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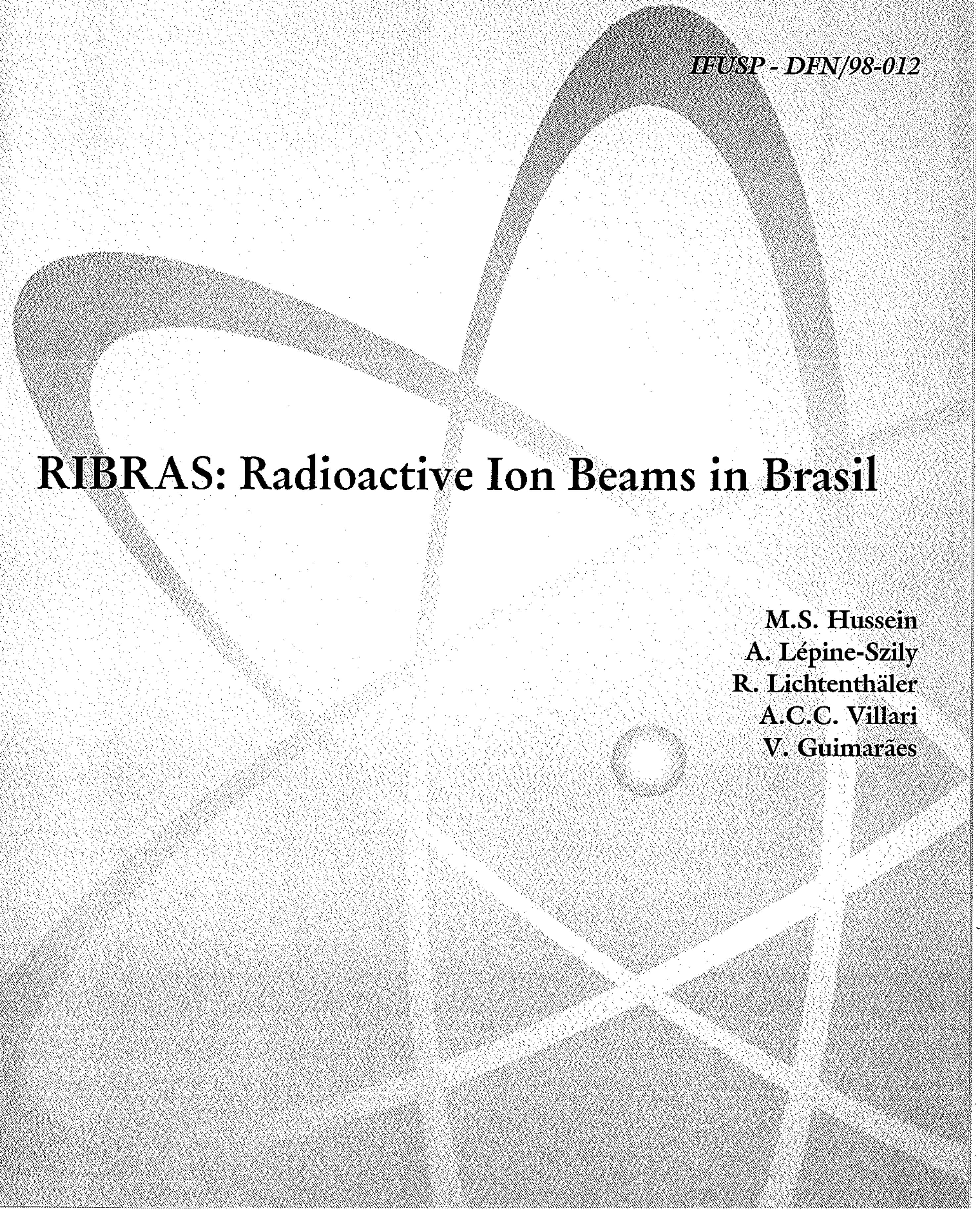
DEPTO. FÍSICA NUCLEAR

Publicação IF - 1337/98

DEPARTAMENTO DE FÍSICA NUCLEAR
INSTITUTO DE FÍSICA
UNIVERSIDADE DE SÃO PAULO

IFUSP - DFN/98-012



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1 Introduction

Nuclear physics has been going through a major evolution over the last decade. The realization that one can investigate nuclei at extreme conditions such as high density, temperature and angular momentum through several sophisticated experimental innovations opened up the possibility of extending this activity to the study of these systems when more neutrons or more protons are added. The resulting, so called radioactive nuclei constitute a new form of hadronic matter whose study, have become a major research activity in Japan, France, USA, Canada, Germany and other countries. More laboratories are going through the process of redirection of their experimental effort towards this activity.

As a matter of fact, the study of nuclear physics using radioactive ion beams started already in the end of the 60's at the ISOLDE-CERN [1] facility where the first isotopic on-line separator has been built. The properties and structure of nuclei far from stability has began to be systematically studied at that time. On the other hand, an important break through has been made in the end of 80's when Tanihata [2, 3] used for the first time a radioactive ion beam to induce nuclear reactions. The measurement of the interaction cross-sections involving light exotic nuclei (^{6,8}He, ^{11}Li) put in evidence for the first time the particular structure of ^{11}Li, called neutron halo, which was never seen before in stable nucleus. After this pioneering experiment, RIB has been used as probe for studying nuclei far from stability, mainly using nuclear reactions.

It is important to stand that several facilities already exist or are being projected in the world, like GSI [4], GANIL/SPIRAL [5], MSU [6], Notre-Dame [7], RIKEN [8], etc. However, each project has its particularities and objectives. In fact, there is no equivalent project among all facilities around the world.

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The aim of this proposal is to install the first RIB facility in the southern hemisphere at the Pelletron-LINAC laboratory of the Department of Nuclear Physics (DNP) of the University of São Paulo (USP), which constitutes the main center of experimental Nuclear Physics activity with hadronic beams in Brazil.

In Brazil, the experimental activity during the last 25 years is concentrated around the Pelletron Tandem Van der Graaf accelerator of 8 MV terminal voltage [9], installed at NPD-USP delivering mainly light heavy ion beams (e.g. ^{9}Be, ^{10,11}B, ^{12}C, 14N, ^{16,18}O, ^{19}F, ^{27}Al, ^{35}Cl, ^{28}Si, ^{56}Fe, ^{58}Ni). Some examples of the research activities developed at the Pelletron Accelerator are:

- Nuclear Structure studies, using in-beam gamma spectroscopy with a small array of Ge detectors and light-ion transfer reactions with a SPLIT-POLE spectrometer.
- Nuclear Reactions studies using elastic, inelastic, transfer reactions and fusion reactions near and above the Coulomb barrier, for light ($A \leq 40$) and intermediate ($A \approx 60$) mass targets.

The energy limitation of the accelerator restricts the research activities to low A and low energy studies making it difficult to compete on the international scenario. For this reason the Pelletron Accelerator is being complemented by a superconducting linear accelerator (LINAC) [10], which can rise the energy of the beam from 3 MeV/A to $\approx$ 10 MeV/A for the mass region $6 \leq A \leq 50$. This project was proposed 15 years ago and has suffered several large delays due to lack of funding. Now it is being constructed and its commissioning is foreseen to occur in the next 3 years

This proposal is based on the installation of a Double Super-Conducting Solenoid (DSCS) placed at the LINAC experimental area. This DSCS will be similar to the presently Notre-Dame University (NDU-SMU) DSCS [7] used with the Tandem Van de Graaff at NDU for production of radioactive ion beams. The particularity of this project with respect to the existent facility at NDU, is the presence of the LINAC, which can deliver heavy ion beams with higher energies than at NDU. The couple LINAC-DSCS constitutes a facility for producing RIB which is unique in the range of energy and nuclear species.

The researchers of the NPD-USP are particularly well placed for studying reactions and structure involving RIB. Their knowledge in low energy nuclear physics as single nucleon transfer, elastic and inelastic scattering and nuclear structure are of paramount importance in the new field of RIB.

Considering the time schedule of the LINAC project and taking into account that a device such as DSCS is a powerful tool also at Tandem energies, it would be desirable to have this facility available even before the commissioning of the LINAC booster both for the purpose of testing the coupled system as well as to actually perform measurements with low energy light RIB's.

Finally, it is important to remember the educational issues of the NPD-USP. The Pelletron-LINAC laboratory has an history of excellence in forming physicist in the field of nuclear reactions and structure. The continuation of this successful history obliges the laboratory to progress always in the direction of the new frontiers of the experimental nuclear physics.

2 PHYSICS AT SP-RIB

I - Nuclear Reactions

In astrophysical environments several reactions involving light nuclei are not known with the precision required by stellar codes, which aim to elucidate longstanding puzzles like: (a) the fate of massive stars, closely related to the reactions $^{12}C(\alpha,\gamma)^{16}O$, or (b) the solar neutrino problem, for which the reaction $^{7}Be(p,\gamma)^{8}B$ plays a fundamental role, (c) the $\alpha(t,\gamma)^{7}Li$ reaction important for Big-Bang nucleosynthesis, etc. [11].

While reactions of astrophysical interest require very low beam energies, typically of order of hundreds of keV, several techniques have been developed to obtain the cross-sections for these reactions by indirect measurements [12]. In fact, indirect measurements are, in some cases, the only way to obtain these information, due to the extremely low values of the astrophysical cross sections.

Indirect experiments may use, e. g., beams of stable (or unstable) nuclei at energies in the range of 1-10 MeV/nucleon. These involve:

1. Elastic scattering experiments, which help to determine the matter density profile of unstable nuclei, not accessible in traditional experiments (e.g., in electron scattering), or the optical potential needed to study the spectroscopy of these nuclei via inelastic experiments [13];

2. Transfer reactions, which are direct probes of spectroscopic factors and matrix elements with the same structure as those involved in astrophysical fusion reactions [14];

3. Charge exchange reactions, which are closely linked to Gamow-Teller and Fermi matrix elements needed to calibrate, e.g., neutrino detectors. This, in fact, maybe the only way to access these matrix elements, since they generally involve neutrino energies which are not directly obtained in beta-decay experiments [15];

4. Tests of fundamental interactions, in sub-barrier elastic and inelastic scattering experiments. For example, in Mott scattering with identical nuclei one can disentangle the tiny effects due to nuclear dipole and quadrupole polarizabilities, vacuum polarization, quasi-molecule formation etc., by looking at shifts in the Mott oscillations [16];

5. Atomic physics effects in fusion reactions. Although the energies involved in astrophysical fusion reactions are too low, compared to the energies considered here, there are very important issues which can be studied at rather higher energies (and with heavier nuclei) which are directly related to the same physics in astrophysical fusion reactions [17]. One of these problems is related to the effect of the screening by atomic electrons in the fusion cross sections of light nuclei [17]. This occurs at energies of a few tens of keV for very light nuclei (e.g., d+p), but increases to some MeV for heavier nuclei. For these later cases, the effect of atomic screening can be studied in this facility. These studies are of extreme relevance, since there is an unsolved puzzle, regarding a factor of two discrepancy between the theoretically calculated and the experimentally observed atomic screening effect on the magnitude of the fusion cross sections [17]. Being a problem of atomic origin, theory should be quite reliable and its failure tends to imply new physics;

6. Coulomb excitation experiments, which is a state-of-art technique to unravel the structure of nuclei [18]. Specially, for radioactive beams, this technique is very useful and beam energies of a few MeV/nucleon have been shown to be ideal for weakly-bound systems [19]. In fact, the Coulomb dissociation of weakly-bound nuclei is considered as one of the best techniques to obtain the cross sections for radioactive capture reaction of astrophysical interest [19].

The list above describes only a few possibilities on how to use a beam in the 1-10 MeV/nucleon range in order to access information on astrophysical nuclear reactions at the 10 keV - 1 MeV energy range, or to study the structure of unstable nuclei.

There follows a few examples of some specific reactions related to the above list and which are by no mens intended to give a complete scope of each field.

1. ^{11}Li + ^{12}C, or ^{11}Li + ^{208}Pb, elastic scattering has been studied in several laboratories at energies in the range of a few tens of MeV/nucleon at GANIL/France and MSU/U.S.A. [20]. Similar experiments have been carried out for ^{6}He, ^{8}He ^{11}B, ^{14}C etc.. At lower energies (1-10 MeV/nucleon), elastic scattering is dominated by a Fresnel pattern [20]. Nonetheless, the coupling of a soft dipole mode to the elastic scattering channel can be studied in such experiments for a large number of light nuclear isotopes of current interest [20].

2. The reaction ^{7}Be(p,γ)^{8}B is a key one to determine the flux of high energy neutrinos from the Sun [21]. The relevant matrix elements for this reaction can be extracted from, e.g., ^{7}Be(d,n)^{8}B or ^{7}Be(^{3}He,d)^{8}B, reactions at 10 MeV/nucleon [22]. A series of spectroscopic factors needed to calculate direct capture reactions of astrophysical interest are not known and must be extracted from experiments. These include light as well as heavy nuclei, e.g., ^{7}Li(d,p)^{8}Li or (d,p) reactions on heavy neutron rich nuclei, close to the N-shell magic number where level densities are expected to be much smaller than those needed to justify the use of statistical calculations (e.g. Hauser-Feshbach type) [23]. R-matrix theory with Breit-Wigner resonances, or a simpler direct capture model might be more justified in these cases [23]. These theoretical calculations are generally the only source of cross sections for rapid neutron capture (r-process) in astrophysical environments [23], like in the hot neutron bubble occurring behind the shock wave in supernovae explosions. Most of these cross sections are impossible to be measured directly on the neutron-rich side of the nuclear chart [23]. However, transfer reactions can provide the theory with reliable values for the spectroscopic factors and level density parameters [23].

3. The ^{37}Cl, ^{71}Ga, ^{127}I and other neutrino detectors need the knowledge of Gamow-Teller and Fermi matrix elements to calibrate them for neutrino capture experiments. Charge exchange reactions of the (p,n) type is an useful tool to obtain these matrix elements. Heavy ion experiments, e.g., (^{12}C,^{12}N) reactions can also be used for such purposes [15]. Both reaction processes can be studied with a 10 MeV/nucleon machine [15].

4. The ^{12}C+^{12}C Mott scattering at about 1 MeV/nucleon has been used to test the effect of vacuum polarization in nuclear scattering [24]. More recently, even the possibility of the existence of long range QCD effects in nuclear elastic scattering at sub-barrier energies has been studied in this way [25]. In this context, atomic effects like the emission of delta electrons, or the formation of quasi-molecules, are far from being fully understood [26]. This facility could test these effects in Mott scattering experiments with several nuclei at energies around 1 MeV/nucleon, or lower.

5. The effect of screening by the atomic electrons on the fusion cross sections can be studied for any possible reaction at about 1 MeV/nucleon, e.g., ^{58}Ni + ^{12}C reaction. The puzzle observed in astrophysical reactions with light nuclei should also manifest in these reaction cases. Thus, setting constraints on the kind of physics which might enter to explain this

puzzle [17].

6. Coulomb dissociation of ^{6}Li, ^{7}Li, ^{8}B, ^{11}Li, ^{11}Be, etc. (and of heavier nuclei) has been used to obtain the response functions of these nuclei to electromagnetic operators [14]. Since (in 1st-order perturbation theory) this relationship is exact [14], knowing the Coulomb dissociation cross section amounts to know photodissociation cross section for these nuclei, too [14]. Detailed balance allows to relate the photo-dissociation cross section to radioactive capture cross section of astrophysical interest. For example, the ^{7}Be(p,γ)^{8}B reaction has been studied by many groups using this method. One can show that [27] for weakly bound system the Coulomb dissociation cross sections are highest in the beam energy of 5-10 MeV/nucleon, just the case of this facility. Numerous reaction of this type could be studied with this technique, specially Coulomb dissociation in the (γ^*,n), (γ^*,p) channels for heavier nuclei. These are of relevance for the r-(and rp)processes [23].

II - Nuclear Structure

It is often thought that nuclear structure physics is basically understood and that the essential ingredients have been well in hand since 1952. In this view, widely held both inside and outside nuclear physics, the basic microscopic underpinnings of nuclear structure in the concepts of shell structure, magic numbers, and the predominant importance of the valence shells were established with the development of the single particle shell model in 1948. In 1952 the concept of coherent notions of nucleons, leading to the ideas of nuclear shapes and collective excitations, was put forward. These twin Noble Prize winning pillars of nuclear physics were linked by the early 1960's with the application to nuclei of the concepts of pairing and quasiparticles and the application of TDA and RPA techniques to provide a microscopic description of collective modes. The infrastructure being established and universal, the rest would be mere details.

But suppose we are now told (or learn through experiment) that we do not know what the applicable shell structure is, or even if the concept of a shell model potential is itself valid; that magic numbers, if applicable at all, are variable; that single particle energy sequences and collective excitations built out of them are different than we thought; and that our understanding of how structure evolves with N and Z may apply only to an isolated set of nuclei. We would then conclude that we do not really understand nuclear structure, and that we need to go back to the basics and recast our ideas in the face of these new ideas and that the field is suddenly perched at a new beginning. Suppose further that we were then handed the experimental tools to probe structure anew and to provide the data to build a new synthesis. We would be glimpsing the horizons of an exciting time indeed.

This is the situation we are presented with now, with new and growing evidence of the fragility of shell structure off the valley of stability, and with the advent of radioactive ion beams (RIBs) as a tool to attack these questions and to forge a new renaissance in our understanding.

Nuclear Structure

The advent of RIB's opens entirely new horizons in nuclear physics generally and in nuclear structure in particular. By giving access to new regions of nuclei with exotic N/Z ratios, RIB's will allow us to stress nuclei in the isospin degree of freedom. There is every likelihood, as recent calculations and experiments have suggested [36]-[38], of new nuclear physics and of nuclear structure and structural evolution unlike anything seen to date.

It is worthwhile briefly outlining some of these opportunities with RIBs, with emphasis on nuclei below A 100 which will be the primary focus of the new RIB facility. For more detailed discussion the reader is referred to a number of recent extensive discussions [39]-citeser96.

One way to view the new physics with RIBs from the many-body quantum mechanical point of view is illustrated in Fig. A. New physics arises from the combination of the Pauli Principle with the typically low degeneracy (2j+1) of shell model orbits, combined with the weakness of the strong force in nuclei. [That weakness implies that nucleons in deeply bound orbits cannot collide since there is insufficient strength to elevate them to unoccupied orbits, and, hence, that structure is largely determined by the valence nucleons.] Hence, additional nucleons occupy new orbits and thus experience new valence nucleon interactions. The physics is N,Z dependent. Therefore, RIB's, giving access to new combinations of nucleon numbers, must lead to new phenomena, new manifestations of collectivity and to the evolution of collectivity.

1. Bounds of the Science

   Nuclear physics, for all practical purposes, is bounded by the proton and neutron drip lines (or slightly beyond the proton drip line in some cases). However, while the proton drip line is quite well established up to Pb (it is more accessible being closer to the valley of stability), the neutron drip line is notoriously poorly known. Figure 1 illustrates a section of the N-Z plane showing the valley of stability and various theoretical loci of the neutron drip line. It is evident that the uncertainty in the drip line (the envelope of these predictions), and therefore in the bounds of our science itself, is as large as the range of known nuclei themselves.

   This uncertainty in the drip line reflects a fundamental lack of understanding of the properties of nuclei with a large excess of neutrons. The reasons for this are important for an understanding of the physics motivation for RIB's. As neutrons fill single particle levels to higher and higher energies they become less and less bound, more spatially extended, and with more diffuse density distributions. Whether such a regime of low density neutron nuclear matter can support the standard shell model potential as we know it is a hotly debated question ([36]-[38], [44] and see below). Moreover, residual interactions will be quite different. For example, pairing will scatter pairs of nucleons into the continuum, and valence p-n interaction of bound protons with nearly unbound neutrons will be vastly difference than near stability.

For all these reasons we are poorly equipped to predict the limits of particle stability in nuclei and it will only be with RIB experiments that access such nuclei and thereby reduce the "lever arm" that predictions be at all constrained.

2. Shell Structure

The concept of shell structure, with magic numbers, inert cores, and valence shells (whose properties determine nuclear structure near the ground state) is the microscopic underpinning of nuclear physics. Virtually all microscopic calculations are based on the concept of magicity and yet doubly magic nuclei are very rare species. The only well studied examples are ^{4}He, ^{16}O, ^{40,42}Ca, (^{90}Zr), ^{132}Sn and ^{208}Pb. The barest minimum is known about ^{56,78}Ni and ^{100}Sn. Yet these are the paradigmatic benchmarks of structure. The possibility of further study of candidates for double magicity is enticing indeed.

3. The Fragility of Magicity

A related concept of the highest importance for nuclear structure is the emerging recognition of the fragility of magicity. Studies of nuclei far from stability over the last two decades have begun to shatter the implicit assumption of the magic numbers and shell structure as we know it. The magic numbers of the standard shell model are likely to be only a particular realization of shell structure as it appears near stability. The $Z = 40$ shell gap disappears near $A = 100$ [45], the $Z = 64$ subshell gap does so near $A = 150$ [46]. More dramatic, ^{80}Zr($N = Z = 40$) is deformed not doubly magic, ^{32}Mg is deformed not singly magic, and there are recent suggestions [47] that S with 28 neutrons is deformed.

Indeed, Nazarewicz and his colleagues have outlined a general scenario of the breakdown of shell structure near the neutron drip line. They argue that the low density neutron skin is unable to support high frequency Fourier components in the Shell Model potential, which then would evolve from a shape given by a Woods-Saxon potential (or a harmonic oscillator plus l 2 potential) to that of a simple harmonic oscillator (maintaining of course the spin-orbit contribution).

The effects of such a scenario are illustrated for nucleon numbers 40-80 in Figure 2, which compares the normal shell model single particle levels with those of a harmonic oscillator. In the latter case, not only are the magic numbers different (now 40 and 70) but the sequence of orbits is radically different. Instead of a $\Delta J = 1$ sequence for the normal parity orbits, one sees a $\Delta J = \Delta l = 2$ sequence. A quadrupole residual interaction will therefore have radically different (and presumably larger) effects in such a case, likely leading to manifestations of collectivity, and to the evolution of collectivity, very different from anything seen to date. Moreover, the return of the unique parity orbit to its parent oscillator shell will inevitably alter the phenomenology of negative parity states and octupole collectivity. Nazarewicz and co-authors have also discussed a "melting" of shell structure entirely. The disappearance of the $N = 82$ gap with increasing N/Z ratio is illustrated in Figure 3.

Of course, new shell structure has impact well beyond nuclear structure. Since much of nucleosynthesis occurs far from stability, there could be significant changes in our understanding, for example, of the r-process. There have, indeed, already been hints that the disappearance of the $N = 82$ gap may account for one of the apparent anomalies in r- solar abundances.

4. N = Z nuclei

Nuclei with $N = Z$ constitute both a unique locus in the N - Z plane and a locus of singularities in residual p-n interactions. For reasons ultimately related to Wigner supermultiplet theory [48], the $T = 0$ valence p-n interaction of the last proton and neutron jumps by a large amount in (and only in) $N = Z$ nuclei. This is illustrated by the spikes in Figure 4. However, the double difference in binding energies needed to construct the p-n interaction in Figure 4 is not known for $N = Z$ nuclei beyond about $N = Z = 32$. Therefore, it is not known whether the apparent decrease in the magnitude of the spikes reflects a straightforward evolution within a given major shell (shell model calculations predict a kind of parabolic systematics of $dV_{pn}(N = Z)$ across a shell) or a dissolution of the $N = Z$ singularities as Coulomb forces grow and as proton and neutron single particle energies begin to migrate. Even a very few, appropriately chosen, mass measurements can add significantly to the data for $N = Z$ nuclei in Figure 4.

$N = Z$ nuclei may exhibit other exotic properties, for example, enhanced $T = 0$ p-n pairing. In such a scenario, odd-odd nuclei could exhibit a pairing gap. Moreover, Coriolis effects may be significantly altered since a p-n pair coupled to $J = 2j$ would not experience a decoupling effect as in like nucleon pairing (where the Coriolis effect is different for the oppositely orbiting nucleons). This could delay or inhibit band crossing and rotation alignment effects. Finally, the study of near N = Z mirror nuclear pairs, such as ^{49}Cr - ^{49}Mn will offer insights into the roles of protons and neutrons coupled to N = Z cores.

5. Proton Radioactivity

   Due to the Coulomb and angular momentum barriers, nuclei past the proton drip line often have particle emission half lives that allow spectroscopy. This is the only situation where we can study structure beyond the limits of nuclear stability. Moreover, the lifetimes for delayed proton emission are structurally revealing since they reflect tunneling through a 3-dimensional barrier. These half-lives are sensitive to single particle orbit (l-value) and to shape (tunneling in a deformed potential can be quite different than in a spherical nucleus). There are several opportunities for such studies below A = 100.

6. Nuclear Structure

   There are a number of highly important nuclear structure questions that can be probed in exotic nuclei. We mention only a few. One, of course, which is of the utmost importance, is the evolution of structure with N,Z, and A. Recently, a number of remarkable correlations of nuclear observables have been shown to characterize all known nuclei. An example is the tri-linear correlation [49] of the energy of the first 4+ state with that of the first 2+ state in even-even nuclei [An analogous phenomenon exists for odd-A nuclei [50]]. Do such correlations appear in new regions with extreme N/Z ratios or are they only a reflection of the nuclei we happen to know? Such a question strikes at the heart of the universality of shell structure and interactions discussed above.

   This yrast correlation is intimately related to the issue of the survival of collective multi-phonon states in nuclei [51]. Such states, long thought to be utterly fragmented by Pauli blocking effects, have recently been discovered in nuclei as diverse as spherical ^{114}Cd, deformed ^{166,168}E and ^{232}Th [52]-[55].

   Another example is that of "Valence Correlation Schemes" (VCS) in which nuclear properties are correlated in terms of simple functions of the valence nucleon numbers Np and Nn. [The NpNn scheme for collective observables or the aNp-Nn scheme (for separation energies) are examples [56, 57]]. A common property of such VCSs is that new nuclei, far from stability, can often be predicted by interpolation rather than the riskier process of extrapolation. Such schemes also usually involve the easiest -to-obtain data on new nuclei and are therefore easy to test (e.g., by Coulomb excitation) with RIBs.

Another way to address the issue of phonon states and nuclear shapes far from stability, without the need for detailed spectroscopy, is to exploit the concept of fusion barrier structure. It has recently been shown that the fine structure of the cross section in the barrier region [d2s/dE2] is sensitive to barrier shape and coupling to inelastic or transfer (collective) channels. Needed for such experiments are only a fine control on beam energy (few 100 keV) and a velocity filter.

Experimental Techniques for Nuclear Structure

Experiments with RIBs are inherently difficult, largely for the three reasons of high background radioactivity from decay of the beam, beam impurities (especially impurities from the primary production beam), and low beam intensities. Solving these issues requires innovative experimental techniques and exploitation of new and more efficient signatures of structure. Examples of the latter are the correlation of observables mentioned just above. Here we focus on the experimental techniques.

As a basis for the discussion below we assume primary beams from the Pelletron/LINAC system with intensities of 1010-1012 particles/sec. Interaction with a production target of thickness in 0.1 mg/cm2 and production cross section of 10-100 mb give a RIB beam intensity of 102-105 particles/sec. Only about 1 in 107-108 primary beam particles is converted to a RIB nucleus. Hence, the first requirement is a primary beam rejection ratio of ≈ 107:1. For some radioactive species up to A ≈ 100, (and for most up to A ≈ 60) this will be possible with the double solenoid system, especially if coupled with other selection devices. If the solenoids are operated with a degrader at the intermediate cross-over point, primary beam and reaction products can be separated according to Z for species of the same E/M. An electrostatic element at this point in the system could further distinguish species. Auxiliary detectors can provide powerful and selective triggers. For example, charged particle, or neutron, detectors near the production target can be used to select fusion evaporation channels and to reject unreacted or inelastically scattered primary beam particles. g-multiplicity detectors (e.g., the existing multi-element NaI array or a new BGO array) can serve a similar purpose. A time-of-flight system can do the same. (See more extensive discussion in Section 4.)

We assume then that we have a reasonably pure radioactive ion beam of intensity up to ≈ 105 particle/sec. Several experiments are immediately feasible with a minimum of difficulty. Primary among these are the study of the radioactive nuclei themselves and of their daughters.

The former can be easily achieved using Coulomb excitation (CE) in inverse kinematics [58]. This does not require precisely defined beam energies (it only requires well known beam energy distributions - e.g., as measured with a scintillator) and hence CE at a variety of incident energies can be done using a set of degrader foils. CE of a RIB of A $\approx$ 50-60, for example, on a light target (e.g. ^{12}C) in inverse kinematics has the advantage that the radioactive nuclei exit the secondary target region downstream and hence do not deposit activity on or near the g detectors surrounding the target. A typical CE apparatus for RIB studies has been developed by the Yale-Clark-BNL Group and is illustrated in Figure 5. Low energy CE ($\approx$ 1.5 MeV/A) followed by higher energy CE (at say, 2-4 MeV/A) can yield successive sets of E2 matrix elements in a rather straightforward way.

Beta decay of the RIB nuclei leads to other exotic species suitable for study. There are many approaches possible. A simple one involves a moving tape collector on which the RIB is deposited for a period of time (several half-lives of the activity of interest). Using a stepping motor the tape is then moved - either to an intermediate "holding position" to await the decay of shorter lived species, or to a b-g detector array. In either case, the decay of interest is subsequently observed in p and g detectors. b-g coincidences or g-g coincidences can be used with decay intensities as low as 103/sec. At $\approx$ 104/sec, one can exploit advanced fast timing techniques such as FEST [59] [Fast Electronic Scintillation Timing], using thin plastic b detectors and BaF2 g detectors, and gating by Ge detectors for cascade selection. FEST can measure level lifetimes down to the 10-20 ps range. Such decay work is ideal for low spin nuclear structure and the study of collective and pre-collective structures. Masses can also be measured by determining QB values.

A clever "piggyback" arrangement combines CE with decay. The RIB nuclei first undergo CE in a light secondary target and then proceed downstream to the moving tape collector.

It is possible to study selected reactions induced by the RIB nuclei as well. The fusion barrier studies mentioned above are one example provided precise enough control of the primary and RIB energies is obtainable.

Another example is fusion evaporation (FE) reactions of the type Trgt (RIB, Xn,Yp,Za). If the RIB energies are just above the Coulomb barrier for the target, only a few reaction channels are important and it often happens that one dominates. Cross sections can be in the 100s of mb range. In optimum cases with a RIB intensity of 105 particles/sec and a 1 mg/cm2 target, on the order of a few residual nuclei of given N,Z can be provided in 10 seconds. This is sufficient for selected experiments of the basic structure. For example, in even-even nuclei, virtually all the g intensity feeds through the yrast states of J #163# 6^+ . Hence, these energies can be obtained. It is conceivable that Doppler Shift analysis of line shapes might even yield spin-averaged lifetimes and hence E2 matrix elements, see ref. [60].

Also possible in related cases will be transfer reactions or deep inelastic scattering provided one or a few channels dominate.

Finally, RIB nuclei produced in an isomeric state raise the intriguing possibility of carrying out CE studies based on excited states (even medium to high spin states).

Careful and detailed study of individual beam intensities and detector configurations will certainly reveal other possible experiments but the above overview provides abundant motivation for this extremely cost-effective upgrade plan.

2.1 Stable Beams

Once the LINAC is in place a number of exciting programs with stable beams become possible. This is not the place for an extensive discussion, but studies of deep inelastic reactions, multi-nucleon transfer reactions, fusion barrier distributions heavy ion induced fission, heavy ion induced b-decay, elastic and inelastic scattering are a few of the techniques available. Studies of shell structure, especially in the medium mass range from A = 60-100 would be very useful especially with the advent of new Shell Model computational techniques (Monte Carlo Techniques) that offer the possibility of new insights in complex multi-particle systems. Studies of the onset and evolution of collectivity near and below A = 80 offer possibilities to study the empirical correlations mentioned above that have primarily been studied in heavier nuclei.

With the installation of the solenoid system, stable beam experiments become even more attractive since the solenoids can be used as an inexpensive but effective fragment separator for in-beam studies of FE or deep inelastic reaction products. Rejection of primary beam particles is easy if small angle entry to the solenoid is blocked. Different reaction products can be discriminated using degrader foils at the cross-over point. Of course, even before RIBs are realized the solenoid system performance can be tested with stable beams. Thus, not only will the solenoid installations be useful for RIB studies but will provide a potent upgrade to the capability for studies with stable beams.

3 AVAILABLE FACILITIES

I - Pelletron-Tandem accelerator

The 8 MV NEC Pelletron Tandem accelerator was the first NEC machine in the world using the pellets technology for charging its terminal. It has been installed at the Department of Nuclear Physics in 1972 under the leadership of Dr. Oscar Sala [9].

The negative ion sources of the accelerator were a duoplasmatron source and Cesium-sputtering SNICS home-made. Recently, the old SNICS has been replaced by a new high current NEC SNICS-II with multiple cathode samples. This new ion source allows, in principle, the production of any ion beam from H^- to U^-. Actually, the limitation in mass of the accelerated species is the carbon stripping foil in the terminal of the Tandem. The intensities which would be soon available at the exit of the Tandem are of the order of 300 pnA (2×10^{12} pps) for light ions and 30 pnA (2×10^{11} pps) for heavier ones.

The excellent emittance of the beam delivered by the Tandem ($\leq$ 10 π mmrad) and the good energy resolution ($\approx$ 10 keV) makes this machine an excellent tool for precise measurements of angular distributions and excitation functions.

The beam of the Tandem can be pulsed in order to perform precise time-of-flight measurements and for injecting the beam in the LINAC booster. The maximum energies available at the exist of the Tandem varies (according to the figure ...) from 2 MeV/nucleon to 4.5 MeV/nucleon depending on the mass and charge state. The minimum energy available is of the order of 0.2 MeV/nucleon.

After analysis, the beam passes through a switching magnet and can be used in one of the 5 experimental facilities available presently in the laboratory, i.e. the multipurpose chamber (30B), the new large volume chamber with an array of 40 particle telescopes soon available (15B), the Enge-split-pole spectrometer (15A), the γ-spectrometer (30A) and the time-of-flight spectrometer (45A). The 45A beam line will give place to the transport line to the new superconducting linear LINAC accelerator.

II - Present status of the Pelletron Linac Project

Historically, our accelerator experience began in the 50s with the construction of a 3.5 MV Van der Graff and was extended in the 70s with the purchase of a NEC pelletron type electrostatic accelerator, a first design, which gave São Paulo the lead in the new technology of pelletrons. In 1982 it became evident that it was time for a major upgrade of our facilities to offer the new generation a more modern and stimulating environment for nuclear physics research. Thus began a series of studies to ascertain what type of accelerator would best serve our research interests yet not overtax our resources of manpower and economic support. This analysis was summarized in a report in 1982 [29] where it was concluded that the best path to take would be the construction of a superconducting linac based on the designs of the ATLAS [30] project developed at Argonne National Laboratory. Furthermore, in dominating the technology of superconducting resonators, we would enter an area of accelerator physics and technology which, by all indications, is the one destined to be used exclusively in the design and construction of future particle accelerators. The Linac of São Paulo will be used as a booster for the existing Pelletron Accelerator (8 MV/m nominal) and will be consisted of niobium split-ring superconducting resonators (Fo = 97 MHz) based on the Argonne design.

Final laboratory projectile energies of 15 MV/A to elements from C to Fe should be achieved after installing the two first cryostat (phase I). In this phase, the superconducting linac will be consisted of 14 niobium split-ring resonators (4 low beta (0.060) and 10 high beta (0.105)) in four cryostat. Two small cryostat for one resonator to the superbuncher (low beta) and rebuncher (high beta) and two cryostat for the other 12 resonators. The configuration of 3 low beta and 10 high beta resonators was the best compromises in the mass region compatible with our experimental program. Figure 1 shows the scheme intended for the Pelletron-Linac system, as well as the distribution of the resonators in the cryostat. The cryostat will be based on the Argonne design.

The beam entering the linac should be bunched into short time pulses of about 100 ps. This is accomplished by a two stage bunching system. The first (or prebuncher) consists of a single gap harmonic buncher (three harmonics, fundamental frequency about 12 MHz) which operates at room temperature and is positioned a few meters upstream from the first accelerating electrode of the tandem. The second stage is a superconducting buncher consisting of one RF resonator situated about 25 meters or so downstream from the tandem exit at the entrance to the linac. The continuous beam out of the the ion source is bunched into 1 ns pulses with a 70efficiency in preserving the beam intensity by the prebuncher and then into 100 ps pulses with almost no loss of intensity by the superconducting buncher. The mechanical part of the pre-buncher is already installed and the RF control system is being built.

Because of the variations which exists in the ion transit time through the tandem, a phase detector is used for dynamic control of the RF phase of the prebuncher pulses, so that the beam pulses arrived at the superconducting buncher with the correct time. Our phase detector will be a 48.5 MHz, spiral loaded resonant cavity based on the design described by Takeuchi and Shepard [31].

The elimination of parasitic beams will be provide by positioning an RF chopper before the analyzing magnet. The chopper will have a 20mm gap and will be positioned at about 2 m from the chopper slits. In this case 5 KV should be enough to separate the parasitic beams. The RF chopper will operate at about 6 Mhz.

All the parts for the first stage of bunching system are already done and practically installed. All the mechanical parts were built in our laboratory and the electronic for controlling this system was bought from Argonne.

The structure of the accelerator tube of our tandem was modified in order to increase the voltage from 8 to 9 MV in the terminal. Basicly, "dead" regions were switched by acceleration tubes with 6 electrodes each. In this way we maximize the energy of the beam entering into the linac. The tandem has been operating satisfactorily after the modifications.

The niobium achieves its superconducting phase under 9 Kelvin. Therefore helium and nitrogen liquid plants are necessary for the operation of the resonators. The closed-cycle helium system, which may be operated in a wide variety of conditions, consists of two Sullair compressors and a CCI refrigerator that nominally yields 300 watts of cooling or alternatively, liquefies 75 liters per hour of helium, if no liquid nitrogen pre-cooling is used. The proposed schematic helium distribution system is shown in figure 2.

The system was designed to provide a continuous flow of cold helium through the superconducting resonators and solenoids. The static heat leak of each cryostat was assumed to be 15 watts, for the cryostat with more than one element, and 5 watts, for the superbuncher and rebuncher cryostat (including the cooling due to RF power dissipation for one resonator). A typical value of 4 watts [32] is expected for the RF power dissipation for each resonator.

Only one of the compressors will be used in phase I because, as it is shown in figure 2, the 150 watts of refrigeration capacity available in this configuration should be enough to maintain the temperature through the accelerator.

Our refrigeration system is totally projected and will be consisted by nitrogen and helium liquid plants and transportation lines. The liquid helium plant production as well as the transportation lines are waiting for installation. For the nitrogen plant we are waiting for the liberation of funds from an approved project presented to a brazilian federal agency. In the same project are also included the cryostat.

Niobium split-ring resonators were chosen to be the acceleration structure in the São Paulo project. The fact of niobium is a better superconductor than lead and Brazil is the largest producer of niobium guided our choice of the material.

The Argonne split-ring resonator has the advantages of more boost per resonator, greater durability of the superconducting surface. Additionally, sections of the Argonne booster, similar to our requirements, were already in operation. Based on these reasons, the choice for this type of resonator was natural.

Therefore, University of São Paulo and Argonne National Laboratory signed a contract (No 31-109-ENG38-85963) back in 1988 for assistance and training in superconductivity technology and the fabrication of 14 niobium resonators. Since then, 7 researchers and technicians from our laboratory have gone continuously to Argonne in order to get trained in this new technology as well as to test the new resonators and electronic equipment associated to the operation of the linac accelerator. Presently, 11 resonators are already in São Paulo and the last three are waiting for a final cold test at Argonne.

Also a new optical system was projected for the beam transport from the tandem exit to the linac entrance and from the linac exit to the experimental area. The experimental area was initially projected for three beam lines. These beam lines will be used for multiple purpose experiments, gamma ray detection and a magnetic spectrograph device.

All the equipment for the beam transport system is already in the laboratory and waiting for installation. Similarly is the situation of part of the electronic equipment for the control of the linac operation.

Due to the layout of the tandem laboratory is not possible to install the new accelerator in the present building without interrupting the research programs for a long period (years). So a new building was projected to accomodate the new equipment described above.

4 NOTRE DAME RIB FACILITY

The Notre Dame - University of Michigan radioactive ion beam facility was conceived approximately ten years ago in order to pursue the exciting physics associated with nucleosynthesis in the Inhomogeneous Big-Bang models. Specifically, Malaney and Fowler showed that a crucial issue in these models is the fact that the nucleus ^{8}Li provides a way around the mass-8 gap and therefore allows the production of nuclei heavier than ^{7}Li (even up to ^{238}U) in the Big-Bang. However, ^{8}Li is radioactive with a half-life of 0.84 s, and none of its reaction cross section had been measured. It was therefore decided to construct a facility, based on a 3.5 T super-conducting solenoid (SCS)(1.5 T.m field integral), that produced the world's first usable radioactive ion beam having energies in the 1-2 MeV/nucleon range. Over the last decade, the initial goal of measuring ^{8}Li-induced reactions was accomplished. A good example is provided by the measurement of the critical ^{8}Li(^{4}He,n)^{11}B reaction cross section; this turned out to be about six times larger than estimates based on the inverse ^{11}B + n reaction which could only determine the cross section to the ground state of ^{11}B. More recently, the program was expanded by the development of a high-pressure gas target that was used to produce a ^{8}B beam for a study of the sub-Coulomb breakup of ^{8}B into p + ^{7}Be. The importance of this work is that it established a limit on the E2 contribution to the Coulomb breakup process, which is important for the understanding of the p + ^{7}Be capture process that results in the neutrino detected by Cl solar neutrinos detectors.

The success of these important radioactive ion beam studies inspired the U.S. National Science Foundation to fund a new facility, currently under construction at the University of Notre Dame, that will extend the capabilities of the original instrument. A conceptual drawing is show in Figure 1. The most important components in this figure are two new super-conducting solenoids having 6 T maximum central field (4 T.m axial field integral) and a 30 cm ϕ clear warm bore. The corresponding maximum energy radioactive ion beam that can be focused by these magnets is given by:

$$E_{MAX} \; = \; 115 \; Q^2/M(MeV) \tag{1}$$

where Q is the charge state and M is the mass number of the ion. This is about 6.5 times greater than the maximum energy of the original facility, and will allow for focusing of radioactive beams up to the maximum energy that can be produced with the Notre Dame Tandem Van de Graaf accelerator. In fact, these magnets are completely compatible with the University of São Paulo (USP) linear accelerator. For example, a charge 20^+ ion in the mass-60 region must have an energy less than 12.5 MeV/nucleon, compared with a maximum energy around 5 MeV/nucleon for phase-1 and 10 MeV/nucleon for phase-2 of the LINAC project. (Since, in the general, the cost of a super-conducting solenoid with central field up to 6-7 T is not a strong function of the field, it does not pay to order a weaker magnet in order to save on the cost of the facility). The liquid He consumption of these solenoids is less than 0.2 L/hr in persistent mode, and less than 1.0 L/hr with an external current of 100 A at maximum magnetic field. Both of these are compatible with the He liquifier capability at USP. The magnets used in the Notre Dame facility can therefore simply be duplicated for the USP RIB project, with a potential saving in design and development costs.

The presence of two magnets in the design is very important in particular, the first magnet transmits all ions with the same magnetic rigidity. Of course, these ions will have very different energies (see eq. (1)), but the purity of the radioactive beam will clearly be rather poor, except in very special cases such as the ^{8}Li beam from the original Notre Dame - Michigan facility where a fortunate set of circumstances allowed for an 80 % pure beam through the use of a suitable blocking aperture for the inelastically-scattered primary beam. With two solenoids, it is possible to use differential energy loss in an energy degrader foil, located at the crossover point between the magnets, to select the ion of interest and move the contaminant ions out of the bandpass of the second solenoid (corresponding to a relative momentum shift of about 3%, depending on the size and location of the beam-collimation apertures in the secondary beam line). This method will not separate isotopes of the same element, however, since the energy loss is very nearly the same for all such isotopes having the same magnetic rigidity. For this reason, the possibility of introducing a coaxial electrostatic (ELCO) lens at the crossover point is being investigated at Notre Dame. Together, the ELCO lens and the second solenoid form a non-traditional velocity filter (Wien filter), with spatially separated electric and magnetic fields, in which the magnetic field is axial and the electric field is radial. Calculations have been done at the University of Michigan which indicate that this field configuration will be useful in separating isotopes of Li with an electric field of perhaps 50 kV/cm at the center of the ELCO lens. The power of this technique should be even greater with the high charge-state medium mass ions that will be available from the USP-LINAC.

In conclusion, the proposed USP-RIB facility, though it will use essentially the same components as the Notre Dame - Michigan "Twinsol" project, will have several important advantages provided by the linear accelerator. In particular, higher-energy (up to 10 MeV/nucleon), higher mass (perhaps up to A = 100) radioactive ion beams can be produced with beam purities approaching 80% in many cases. In addition, the pulsed time structure of the beam will provide a powerful time-of-flight parameter that can be used to reduce backgrounds in many experiments. The capabilities of the Notre Dame Tandem Van de Graaff accelerator (similar in many respects to the USP 8 MV accelerator) limit the reaction mechanism used to make radioactive ions beams to one- and two-nucleon transfer process with primary beams of mass less than 40. This is a very significant restriction. On the other hand, the higher energies available from the USP-LINAC will allow fusion-evaporation and possibly even fragmentation reactions to be used. On a more speculative note, if Uranium beams could be accelerated to energies of a few MeV per nucleon, transfer induced fission reactions could be used to produce a wide variety of very neutron rich fission fragments. The beams formed in this way are not likely to be very pure, but they could be useful in a number of experiments. However, this extended project would require the installation of a low-β initial acceleration stage and an ECR source at the LINAC, and possibly even the addition of more resonators to increase the energy of the primary beam. Finally, it should be noted that setting up the solenoid system prior to the completion of the LINAC is an important consideration, since it would then be possible to begin experiments with a facility similar to that at Notre Dame, with the aim of learning how use the solenoid system to produce usable radioactive ion beams.

Acknowledgements

We are happy to thank the important input given by several colleagues to this report. In particular we like to mention Jin Kolata, Richard Casten and Carlos Betulani.

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UND-UM *Twinsol* Facility

Magnet Specifications:

60 cm coil length

30 cm bore

Max Field: 6 Tesla

Production Target: 12 μ ^{9}Be foil

^{7}Li(^{9}Be,^{8}Li)^{8}Be

^{7}Li(^{9}Be,^{6}He)^{10}B

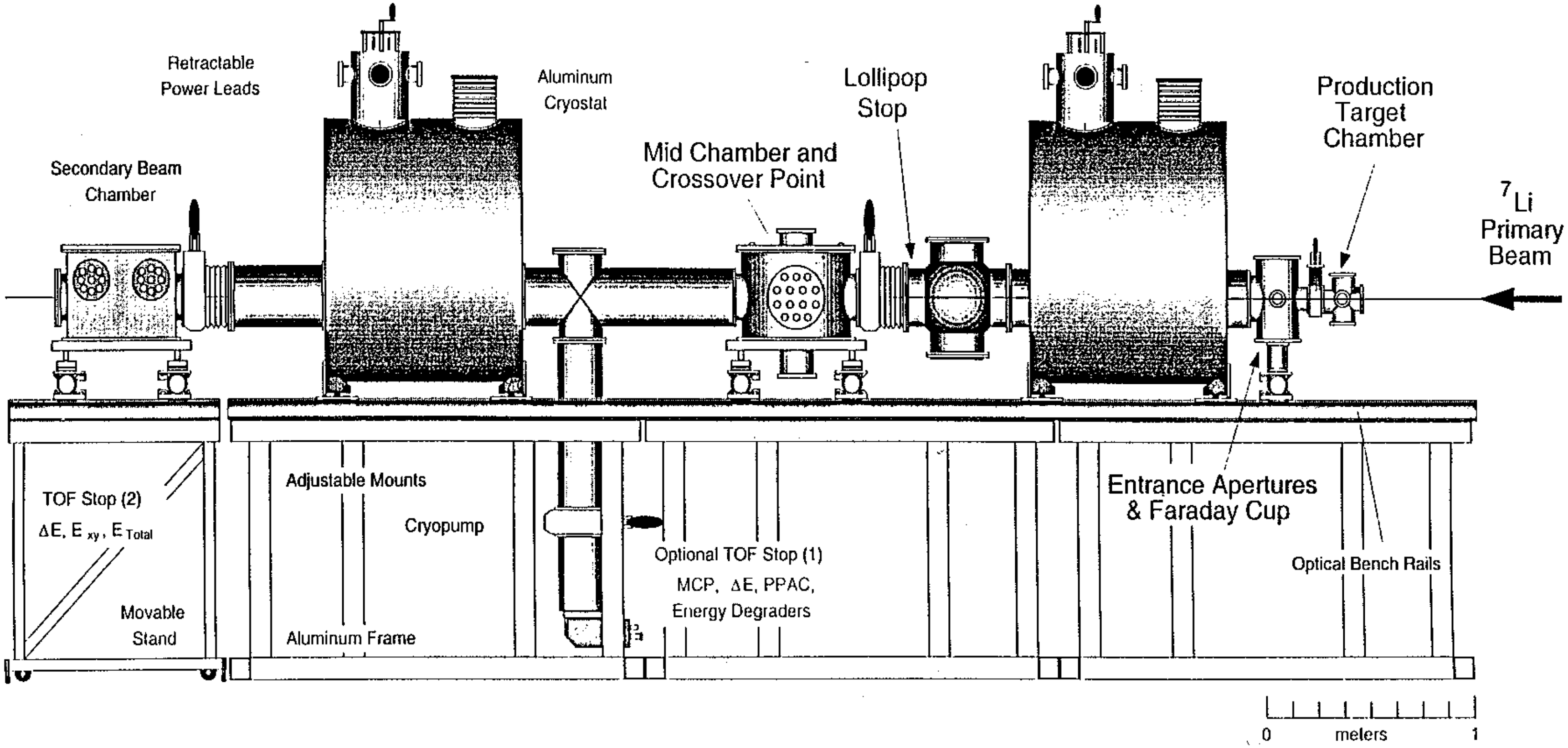

Figure 1: Scale illustration of the University of Michigan - University of Notre Dame double solenoid ion-optical RNB system, Twinsol.

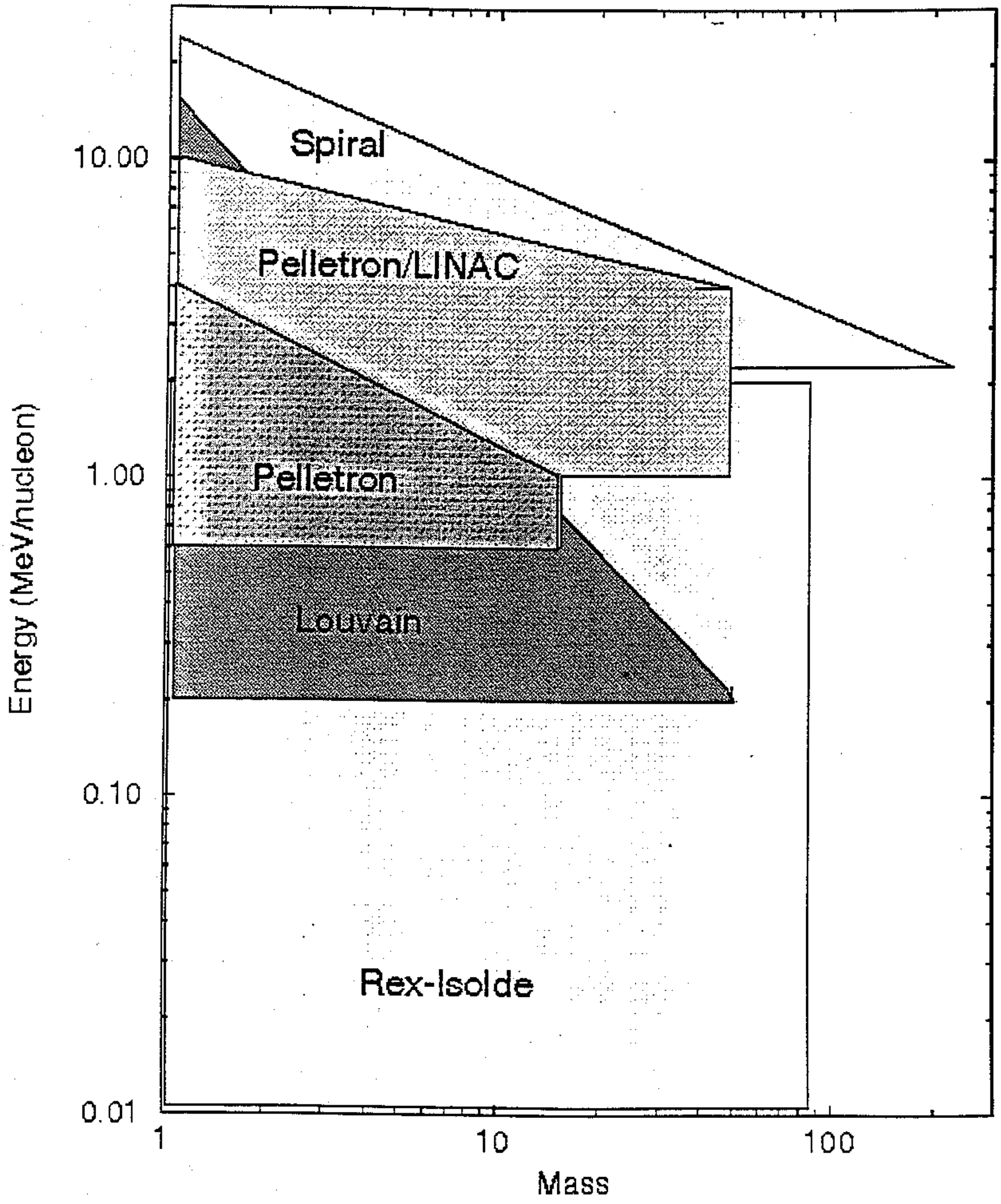

Figure 2: The regions in terms of mass and energy of operations of several RIB facilities.