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USE OF EXOTIC NUCLEAR BEAMS FOR NUCLEAR STRUCTURE STUDIES

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Use of Exotic Nuclear Beams for Nuclear Structure Studies

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Abstract

Possible experiments are discussed for nuclear structure studies using, as secondary beams, projectile fragments produced by high-energy heavy-ion collisions. They are, specifically, a) determination of nuclear sizes from measurements of the total interaction cross sections of nucleus-nucleus collisions, and b) determination of static electromagnetic moments, μ's and Q's, of short-lived β-radioactive nuclei.

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Introduction

The projectile-fragmentation process in high-energy heavy-ion collisions has been studied extensively,[1,2] since the high-energy heavy-ion accelerator complex, the Bevalac, became operational. It was realized that a wide variety of isotopes can be produced through that process,[3] in which the fragments are emitted into a very narrow cone in the incident-beam direction with velocity nearly equal to the incident nuclei; the momentum spread of light nuclear fragments is typically a few per cent and the angular spread is of the order of a few degrees when the incident energy is about 1 GeV/nucleon. These characteristics of the projectile fragments have suggested the possibility of using unstable nuclear beams for nuclear-structure studies of exotic nuclei.

The possibility is twofold. One is the use of those exotic nuclear beams for the study of heavy-ion nuclear reactions. In relation to this direction, a storage-ring facility for the secondary beam may well be a possible future prospect, with increase of the desirable reaction rates. The other is the use of separated and stopped isotopes for the study of their β- and γ-decay properties and their electromagnetic moments.

The remarkable advantage of the present isotope-production method, compared with the other methods, rests on the following facts: a) Essentially the total yield of the projectile fragments is readily usable. As a result, a fairly large number of usable nuclei can be obtained even for the case of a small production cross section. b) A clear separation of isotopes is easily obtainable through a magnetic-rigidity separation combined with an energy degrader, irrespective of their lifetime or their atomic properties.

In this paper some possible experiments are discussed, among them are one which is currently ongoing and another which is in preparation. They are as follows:

1) *Determination of Nuclear Sizes.* One can measure the total interaction cross section through a transmission-type experiment. Here the total interactions cross section

is defined as the total cross section for nucleon (proton and/or neutron) removal from the incident nucleus, when a beam of nuclei with ≈1 GeV/nucleon is incident on and transmitted through a target material. At a beam energy of 1 GeV/nucleon, the impact at a nuclear collision is far beyond the internal energies of nucleons inside nuclei. The cross section thus determined, therefore, can reflect unambiguously the size of nuclei, and the cross section can be well represented by

$$\sigma = \pi(R_P + R_T)^2, \tag{1}$$

where R_P and R_T are the effective radii of the projectile and the target nuclei, respectively.

We have made the first measurements on the isotopes of the light elements He, Li, Be, etc. The details of this topic will be discussed in the other session of this workshop.[4]

2) *Determination of Static Electromagnetic Moments.* We are planning to extend the studies on isospin multiplets--so far pursued up to the mass number A = 40 region--to the f shell, A < 56 and beyond, hopefully all the way to the A = 100 (^{100}Sn) region. This subject will be discussed in the next section.

3) Many other kinds of studies are certainly possible. One specific example, worth mentioning briefly here, is the electromagnetic dissociation of relativistic heavy ions, which has been studied recently by using a stable isotope beam.[5] The bombardment of a high-Z target by a beam of relativistic nuclei produces a situation in which, for impact parameter greater than the range of nuclear forces, the projectile can be dissociated by the electromagnetic field of the target nucleus, in effect seeing a virtual photon target. The measurements have been made on ^{18}O, looking for the principal photonuclear breakup modes, i.e. (γ, n), (γ, 2n), and (γ, p). Using exotic nuclear beams many more experiments of this kind can be done.[6]

Measurement of Mirror Magnetic Moments[†]

In a pair of mirror nuclei, the respective roles of protons and neutrons are simply interchanged owing to the charge symmetry of nuclear interactions, and the asymmetry due to Coulomb interaction can in the first approximation be neglected. Pairs of nuclear moments, therefore, provide valuable information on the nuclear structure. So far, 13 pairs of magnetic moments of isospin doublets have been determined, with accuracies of $\lesssim 10^{-3}$, up to mass number A = 41. These moment values together with the accurately known ft values, for the analog β decays between mirror nuclei, give us a unique chance to study the renormalization due to mesonic effects on the g-factors and the β-decay coupling constants for nucleons inside nuclei, besides providing useful information on the configuration mixings.[7]

We are planning to extend these kinds of systematic studies up to the f-shell nuclear region, combining the present production method of those isotopes and the nuclear-magnetic-resonance (NMR) method applicable to the short-lived β-emitting nuclei.[8] The experiment consists of the following seven steps:

1. Production of β emitters in the projectile fragmentation process in high-energy heavy-ion collisions at ≈300 MeV/nucleon.
2. Separation of isotopes by their rigidity in a magnetic analyzer combined with charge separation using an energy degrader.
3. Production of nuclear spin polarization by the tilt-foil technique at slowdown ion velocities of around 1 MeV/nucleon.
4. Implantation of the separated and polarized isotopes in a stopping foil using the residual kinetic energy.

[†] This experiment is being prepared by K. Asahi, T. Minamisono, and Y. Nojiri, Department of Physics, Faculty of Science, Osaka University; H. Hamagaki, Y. Shida, I. Tanihata, Institute for Nuclear Study, University of Tokyo; and D. Greiner, K. Sugimoto, and J. Symons, Lawrence Berkeley Laboratory, University of California, Berkeley.

5. Preservation of nuclear polarization during the lifetime of β decay in a suitable implantation medium by applying a holding external magnetic field in the polarization direction.
6. Detection of polarization by observing the symmetric β-ray distribution.
7. Resonant destruction of nuclear polarization by an RF field (NMR).

The experimental arrangment is schematically shown in Figs. 1 and 2.

Production of the Isotopes. A primary nuclear beam of ≈ 300 MeV/nucleon, taken from the Bevatron by the fast extraction method, is incident on a production Be target (TI) of $\approx 1\, g/cm^2$ thickness. Nuclei produced through the projectile-fragmentation process are rigidity analyzed and separated from the primary beam. Since the beam analyzing and transport system consists of a magnet combination only, nuclear species with the same mass-to-charge ratio, A/Z are transported downstream all together. The nuclei then pass through the first energy degrader (Ab-1) and are degraded in their energy to ≈100 MeV/nucleon. Because of the A/Z^2 dependence of the stopping power of material, nuclei with different Z lose energy differently in the degrader, so that they can be separated afterwards. The final isotope separation is provided by the second energy degrader (Ab-2) combined with a thin stopper foil.

As a typical example of the present case, let us take the isotope ^{55}Ni. It can be produced from the primary beam of ^{58}Ni with the production cross section of ≈10 mb and separately stopped in a stopper, several 10's of mg/cm^2 in thickness. The production yield of the isotope is estimated to be $\approx 10^4$/pulse with a primary beam intensity of $\approx 10^8$/pulse, and with a reduction of ≈20% due to the secondary reactions in the energy degrader of $\approx 4.5 g/cm^2$ total thickness before implantation into the stopper.

Nuclear Spin Polarization. The nuclei, slowed down in their kinetic energy by the degrader (Ab-2) to a few MeV/nucleon, capture orbital electrons from the material going through, so that the tilt-foil technique can be applied to produce nuclear polarization.[9] After ions pass through a tilt foil their atomic spin polarization is expected to be in parallel to $\vec{n} \times \vec{k}_i$, where $\vec{n}$ is normal to the tilt-foil surface and $\vec{k}_i$ is the momentum vector of the ion. In free space, the atomic polarization is partially transferred to the nuclear spin polarization through the atomic hyper-fine interaction. Multiple tilt foils will be used in order to enhance nuclear polarization. The nuclear polarization thus produced is expected to be a few per cent.

Detection of Nuclear Spin Polarization. The angular distribution of β rays from polarized nuclei is given by

$$W(\vartheta) = 1 + P(v/c)A\cos\vartheta. \tag{2}$$

Here, $P = \langle I_z \rangle / I$ is the nuclear polarization, ϑ is the polar angle of the β-ray emission, and v/c is the β-ray velocity divided by the light velocity. Since the maximum energies of β decays concerned here are $E_\beta^{\max} = 6-8$ MeV, the factor v/c is close to one. The asymmetry parameter A can be estimated from the Gamow-Teller matrix element derived from the known ft values, and $A \approx 0.8$ for the present cases. A high analyzing power for the polarization measurement is therefore expected by detecting the β-decay asymmetry.

NMR Detection. Nuclear polarization, kept during the β-decay lifetime (a few tenths of a second) at a suitable environment in a stopping material with the holding magnetic field B_0 (a few kG), can be monitored by the asymmetric β-ray emission. Then the NMR experiment is ready to perform by applying a radio-frequency (RF) magnetic field B_1 cross to the static field B_0 and by observing the resultant change of the β-decay asymmetry. The magnetic moment μ can thus be determined from the NMR as $\mu = h\, \nu_r I / B_0$, where ν_r is the RF resonance frequency.

Summary

Possible use of the exotic nuclear beam produced by the projectile-fragmentation process in high-energy heavy-ion collions is discussed together with some practical experiments currently being pursued. Using the methods discussed here at high-energy heavy-ion accelerator facilities we hope to greatly expand our knowledge of nuclei situated far from the stability line.

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Figure Captions

Fig. 1. Experimental arrangement for stopped exotic nuclear beams.

T1: production target; Ab-1 & 2: energy degrader.

Fig. 2. Experimental arrangement for NMR detected by the asymmetric β decay.

Ti: tilt foils (90° rotated); I: stoppers; C: RF coil; P's & S's: β counters.

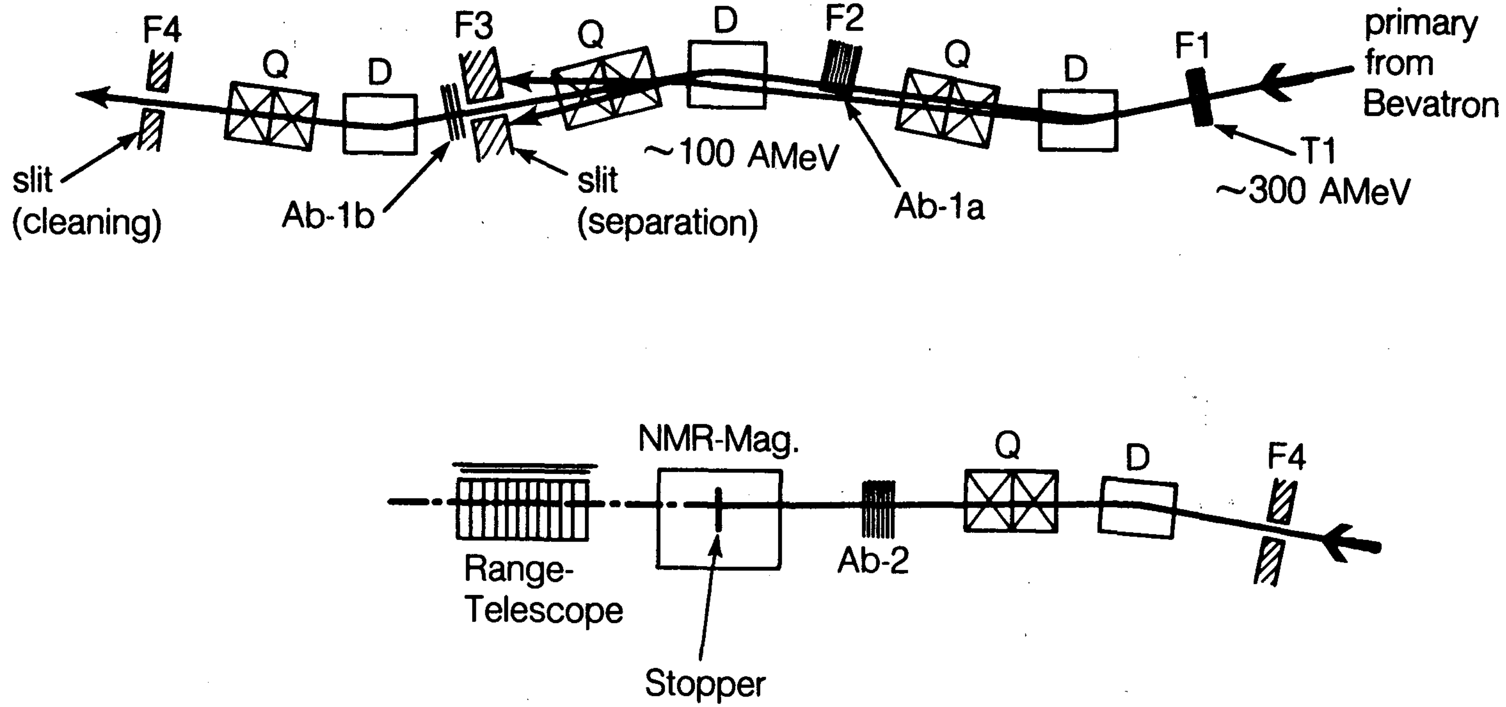
F4
Q
D
F3
Q
D
F2
Q
D
F1
primary from Bevatron
T1
~300 AMeV
~100 AMeV
Ab-1a
slit (separation)
Ab-1b
slit (cleaning)
NMR-Mag.
Q
D
F4
Range-Telescope
Stopper
Ab-2

Fig. 1

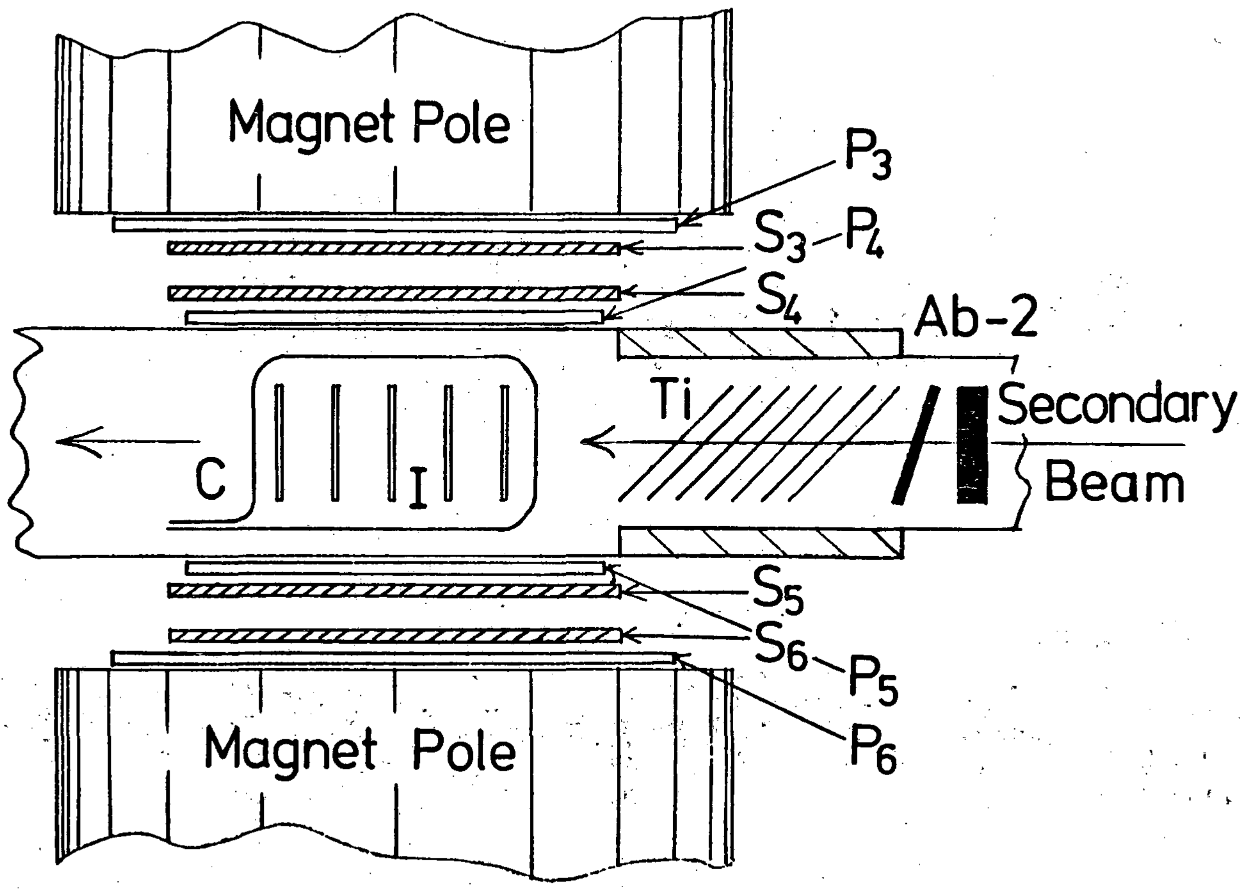
Magnet Pole
P3
S3
P4
S4
Ab-2
Secondary
Beam
Ti
I
C
S5
S6
P5
P6
Magnet Pole

FIG. 2

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