kV, the accelerator involves two strippers. The total transmission will then depend critically on the duty cycle of the RFQ, as well as the charge state fractions in the strippers. Assuming a 50% duty cycle yields a transmission curve that varies between ~ 40% at A~ 8 to ~ 3% at A ~ 80. The need for the first stripper is removed if the ion source can produce q/A values of the order of 0.1 or better. In addition, the RFQ stage is considerably simplified and eventually disappears if the ion source platform voltage can be increased or if superconducting resonators with lower ß (=v/c) values can be constructed. The total number of resonators required to reach 5 MeV/A is also significantly reduced in the high charge state case.

It is therefore clear that R&D in the area of multiply charged ion-sources could provide extremely important input to the eventual design specification. The RFQ is also an essential part of the design problem but its specification depends on the type of ion source and the velocity of the incoming ions. Technical difficulties will have to be overcome due to the required high duty cycle. The possibility of putting the RFQ on a high-voltage platform should be considered and also of raising the initial acceleration voltage. It should be noted that the stringent stability specification of the initial HV should not be relaxed because this would preclude the use of the HRS to resolve isobars. The cost of the device will be dependent on the duty cycle, operating frequency and the voltage platform used. Detailed work is therefore necessary to consider the costs and feasibility of each route.

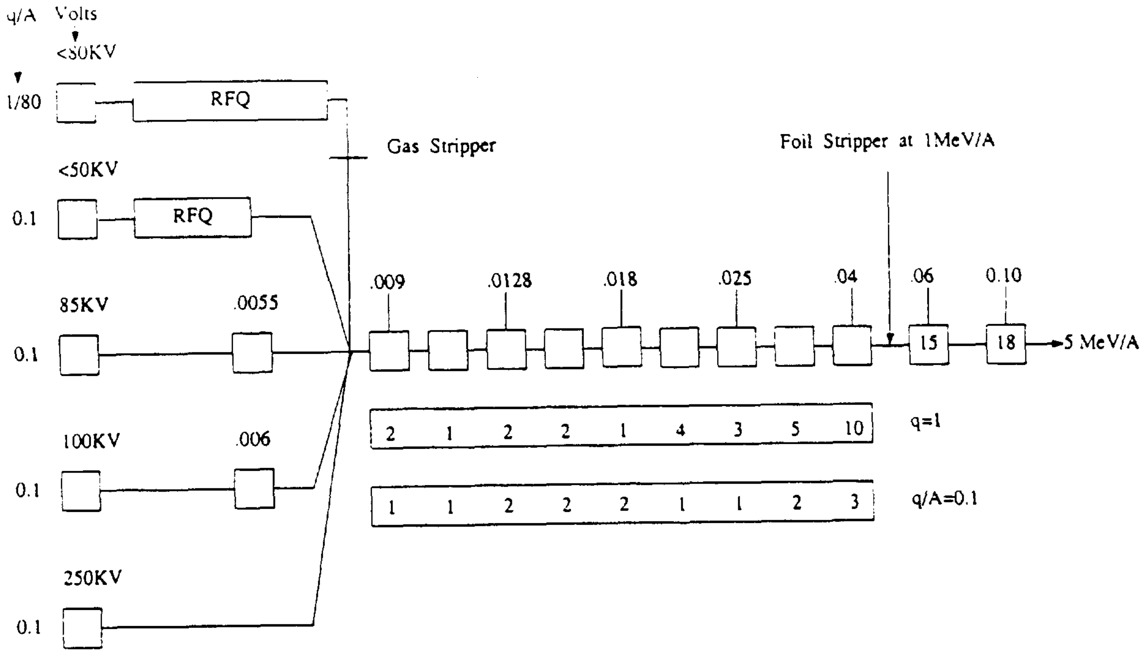

Figure 1 : Schematic indication of options for the linear post-accelerator for different initial charge states and ion source extraction voltage. Numbers in boxes denote the number of resonators required: numbers above give ß-values.

4 Summary and Request for Technical Support

The proposed specification represents a realistic limit on what can currently be achieved within the constraints of existing technology. Given the broad range of exotic nuclei which have been produced at ISOLDE on both the neutron-rich and neutron-deficient sides of stability, it offers a unique opportunity to take the lead in what promises to be the next generation of nuclear physics accelerators.

The full physics case in support of this proposal is currently being prepared by a large number of collaborators throughout Europe and elsewhere. At this stage, the project is in need of technical expertise to solve some of the problems/options cited above in relation to the design of the post-accelerator. At this stage, therefore, we would request technical support from CERN, in the following two areas:

1. Support to to investigate options for multiply charged ion sources or electron beam ion strippers at ISOLDE in a R&D programme.

2. Support to produce a realistic appraisal and costing of the options for the ISOLDE post-accelerator.

APPENDIX 1

Summary of Conclusions and Recommendations - from the Report on the European Radioactive Beam Facilities of the Nupecc Study Group

In the following a summary of the most important conclusions and recommendations is given.

- There is a strong physics case to be made for studies with radioactive beams. These encompass a wide range of topics from pure nuclear physics to interdisciplinary investigations such as nuclear astrophysics and the application of nuclear methods to solid state physics. The nuclear physics studies with radioactive beams may lead to a renaissance of nuclear structure physics.

- Nuclear physics with RIB may well be the only way for the continuation of a high level research in the field of low energy nuclear physics. The continuation of such an activity is crucial if one wants to keep a high level of competence in a field which is very important for the applications of nuclear methods to other fields.

- There is a large community of potential users of radioactive beams. We estimate the number of senior scientists in Europe interested in this topic to be in the order of 200 - 300.

- The proposed European facilities are largely complementary in their production methods of radioactive ions, and thus in the characteristics of the useful beams of isotopes far from stability that they can deliver. Furthermore, there are important differences in the proposed post accelerators and thus in the energy ranges and the energy variability between the various facilities. There is also complementarity of the large scale equipment associated with the different laboratories.

- The presently proposed facilities must be viewed as first generation facilities. This description pertains both to their expected currents of radioactive beams and the range of beams they can produce and accelerate. These facilities are modestly priced on a level that can still be handled by the individual institutions.

- For a true second generation machine on a European level in the spirit of e.g. the US Isospin Laboratory, implying complete coverage of the mass range, energies up to the Fermi energy and beam currents that are at least two orders of magnitude larger than those of the presently planned facilities, considerable R&D is still required. This pertains especially to the use of high intensity primary beams with present targets. Research on such production methods and target techniques is just being started.

- First experiments with radioactive beams have shown these to be far from routine. They are very time consuming, and new detection methods may have to be developed to cope with the high background radioactivity.

- In view of the foregoing considerations, a second generation European facility would seem premature at this moment. In particular the picture of a "turn-key" facility producing any desired radioactive beam on request seems overoptimistic. The Study Group recommendation is therefore to go ahead with first generation facilities and to build on the experience gained with these in working towards a true second generation facility. In view of the complementarity of the proposed facilities and the beam time needed to do experiments with radioactive beams, the construction of more than one first generation facilities would seem highly justified.

- The knowledge gained from studies with first generation and R&D facilities will serve as the foundation for the eventual construction of a second generation facility in Europe. To this end, the Study Group strongly recommends that a European network be set up, with the endorsement of Nupecc, to coordinate R&D on RIB facilities to avoid duplication of effort and to aid in their later utilisation with funding for travel and exchanges of scientists. The aim would be to find the optimum combination of primary production mechanism, ionization scheme and post-accelerator to define a large-scale European RIB facility for the new millennium

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