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Gas-filled recoil separator for studies of heavy elements ☆

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Abstract

A gas-filled recoil separator for the study of heavy elements has been constructed. The separator is of type QDQQ with the first, vertically focusing, quadrupole providing improved matching to the acceptance of the dipole magnet. The separator has been designed also for use in vacuum mode in which case a mass resolving power of ≈ 100 is estimated. The deflection angle is 25° and the radius of curvature is 1850 mm. Maximum beam rigidity is 2.2 T m. In the first experiments, new isotopes in the region $Z = 85$–90 have been synthesized.

1. Introduction

Recoil separators for heavy-ion-induced fusion products have become primary tools for studying production and decay properties of heavy elements [1–3]. In these devices, reaction products recoiling out of a thin target are separated in-flight from the accelerator beam by using electric and/or magnetic fields. Instruments of this kind provide short separation times on the order of 1 μs and high efficiency, typically on the order of 10–20% in the case of sufficiently heavy ions ($A > 30$). To achieve the sensitivity needed to study nuclides with production cross sections below 1 nb, mass resolving power of the separators has been sacrificed. Identification of the reaction products is normally based on observing decay chains which lead to known nuclides.

A well-known method to achieve high efficiency is to use a dipole magnet with the field region filled with dilute gas [3,4]. Collisions between reaction products and gas atoms lead to charge state focusing: ions of a certain species follow approximately the trajectory determined by the average ionic charge state in the gas, independent of the original charge state at the exit of the ion from the thin target. In the following, the gas-filled recoil separator RITU at the Accelerator Laboratory of the University of Jyväskylä will be described. Preliminary results from studies of very neutron-deficient Th isotopes will be presented.

2. Gas-filled separators as tools for studying heavy elements

The relationship between the magnetic rigidity $B\rho$ and the average charge state q_{ave} of ions of a nuclear species ^{A}Z is given by the formula [3]

$$B\rho = mv/eq_{\text{ave}} = mv/\left[(ev/v_0)Z^{1/3}\right] = 0.0227A/Z^{1/3}\ \text{T m}, \tag{1}$$

where mv is the momentum of the reaction product and v_0 is the Bohr velocity $= 2.19 \times 10^6$ m/s. The expression $q_{\text{ave}} = (v/v_0)Z^{1/3}$ is approximate and is given by the Thomas–Fermi model of the atom. Formula (1) can be used for a rough estimate of the degree of separation between target-like products and fusion evaporation residues. The average charge state q_{ave} as a function of gas pressure and ion velocity has been determined experimentally over a range of velocities and pressures for He and H_2 filling gases [3,5].

The optimum pressure is determined by the interplay between charge focusing and multiple scattering in the filling gas. Usually, pressures on the order of 1 mbar lead to the minimum focal plane image size. In heavy element studies, helium and hydrogen are the practical choices for filling gas due to their favorable scattering properties. The choice between these alternatives may be dictated by background suppression properties, safety considerations, or by the fact that higher field strengths are required in case of hydrogen and very asymmetric reactions [5].

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2.1. *RITU, the JYFL gas-filled recoil separator system*

The standard ion optical configuration for gas-filled separators used in studies of heavy elements (see e.g. Refs. [3,6]) has been DQQ, the reason being that separation of the primary beam immediately downstream from the target reduces the background at the focal plane. In designing the gas-filled separator at the Department of Physics of the University of Jyväskylä (JYFL), another view was taken. For better matching to the dipole magnet acceptance, a strong vertically focusing quadrupole was placed in front of the dipole. An additional benefit is that the mass resolving power in the vacuum mode is increased. The estimated value of $A/\Delta A$ is ≈ 100. Also, a hexapole was placed at the exit of the dipole to correct some of the aberrations. An angular acceptance of ± 80 mrad (vertical) by ± 30 mrad (horizontal) was calculated. The acceptance is approximately 30% higher than for the standard DQQ design.

The addition of the quadrupole and hexapole elements increases the total length of the separator as measured from target position to focal plane by approximately 1 m. Since the lateral spread at the focal plane due to multiple scattering in the helium gas increases with pressure p and path length L as $p^{0.85}L^{1.85}$ [3], it was expected that somewhat reduced gas pressures would be needed for optimum efficiency. The separator vacuum chamber is filled with helium from the target region to the focal plane detector setup. A 0.5 mg/cm^2 Ni foil separates the helium filling from the high vacuum of the beam line. Continuous helium flow into the target chamber is regulated by a mass flow controller.

At the focal plane there is a position sensitive PIPS detector from Canberra with dimensions 80 mm (hor.) × 35 mm (vert.). The detector is divided into 16 pads of 5 mm width, each of which is position sensitive in the vertical direction. For each event observed in the detector, the energy, position, and time of occurrence are stored for correlation analysis.

The most important parameter values of RITU are shown in Table 1. Fig. 1 is a schematic view of the separator system. The magnets and the power supplies were delivered by DANFYSIK A/S, according to specifications determined by JYFL.

Table 1
RITU parameter values

Magnetic configuration	$Q_1DQ_2Q_3$
Maximum beam rigidity	2.2 T m
Bending radius	1.85 m
Acceptance	10 msr
Dispersion	10 mm/%
Mass resolving power (vacuum mode)	100
Dipole bending angle	25°
Dipole entrance angle	0°
Dipole exit angle	−25°
Pole gap (D)	100 mm
Q_1 maximum gradient	13.5 T/m
Q_1 effective length	350 mm
Q_1 aperture diameter	105 mm
$Q_{2,3}$ maximum gradient	6.0 T/m
$Q_{2,3}$ effective length	600 mm
$Q_{2,3}$ aperture diameter	200 mm
Total weight	17500 kg
Total length	4.8 m

3. Performance of the separator system

Studies of separator efficiency as a function of gas pressure and magnet settings have been performed in connection with production runs. Thorough determination of the separator performance has to await the completion of beam line diagnostics in the new accelerator laboratory but the following results are available.

Separation efficiency was studied as a function of helium pressure using the reaction $^{40}Ar + ^{165}Ho$. Maximum efficiency was reached at a pressure of 1.5 mbar which is somewhat higher than expected on the basis of the results from [3], considering the length of the gas-filled volume. Absolute efficiency was determined for the reaction 185 MeV $^{40}Ar + ^{175}Lu \rightarrow ^{210,211}Ac + xn$. A comparison of our measured yield with the cross section obtained from [7] gives the value 25% for the efficiency of the separator. This value should be considered a lower limit in the sense that it was determined by assuming 100% transmission of the primary beam from the last Faraday cup to the target. The uncertainty of the reference cross section [7] is approximately 40%.

The suppression of the full energy primary beam in reactions induced with ^{35}Cl, ^{40}Ar, and ^{56}Fe ions has been determined to vary from 5×10^{-12} to 2×10^{-15}. The total counting rate of target-like nuclei and scattered beam particles in the energy window of evaporation residues in the PIPS detector was typically less than 1/s, normalized to a primary beam intensity of 10^{12}/s.

The effect of target thickness on separation efficiency was studied in the reaction $^{40}Ar + ^{169}Tm$ using targets of thicknesses 380 $\mu g/cm^2$ and 670 $\mu g/cm^2$. The absolute counting rate of alpha particles from xn evaporation prod-

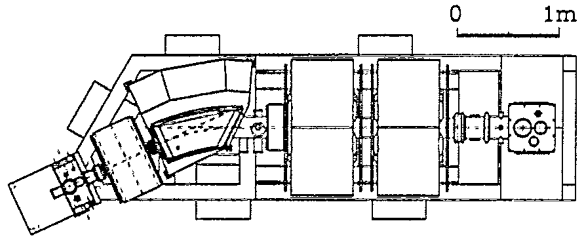

Fig. 1. Scheme of recoil separator RITU.

ucts in the focal plane detector was higher by $48 \pm 6\%$ in the case of the thicker target.

4. Studies of neutron-deficient isotopes of heavy elements

In the first experiments, decay properties of very neutron-deficient isotopes of At, Rn, Fr, Ra, Ac, and Th have been studied. Altogether 10 new isotopes have been identified, among them ^{194,195}At on which preliminary data were collected earlier using the LBL gas-filled separator SASSY [3]. In the following, synthesis of the new isotopes ^{210,211}Th will be described.

4.1. The new isotopes ^{210,211}Th

The most neutron-deficient thorium isotope known so far has been ^{212}Th [8]. In the present work, Th isotopes were produced in the reaction ^{35}Cl + ^{181}Ta. The thickness of the target was 350 μg/cm^2 and it was prepared at the GSI target laboratory by rolling.

The assignment of alpha decay activities was based on the observation of event chains consisting of the arrival of a nucleus in the PIPS detector and two or three subsequent alpha decays within pre-determined maximum time intervals and at the same position. The daughter or granddaughter decays were identified on the basis of known alpha decay energies and half-lives.

At 186 MeV and 193 MeV bombarding energies, a total of five decay chains with three alpha decays, originating from the new isotope ^{211}Th, were observed. The measured daughter alpha particle energy $E_\alpha = 7136 \pm 15$ keV, and half-life, $1.13^{+0.86}_{-0.34}$ s, can be assigned to either ^{207}Ra or ^{208}Ra. The measured alpha energy, 6499 ± 15 keV, and half-life, ≈ 50 s, of the granddaughter can be uniquely assigned to ^{203}Rn which provides the identification of ^{211}Th. The error probability of the assignment as determined by the average counting rate of alpha particle-like events within the energy range of 6470–6530 keV was $< 10^{-3}$. The measured alpha energy and half-life of ^{211}Th are 7792 ± 20 keV and 37^{+28}_{-11} ms, respectively.

At 193 MeV bombarding energy, one decay chain assigned to the new isotope ^{210}Th was observed. The identification was based on the measured alpha decay energy of 7263 ± 20 keV and lifetime of 0.99 s of the daughter decay. These are compatible with the measured decay properties of ^{206}Ra ($E_\alpha = 7268 \pm 10$ keV, $T_{1/2} = 250 \pm 50$ ms) from our work on the decay of neutron-deficient Ra isotopes. The measured alpha energy and half-life of ^{210}Th are 7896 ± 25 keV and 10^{+50}_{-5} ms, respectively. In Fig. 2, the mother and daughter alpha decay energies of all observed decay chains of the type evaporation residue–alpha–alpha are shown.

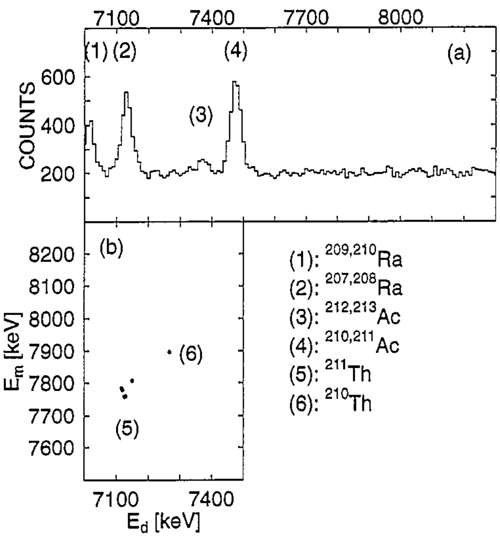

Fig. 2. (a) High energy part of alpha particle singles spectrum from the reaction 193 MeV ^{35}Cl + ^{181}Ta. The continuum is caused by scattered beam particles. (b) Mother (E_m) and daughter (E_d) alpha energies for all chains of type recoil nucleus–alpha–alpha. Maximum search times were 0.2 s for the pair recoil nucleus-alpha and 4 s for the pair alpha–alpha.

5. Conclusion

A gas-filled recoil separator for studies of heavy-ion-induced fusion products has been constructed. During the first year of operation, the device has proven its usefulness through the discovery of 10 previously unpublished isotopes in the At–Th region.

One cannot conclude yet how much the efficiency of the gas-filled separator can be increased by the addition of the quadrupole in front of the dipole magnet. It has not been possible so far to apply the full field value suggested by ion optical calculations to the quadrupole since this has led to increased background in the detector. This problem is largely due to the excessive angular spread of the primary beam and can be significantly reduced by tuning the beam.

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