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RECOIL SPECTROMETER FOR THE DETECTION OF SINGLE ATOMS

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ABSTRACT

A much improved version of our gas-filled spectrometer for heavy-ion-induced fusion reactions is described. This instrument (SASSY II) is of the type D-Q-D wherein the dipoles are made with strong vertically-focussing gradients. The problems associated with experiments with cross sections in the picobarn range are discussed. In such experiments it is necessary to identify single atoms with a high degree of confidence.

The ability to identify one atom with a fair degree of certainty by purely physical methods was developed almost twenty years ago during the work leading to the discoveries of rutherfordium and hahnium, elements 104 and 105. The method used was to identify a new alpha-particle-emitting atom by relating it to its daughter atom decaying subsequently at the same location also by alpha particle emission. This was known as the genetic method. Another technique also used at that time was to correlate the daughter activity as an atom which had recoiled from a particular location after its alpha-emitting parent had decayed.

Later work by Peter Armbruster's group[1] at GSI led to a further refinement of the genetic method wherein the new atoms to be identified which had been produced by heavy-ion reactions were implanted deeply into silicon detecting crystals by their high recoil velocities. These detectors had accurate position-sensitive capabilities so that the

subsequent radioactive decays could be highly localized and correlated with the position of the recoil itself thus essentially eliminating background effects in most cases. This technique also meant that half-lives in the microsecond range could be measured since the flight time of the recoiling atom from target to detector was in this range.

The instrument used to isolate the transmuted atoms from the heavy ion beams that produced them was the 12-meter long recoil velocity selector SHIP using crossed electric and magnetic fields. This device led to the discoveries of elements 107, 108 and 109 but with ever-decreasing production cross sections, that for element 109 being so small that only a single atom was detected during the three weeks that the experiment was conducted. For element 110 it is expected that the cross section will be even lower, a value of a picobarn being projected.

This prediction suggests that elements 110 and higher are essentially out of reach because of the large amounts of beam time that would be required if existing techniques were to be utilized. However, there are two ways of increasing the detection rate: (1) Increase the efficiency of the detection scheme from the present ~10% to almost 100%, and (2) Increase the intensity of the heavy ion beam that produces these atoms by about an order of magnitude.

It turns out that both of these objectives can be attained by the use of a gas-filled magnetic spectrometer to separate the rare recoiling evaporated residues from the heavy ion beams. We believe that it is possible to achieve a total efficiency greater than 50% with such a device and that it will be able to handle beam currents greater than a particle microampere. The net result of the gains in these two parameters is that it should be possible to observe element 110 if SASSY II performs as expected.

The predecessor of the present instrument was SASSY (Small Angle Separator System)[2]. Valuable experience was gained with this device but its performance fell short of the above goals although its efficiency was comparable to that of SHIP. The main problem with SASSY, a gas-filled system with a dipole followed by a quadrupole doublet, was that it had a long 4-meter path of low pressure helium through which the recoils had to travel. This resulted in a substantial scatter of many of the recoils outside the area of the detecting crystals by the time they arrived at the focal plane. Another problem was that the bending angle was only 22° and this fact allowed many multiply-scattered beam particles and target-like recoils to reach the focal plane. Our new design, SASSY II, reduces the total path by almost a factor of two and has a total bending angle of 55°.

Our new spectrometer, which we have built ourselves, essentially, was designed (see Fig. 1) using the BELIN computer program. It is a double-focussing all magnetic system operating in an ambient pressure of about 1 torr of helium. The purpose of the helium gas is to produce an equilibrated charge state $\bar{q}$ throughout the spectrometer.

In a heavy ion fusion reaction, e.g., $^{209}Bi + {}^{59}Co \rightarrow {}^{267}110 + n$, the momentum p of the recoil product is the same as that of the beam that produces it. Because of this, in a magnetic field the magnetic rigidity $B\rho$ which is proportional to p/q will be about the same as for the beam if the recoil is emitted into a vacuum. This means that it is very difficult to separate the recoils from the beam in vacuum by magnetic fields only. Certainly it is impossible to do with very high efficiency. On the other hand if the recoil is emitted into a low pressure (~1 torr) environment of a light gas such as He, its mean charge state distribution is lowered by more than a factor of two whereas that of the heavy ion beam is essentially unchanged. Furthermore, each recoil particle will have the

same $\bar{q}$ as it travels through the magnetic fields because each will iterate through the whole distribution of charge states by making many charge-changing collisions per millimeter of path length. This means that each recoil will behave as if it had the same unique charge value, that predicted for the element 110 recoil being about 6.2.

Unfortunately, as well as making charge-changing collisions the recoil also undergoes scattering along its path as well as slight changes in direction so that it is important to keep the total path through the spectrometer to a minimum. SASSY II is only 2.5 meters long compared to 4 meters for its predecessor. The magnetic system uses two dipoles separated by a horizontally-focussing singlet quadrupole. We have obtained the necessary vertical focussing by designing the pole tips of each dipole to provide a strong vertically-focussing gradient. In this manner the recoil particles are undergoing large focussing most of the time as they traverse the spectrometer. The system is designed to have an admittance of ±50 milliradians in each plane and we expect the total efficiency to be 50-75% for the reaction that produces element 110.

In the case of SHIP the targets must be bombarded in vacuum and this means that the only cooling to dissipate the power deposited by the beam must be by radiation. This condition is alleviated to some extent by using a wheel containing many targets which rotate rapidly through the beam during each beam pulse; however, for low melting targets such as Pb or Bi this still places an upper limit on the beam that can be handled. In the case of the element 109 experiment a limit of about 100 pna was used.

In the case of SASSY II special attention has been devoted to the design of the target-window portion of the instrument so that the maximum cooling effect can be obtained from the helium gas as it streams by to

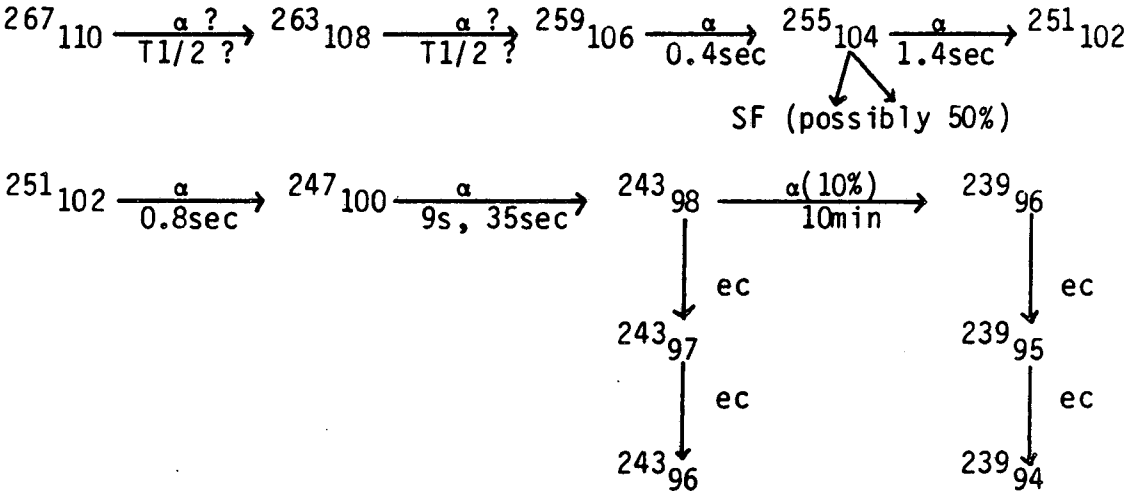
become the charge-changing gas for the spectrometer. As well as using fixed targets the system has a rotating wheel containing nine targets so that an additional factor can be obtained. The weak link in SASSY II may lie in the fact that all of the beam must pass through the window which isolates the 1 torr of He from the vacuum of the beam line. Fortunately, the window can be very thin; as little as 30μgm/cm^2 of aluminum can be used. The upper beam limit has not been determined yet nor have other materials than Al been tried. As much as 100 pna was handled easily by the original SASSY over a smaller fixed area (now 10 mm dia). We expect that our new spectrometer will be able to handle much more, especially when using the rotating target wheel system.

After emerging from the magnetic separator the recoils are implanted into the focal plane detector for measurements of energies and times for the recoils themselves and for the subsequent radioactive decay chain. Our present detector consists of five Si wafers 28 mm high, each divided horizontally in front into 3-mm wide strips. The back of each wafer has common top and bottom conducting strips to provide position sensitivity in the vertical direction. Depending on pulse size, charge division provides a precision in position better than ± 0.5 mm so that each event can be localized to an area roughly 1 x 3 mm in size.

Fifty preamplifiers, amplifiers and linear gates are provided to amplify the Si detector signals for presentation to our LSI-II computer for data acquisition. This system works adequately for times down to a fraction of a microsecond where superposition due to pulse shape begins to occur. For times shorter than this, where successive decays occur quickly in the same crystal, a commercial transient recorder will be used.

After each recoil is implanted there is about a 55% chance of observing a full energy alpha decay. However, if the amplifiers are made

sensitive to pulses as small as 0.5 Mev there is a 100% chance of observing all alpha events, at least as to the time of decay, because a high energy alpha particle emerging in the backward hemisphere normal to the face of the crystal has a minimum energy of 0.5 Mev. This is important because the detection of all members of the chain is highly desirable. In the case of the postulated $^{267}110$ the decays for this series are the following:



The first two members of the series are unknown but the others are well-established. As can be seen there is a potential decay of seven successive alpha decays within minutes after the implantation of the $^{267}110$ atom. The detection of such a decay chain would make the identification of that atom absolutely certain since the combinations of alpha energy and half life are very specific.

What is the final yield for such an experiment?

Let us be optimistic. For a 500 $\mu gm/cm^2$ Bi target

For 1000 pna ^{59}Co beam

For σ = 1pb ($10^{-36} cm^2$)

We would produce 0.75 atoms per day of bombardment.

For a 50% total efficiency this would mean that a single atom of $^{267}110$ would be deposited in the focal plane detectors every three days where we would have a 100% probability of detecting it or its daughters.

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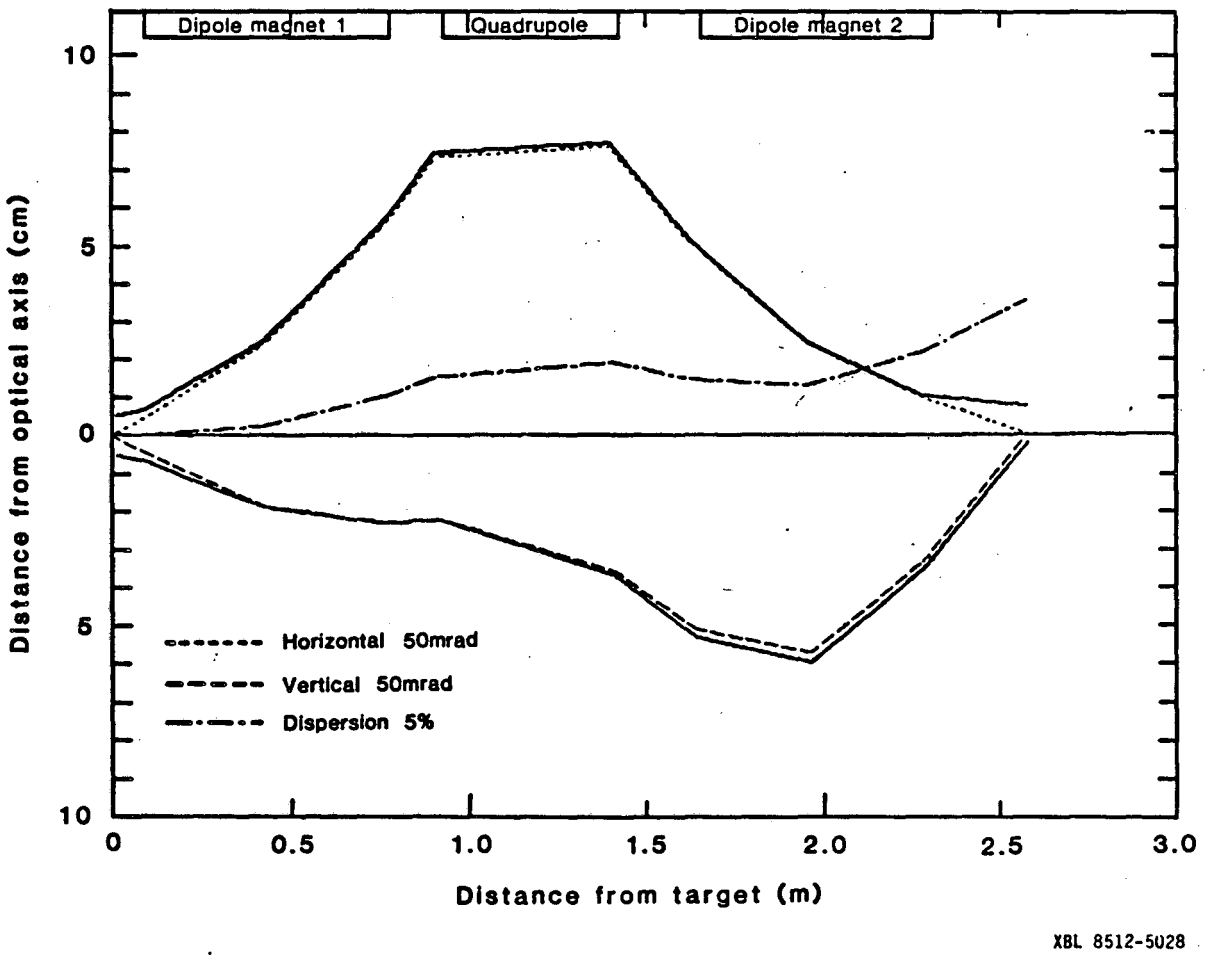

Fig. 1. The trajectories of fusion evaporation residues through SASSY II as predicted by the BELIN program

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