PHYSICS WITH CYCLOTRONS

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Some of the main themes of modern nuclear physics and opportunities for novel contributions by cyclotrons will be highlighted with a strong emphasis on research opportunities with radioactive beams.

1 Introduction

Trying to give a reasonably complete overview of the physics opportunities with cyclotrons within the constraints of a short talk would either be presumptuous or futile. Thus I will refrain from reviewing what has been done in the past and omit discussion of the many important societal applications of cyclotrons and the related physics or interdisciplinary research. Instead, I will give a selective and admittedly biased picture of what can be done in the future. For this purpose, I will set a rough framework for the main issues addressed by modern nuclear physics research, characterize where cyclotrons fit in, and then give a few selected examples.

2 Accelerators at the frontiers of subatomic physics

It may be useful to summarize the properties of cyclotrons from a user's perspective: Since cyclotrons typically produce beams of less than 1 GeV/nucleon, they do not push the energy frontier. They do have, however, a number of nice features which make them popular with nuclear physicists. Cyclotrons are well understood and generally very reliable. They produce continuous wave beams (which is good for coincidence experiments), and they can accelerate ions from hydrogen to uranium with variable energy, good intensity, and good emittance. Furthermore, cyclotrons are attractive because they are very compact (especially superconducting cyclotrons): in terms of performance per square meter of real estate they are unsurpassed. Compactness, however, comes with the engineering challenge of tight tolerances which can be a problem when pushing the other frontier of accelerator-driven nuclear physics -- the sensitivity frontier which essentially translates into an intensity frontier for the accelerators. Nevertheless, cyclotrons continue to play an important role at the sensitivity frontier where intense primary beams are often used to produce beams of secondary particles, e.g., pions, muons, or radioactive beams. An important challenge for cyclotrons will be to compete with linacs at the intensity frontier, e.g., as drivers for the next generation of radioactive beam facilities.

3 Key questions for nuclear physics

Most of the mass we know is concentrated in atomic nuclei, objects smaller than 10^{-14} m in diameter, but of such immense density that the earth would have to be compressed to a sphere of slightly less than 200 m radius to reach nuclear matter density. Extended objects at this density, neutron stars, exist in the universe, but not in our solar system. Their properties and the cataclysmic conditions under which they form are among the many intriguing questions nuclear physicists are about to answer.

On earth, the detailed properties of nuclei and nuclear matter must be inferred by investigating how nuclei decay, transform from one species into another, or how they behave when subject to extreme conditions of pressure, temperature, density, deformation, rotation, etc. These conditions are mostly created and studied in nuclear collision experiments -- and it is here where cyclotrons make an outstanding contribution.

At the risk of oversimplification, I would like cast the main thrusts of modern nuclear physics research into a few overarching themes. It will be obvious, that cyclotrons play an important role for virtually all of them.

- *What are the building blocks of matter and how do they interact?*

The Standard Model incorporates the known elementary particles and forces (QCD, electromagnetic and weak interactions). While it has been remarkably successful in explaining many phenomena, it is believed to be an incomplete theory. Therefore, it is being subject to ever more stringent scrutiny in order to discover its limitations. In these studies of fundamental interactions and symmetries, cyclotrons play a significant role.

We still do not know why the number of neutrinos detected from the sun is smaller than calculated and whether neutrinos have mass. The answer may come form the next generation of neutrino experiments to be performed within the next decade.

At the most basic level, the origin of mass is still a mystery. The related question of Chiral Symmetry Restoration, whether quarks become massless at high energy density, is an important question to be explored at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) under construction in the United States and Europe, respectively.

- *How do we build complex systems (nuclei) from elementary building blocks (quarks and gluons)?*

Two bridges must be built: We still cannot derive the properties of nucleons from those of quarks and gluons, nor can we predict the properties of large nuclei, e.g., their shapes and collective motion, from the known interaction of protons and neutrons. This "constructionist" aspect of nuclear physics is fundamentally different from the predominantly "reductionist" approach of high energy physics. The task of building these bridges presents a formidable theoretical challenge which can only be tackled with the help of the most advanced computers and may require fundamentally new approaches. Cyclotrons play an important role in the experimental exploration and/or verification of the second bridge.

The related more general problem of understanding the self-organization of complex systems from simple substructures lies at the heart of may scientific endeavors and constitutes, in my opinion, one of the great challenges for science in the coming century. The self-organization of matter is a far-reaching theme -- extending for example to the biological sciences trying to understand (and *design*) the functional properties of proteins and other large molecules in living cells.

- *What are the phases of strongly interacting matter?*

Two phase transitions are predicted to occur: a liquid-gas phase transition at modest temperatures ($\approx$ 10 MeV), and a deconfinement transition at much higher temperatures ($\approx$ 200 MeV). The manifestation of these phase transitions in finite strongly interacting systems formed in heavy-ion collision experiments will be a subject of intense experimental and theoretical work during the next decade. The liquid-gas phase transition is being studied at existing medium-energy facilities (e.g., GSI, GANIL, MSU -- the latter two are cyclotron facilities), and the deconfinement transition to a quark-gluon plasma will be investigated at the high-energy colliders, RHIC and LHC.

Knowledge of the equation of state of nuclear matter, including its dependence on neutron-to-proton ratio, is important for the understanding supernova explosions.

- *What is the origin of the elements in the cosmos?*

Many elements are formed in explosive stellar environments with reaction paths proceeding via very neutron-rich or, under different circumstances, very proton-rich nuclei. The properties of either are largely unknown. Moreover, the sequence of events leading to supernovae explosions (in which most of the heavier elements on earth were formed) is not fully understood. While the approximate paths of element formation inside stars can be outlined by extrapolating theoretical model calculations to unknown nuclear species, there is a critical need for experimental data which could either provide benchmark tests for these theoretical predictions or which could provide an empirical input to numerical reaction simulations. Cyclotrons play an important role in the production of the nuclei far form stability needed for these studies.

- *What are the limits of nuclear stability as a function of proton and neutron content, and what are the properties of nuclei with very unusual neutron-to-proton ratios?*

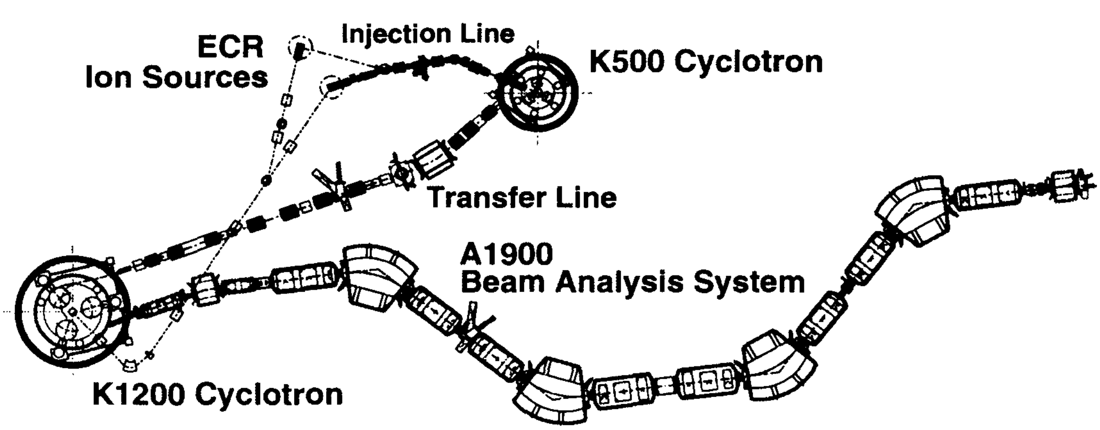

Figure 1: Layout of the K500⊗K1200 coupled cyclotron facility presently under construction at Michigan State University. A high-intensity beam of low-charge-state ions is injected into the K500 cyclotron, accelerated to moderate energy, transported into the K1200, stripped, and then accelerated to full energy. A newly built A1900 fragment separator provides efficient collection and separation of the projectile fragments of interest. Capability for K1200 stand-alone operations is retained.

While this question is of much interest for nuclear physics *per se*, it is also important for nuclear astrophysics as discussed in the preceding paragraph. Some very neutron rich nuclei have extended distributions of dilute, nearly pure neutron matter (neutron "skins" and "halos") which are of much theoretical interest and a subject of intense investigation. Most of the research in this area is currently carried out at modern cyclotron facilities.

4 Radioactive beam facilities

Important advances, especially in nuclear astrophysics and nuclear structure research far from stability, will be possible with intense beams of short-lived isotopes ("radioactive beams"). Advanced radioactive beam facilities will allow the production and study of many new nuclei with presently unknown properties. Here again, cyclotrons play an important role. There is consensus that this research is best carried out by building several second-generation radioactive beam facilities around the world. For example, in the United States the 1996 Long Range Plan for Nuclear Science of the DOE/NSF Nuclear Science Advisory Committee (NSAC) recommends: "The scientific opportunities made available by world-class radioactive beams are extremely compelling and merit very high priority.... The fragmentation and Isotope Separator On-Line (ISOL) techniques are complementary in the species and energies of the beams produced. Thus, they drive different aspects of the science."

Projectile fragmentation facilities have the advantage of fast separation by *physical* means which makes them particularly well suited for the production of beams of short-lived ($\tau > 1$ μs) nuclei far from stability. This technique produces medium energy beams of modest emittance, but it is hard to produce high quality beams of low energy. As an illustration, Figure 1 gives the layout of K500⊗K1200 coupled cyclotron facility presently under construction at Michigan State University. More details about this upgrade will be given by Richard York later at this conference.

ISOL facilities have the advantage of being able to deliver low energy beams of excellent emittance needed for some nuclear structure and astrophysics applications. Disadvantages are (i) the slower and *chemistry-dependent* diffusion of isotopes from the production target which makes this method less useful for lifetimes much shorter than about 1 second, and (ii) the high levels of radioactivity in the ion source, which necessitates robotic handling and throw-away ion sources.

Most radioactive beam facilities under construction use cyclotrons, but emerging plans for some of the most advanced high-intensity facilities employ high-intensity linacs.

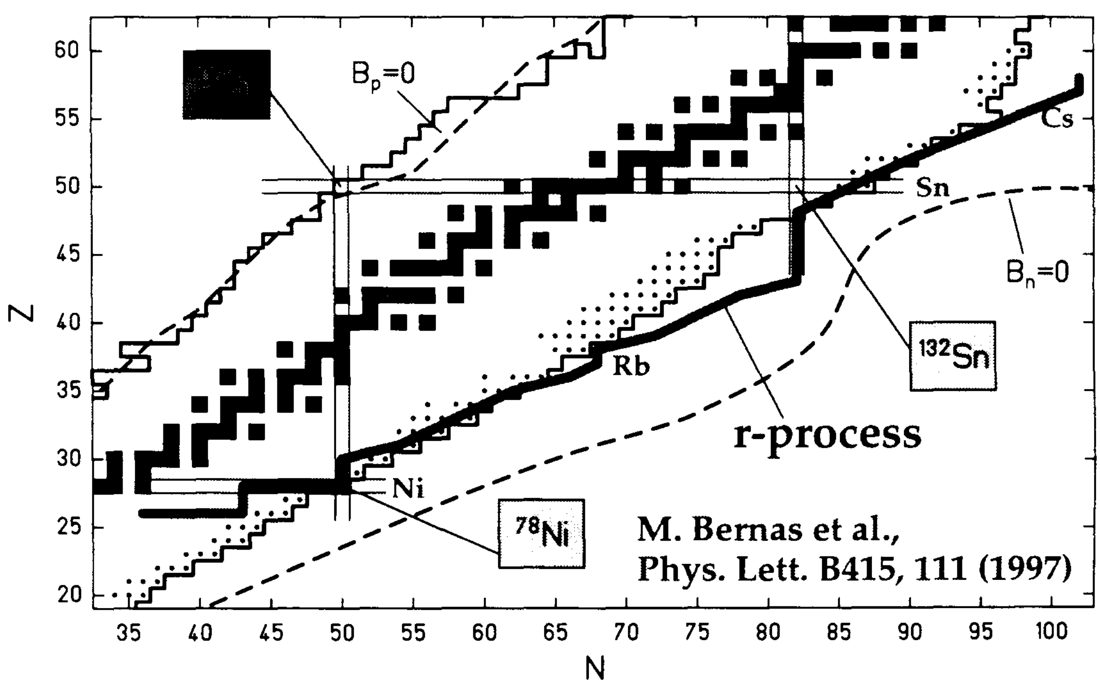

Figure 2: New isotopes (indicated by dots) recently produced at GSI [2]. Important shells and the path of r-process nucleosynthesis are indicated.

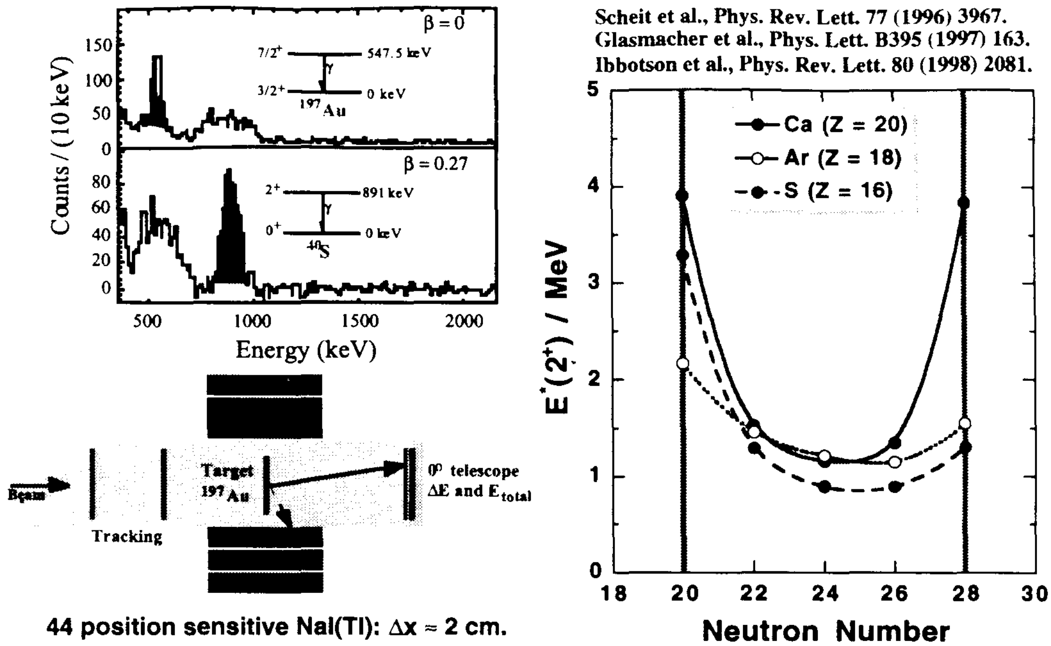

Figure 3: Coulomb excitation experiment with fast beams performed at MSU [3]. The left part of the figure illustrates the technique, and the right part gives the measured systematics of $E^*(2^+)$.

5 Selected Physics Examples

The abundance of elements produced by the rapid neutron capture (r-) process in stars provides circumstantial evidence that shell effects, well known and understood for stable nuclei, may be weakened ("quenched") for very neutron rich nuclei [1]. Recent beautiful experiments by a GSI/Orsay collaboration [2] have demonstrated that it is possible to produce several r-process nuclei in the laboratory by fission of relativistic uranium nuclei and isotope separation in flight, see Figure 2. Thus, direct investigation of shell structure far from stability will clearly be possible with intense radioactive beams provided by next generation radioactive beam facilities.

For lighter nuclei, first interesting measurements [3] of the excitation energies of low-lying 2^+ states in even-even Ca, Ar, and S nuclei indicate a weakening of the N=28 shell in the lighter, more proton deficient, nuclei. These experiments were performed by Coulomb excitation of fast neutron-rich projectiles at very small angles. The use of a position sensitive NaI(Tl) detector array allowed to perform the necessary Doppler-shift correction and clearly identify the lowest 2^+ state in the projectile, see Figure 3. Such experiments can be done with beam intensities as low as 10 s^{-1}. New granular Germanium arrays will significantly improve the resolution for future experiments.

Important structure information can already be obtained by precision mass measurements. Figure 4 illustrates the uncertainties of mass predictions of very neutron rich Sn nuclei [4]. While virtually all models fit known masses, large discrepancies exist when the models are used to extrapolate far into the region of (unknown) neutron-rich nuclei. In particular, the location of the neutron drip-line is highly uncertain.

Mass measurements far from stability require highly sensitive methods, which need only few nuclei to do the measurement. The Schottky mass spectrometry technique developed at the ESR at GSI represents a beautiful example of highly efficient mass measurements. Within a few days, previously unknown masses of more than 100 nuclei were determined with accuracy in the 80-220 keV range [5]. New mass spectrometers and ion traps under development will allow comparably efficient measurements with much improved resolution.

Detailed studies of halo-nuclei with extended neutron distributions are of great current interest. Most information on these nuclei has been obtained in the A<20 region, with ^{11}Li being the most interesting and most studied case, but extended halos and potentially new interesting modes of collective excitations are predicted to exist also for significantly heavier nuclei, see Fig. 5 as an example [4].

6 Conclusion

Many new discoveries can be expected with the next generation of radioactive beam facilities for which cyclotrons will play an important role. Equally important, however, for the full exploitation of this new sensitivity frontier will be the development of highly efficient high-resolution detectors.

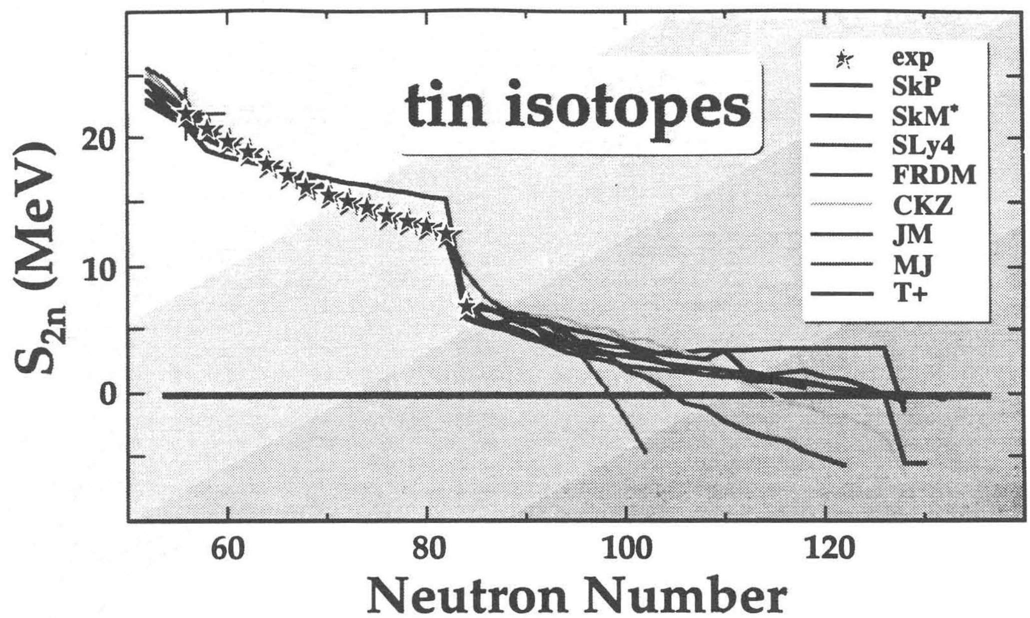

Figure 4: Two-neutron separation energies of even tin isotopes predicted by different models and mass formulae. Experimentally known values are indicated by stars [4].

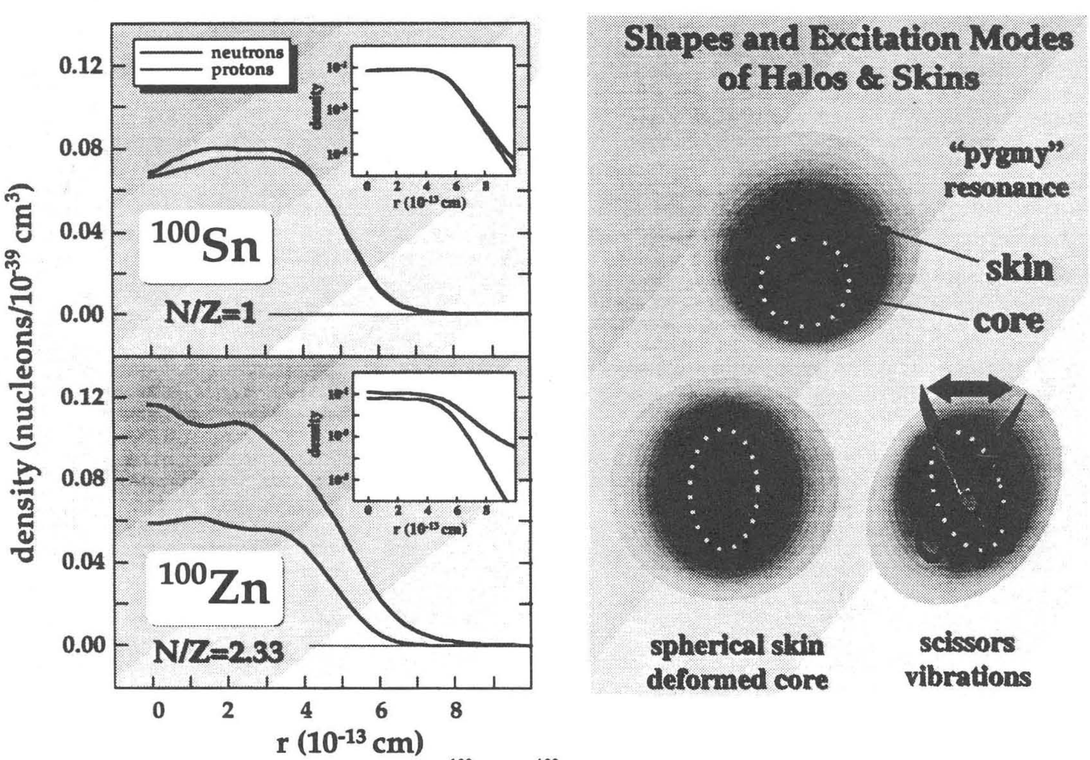

Figure 5: Proton and neutron density distributions predicted for ^{100}Sn and ^{100}Zn (left panel). Illustration of possible new modes of collective excitations (right panel) [4].

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