CONF-960950--1
ANL/PHY/CP--92085

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JAN 16 1997

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Nuclear structure and reactions with stored nuclei

W. Henning

MASTER

Physics Division, Argonne National Laboratory, Argonne, IL 60439-4843

The use of ion-storage rings is discussed for studies of nuclear reactions and structure, with emphasis on energetic beams of short-lived, radioactive nuclei. Aspects of internal versus external luminosity are considered as well as other issues connected with the inverse kinematics of reactions induced by a circulating beam of complex nuclei. Some of the physics motivation that is driving studies with radioactive beams is described.

1. INTRODUCTION

Storage rings have developed into excellent tools for manipulating ion beams through acceleration and deceleration, cooling, bunching, and charge-state changes in an internal target. An area of potentially broad use for ion storage rings is the study of nuclear structure and reactions with beams of short-lived, radioactive nuclei. The interest in such "radioactive beams" arises on the one hand from the desire to explore nuclear structure far away from stability, and on the other from the perspectives of nuclear astrophysics. In particular for high-energy fragmentation facilities where radioactive beams are generated in-flight via projectile fragmentation, an ion storage ring might be an ideal instrument. Because of the breakup process of the primary beam particles, the quality of the secondary radioactive beam is generally rather poor. The storage ring will allow us to manipulate and improve the beam properties.

In addition, the prompt capture of the in-flight fragments into the ring permits us to study nuclei of very short half lives. Of course, beam manipulations like electron cooling take some time, from milliseconds to possible seconds, so this statement may not always apply. To a certain degree nature helps. It is only on the proton-rich side that nuclei decay via the strong interaction (spontaneous proton and alpha emission); these decays can have very short lifetimes (nanoseconds or below). Decays on the neutron-rich side are governed by weak (beta) decays and thus are rather slow, of the order of milliseconds or longer. (Spontaneous neutron emission can occur but is essentially prompt for lack of a Coulomb barrier; centrifugal barrier effects may yield finite lifetimes for neutrons just barely bound).

An impressive example for the usefulness of storage rings with radioactive beams are the mass measurements performed recently at GSI and presented at this meeting [1]. Precision Schottky scan measurements with "beams" as low as a single circulating ion have been performed! This example is a specific illustration of the more general interest in exploring nuclear structure with radioactive beams. The new technique of energetic beams of short-lived nuclei allows us to extend our studies on nuclear structure and reactions far from the valley of stability to nuclei with extremes in proton-to-neutron ratios. As in any other physical system, measurements at the limits can provide important simplifications that shed light on the underlying symmetries and lead to new insights and understanding.

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An attempt to summarize this interest in a broad yet more specific way is illustrated in Figure 1. There, rather schematically, our current theoretical understanding and description of the nuclear many-body problem is outlined: For the lightest nuclei exact quantum Monte Carlo calculations of

Figure 1. Chart of the nuclides with stable nuclei (black symbols), and the regions of nuclei where some property is known (gray area) or which are at least predicted to be particle stable. The rectangles indicate schematically the broad areas of (overlapping) theoretical approaches that might lead to a broader, more consistent understanding of the many facets of the strongly interacting nuclear many-body system.

the few-body system using the latest fully realistic interactions as determined from nucleon-nucleon scattering (for example the Argonne v18 potential [2]) can now be performed; new Monte Carlo shell-model calculations based on functional integrals and effective interactions can now calculate medium-mass nuclei with increased configuration space, taken into account more open shells than previous shell-model calculations; finally, for the heaviest nuclei sophisticated mean-field calculations based on effective interactions have become computationally feasible thus allowing to explore wide parameter ranges. Hence there is, at least in principle, a consolidation from a multitude of nuclear models to a few basic theories with the regions of validity determined to some degree by computational feasibility. As also indicated in Figure 1, these approaches overlap thus progressively connecting to a more microscopic base when going back from the most complex to the simplest nuclei (the square at mass $A = 1$ symbolizes the most microscopic level: the subnucleonic degrees of freedom of QCD in describing the nucleon). One feature in Figure 1 is definitely incorrect: namely, the range of validity implied by the rectangular areas for the various theoretical approaches. In reality these theories can reliably describe only nuclei near stability at present. The studies with radioactive beams will allow us to explore this dimension and provide the experimental underpinnings for the understanding of the nuclear many-body system when moving away from stability.

2. INTERNAL- VERSUS EXTERNAL-TARGET LUMINOSITIES

A particularly attractive feature of storage rings is the repeated passage, and thus "multiple use", of the circulating beam through an internal target. Especially in studies where the physics limits the target thickness this can provide increased luminosity. When studying certain important classes of nuclear reactions with millibarn or sub-millibarn cross sections, this becomes particularly crucial in measurement with radioactive beams which - as secondary beams - always suffer from low intensity.

However, the discussion of internal luminosity (i.e. internal target and circulating beam) vs. external (i.e. extracted beam on a fixed target) is quite subtle for ion-beam induced reactions. Aside from the instrumental efficiency for capturing the secondary fragments into the storage ring, there are qualitative arguments that suggest a delicate balance between the two (this is different for beams of electrons and protons, or at high energy for the very lightest nuclei). For beams of heavier nuclei it is in principle the same physical process that defines the experimental limitations in internal and external luminosity: charge-changing processes of the ion. Simply said, in the ring charge changes will lead to a change in magnetic rigidity and thus in general to a loss of beam. In the external target they limit resolution because of the dominance of charge-change straggling in the energy loss mechanism, i.e. the statistical fluctuations in the charge state and thus in the energy loss.

Let us consider the first situation. For an internal target the reaction rate R_i , given as the product of the nuclear reaction cross section σ_r and internal luminosity L_i , can be written as

$$R_i = L_i \cdot \sigma_r = N_b^s \cdot N_t^i \cdot f \cdot \sigma_r \quad (1)$$

where N_b^s and N_t^i are the numbers of circulating (stacked) beam particles and target nuclei, respectively, and f is the beam circulation frequency. Defining the beam lifetime τ_r in the ring via the charge-changing (loss) cross section σ_o or (effectively) the ratio of stacked particles divided by the beam current N_b injected from the accelerator (particles/sec), we obtain the relation

$$\tau_r = \frac{1}{\sigma_o \cdot N_t^i \cdot f} \approx \frac{N_b^s}{N_b} \quad (2)$$

From (1) and (2) one obtains the approximate relation

$$R_i = N_b \sigma_r / \sigma_o. \quad (3)$$

Figure 2. Internal versus external luminosities for an ion-storage ring as obtained for specific experimental conditions [3].

For an external target with particle number N_t^e one obtains the corresponding reaction rate R_e as

$$R_e = L_e \cdot \sigma_r = N_b \cdot N_t^e \cdot \sigma_r \quad (4)$$

The target thickness is determined by the requirements for the energy resolution in an experiment. Since, as already mentioned above, charge-changing straggling dominates for (heavier) ions, N_t^e is physically directly connected to, again, the charge-changing cross section σ_0 . For $\sigma_0 N_t^e \approx 1$ we would recover the identical relation (3) as found for the internal target (a physical situation where this might be approximately the case is at high energy, with only one or a few inner electrons left; energy losses of a few percent may occur in such an experiment with at the same time very few charge changes).

So we see that in this simple picture similar expressions govern the limitations for internal and external target experiments. In an attempt to quantify this in a more realistic way, Figure 2 shows explicit calculations [3] for the specific case of an internal target of about 10^{14} atoms/cm² and an external target of approximately one milligram/cm² (for more details see reference 3), and for different beam energies. From this figure it is obvious that there can be a substantial advantage in luminosity for the internal target, in particular if the lifetime of the ion is long enough so that stacking and cooling (and thus optimum filling of ring phase space) can be performed. On the other hand, for heavier nuclei and low incident energies, internal and external luminosities are comparable. In this situation the choice will depend sensitively on the specific details of the experiment and the ring properties. For example, if one needs to detect low-energy recoils near 90°, the thin internal target might strongly favor an in-ring experiment.

3. ASPECTS OF IN-RING STUDIES WITH RADIOACTIVE BEAMS

Let us now consider the situation of an internal-target experiment. The inverse reaction kinematics that will generally be employed exhibits some interesting features. This is illustrated in Figure 3 for the example of a heavy collision system. In one case a beam of mass 40 is assumed to be incident on a target of mass 208, and the reverse in the other case. For the situation of the light

Figure 3. Kinematics for a heavy collision system and reaction products near 80° in the laboratory.

target the energy of the recoiling nucleus and consequently also its sensitivity to the inelasticity (Q -value) of the reaction is much higher and thus more favorable for the study of direct reactions.

Figure 4. Chart of nuclides with closed shells and new doubly-magic unstable nuclei that will be available as radioactive beams. Also shown is the schematic approach to measure nucleon-nucleon effective interactions from particle (hole)-particle (hole) energies in near-closed shell nuclei.

A class of experiments involving complex short-lived nuclei that might preferably be performed in-ring are quasielastic reactions, including nuclear inelastic and Coulomb excitation and nucleon transfers. Such reactions have been well-established tools of nuclear structure research for many decades. The emphasis here, of course, is to apply them to the new regions of nuclei accessible with radioactive beams. Figure 4 shows the chart of nuclides with shell-closures and new doubly-magic nuclei that become accessible. Studying, for example, single-particle levels and particle(hole)-particle(hole) interactions near doubly-magic ^{56}Ni and ^{132}Sn , will provide, important new information on effective interactions in nuclei as schematically illustrated in Figure 4. This will provide needed input to shell-model and mean-field calculation. Of course, the new technique of inverse kinematics requires new technical approaches and innovative or at least tailored instrumentation.

Inverse reactions with radioactive beams on a light (proton) target have been performed at several laboratories to study low-lying states via inelastic scattering. These were all done with external beams on a fixed target, but they serve to illustrate the type of reactions that might be carried out advantageously in in-ring experiments. The first such experiment, performed at GSI, measured the transition probability to the first excited 2^+ state in doubly-magic ^{56}Ni [4]. Figure 5 describes the experimental setup, with a radioactive ^{56}Ni beam and a proton target and the results which provided a crucial test of shell-model calculations. Since then, similar measurements have been performed on other nuclei and at other laboratories. An interesting example, involving two heavier nuclei, are Coulomb excitation measurements at MSU. High-energy, neutron-rich sd-shell nuclei were Coulomb excited in a lead target and the decay gamma rays from first-excited 2^+ states were detected [5]. A system of position-sensitive sodium iodide detectors packed around the beam pipe allowed for Doppler shift corrections. The experimental setup and an example of a gamma-ray spectrum, uncorrected and corrected for Doppler shifts, are shown in Figure 6. (Also indicated

are similar measurements that have been performed at other facilities.) The configuration sketched in Figure 6 could be easily adapted to a storage ring and possibly allow high-statistic measurement or, conversely, measurements with very low beam intensities, well below those used in the MSU experiments (typically a few thousand beam particles per second).

Other classes of measurements that fall in a similar experimental category and could be done in-ring in similar configurations include inelastic excitations to high-lying states and (giant) resonances in unstable nuclei (see the contribution in these proceedings on the M1 spin-flip excitation of ^{56}Ni [6]). Other possibilities are charge-exchange reactions in inverse kinematics in order to determine, for example, Gamow-Teller strengths in nuclei far off stability and of importance to explosive nucleosynthesis, or the nucleon-transfer reactions mentioned above.

Figure 5. Experimental setup (top right), kinematics (bottom left) and measured cross sections (top left) for inelastic scattering to the first excited 2^+ state in ^{56}Ni , using a proton target and a radioactive ^{56}Ni beam in an inverse kinematics (external target) setup. A ring of detectors provided for 2π coverage in azimuthal angle at a scattering angle $\theta_{lab} \approx 80^\circ$ where the cross sections peaks in the angular distribution for the 2^+ state [4].

4. CONCLUDING REMARKS AND OUTLOOK

The interest in the study of nuclei far from stability arises on the one hand from our desire to study nuclei at the extremes, as a test of our understanding of the nuclear many-body system, and on the other from the astrophysics interest in reactions involving nuclei far from stability.

For questions of astrophysics, ion-storage rings can provide valuable information through mass and lifetime measurements as convincingly demonstrated with the recent mass measurements at the GSI/ESR [1]. However, the rather low energies relevant for nuclear reactions of astrophysical interest will make such reaction measurements at ion storage rings quite challenging. While internal targets have the advantage of being very thin, thus allowing a precise determination of the reaction energy (a most impressive example are the recent pion production measurements

near threshold with the Indiana Cooler [7]), the generally required low energies for reactions of astrophysical interest pose severe problems due to partially filled electron-shells of the ions and large atomic capture and ionization cross sections at very low energies (see also Section 2).

An experimental aspect of in-ring studies is the fact that studies using radioactive ion beams pose substantial challenges for instrumentation and detectors. They require novel approaches, some already implemented in the early experiments: separators with sophisticated detection equipment at the fragmentation facilities, the large solid angle, position-sensitive gamma-ray array mentioned above for the Coulomb excitation work at MSU [5], the 2π high-resolution detector array used in the ^{56}Ni inelastic scattering [4], the Schottky scans in making the mass measurements at GSI [1], and many others [8].

Figure 6. Schematic setup for a Coulomb excitation experiment at MSU with beams of short-lived sd-shell nuclei [5]. The middle of the figure shows spectra for ^{42}S , both uncorrected and corrected for Doppler shifts. Also indicated are other similar studies at MSU and other laboratories.

An example of a new type of high-resolution particle detectors are bolometric detectors working at very low temperatures (typically $\sim 1\text{K}$). Figure 7 shows results for such a 'cryo' detector: a sapphire absorber to stop the particle, here a $2.4 \text{ GeV } ^{209}\text{Bi}$ nucleus, and a germanium thermistor plus associated electronics to read out the temperature change in the absorber [9]. A symmetric peak for the ^{209}Bi beam particles is observed with $\Delta E/E = 1.8 \times 10^{-3}$ energy resolution. While this detector is yet limited in count rate its good resolution for such a heavy energetic particle make it an interesting candidate for a high-resolution particle detector. This is just one illustrative example; many other developments are underway [8].

Figure 7. Pulse height spectra for a cryogenic detector, consisting of a sapphire absorber and a germanium thermistor to read the temperature increase for 11.4 MeV ^{209}Bi ions incident on the sapphire absorber [9].

In conclusion, ion-storage rings provide unique opportunities for studies of nuclear structure and reactions with circulating beams. The interest in exploring nuclear structure at the extremes, as well as the astrophysics interest in nuclei far from stability provide the basis for broad areas of future nuclear physics research with short-lived nuclei that can be uniquely pursued at such rings.

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