PRODUCTION OF NUCLEI FAR FROM STABILITY BY FRAGMENTATION OF HIGH ENERGY HEAVY IONS

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Abstract

The application of relativistic heavy ion beams to the production of nuclei far from stability is discussed. Production cross sections obtained using ^{40}Ar and ^{48}Ca projectiles accelerated by the LBL Bevalac are presented together with the first results of half life measurements made using an extension of these techniques.

1. Introduction

For nearly forty years, accelerators and techniques for the production of nuclei far from stability have evolved together. From the early, pioneering, studies using low energy electrostatic machines to the present generation of isotope separators, introduction of a new accelerator has almost always been followed by its application to the study of some region of the table of isotopes. The incredible variety of techniques presented at this conference provides the most eloquent testimony to the ingenuity of the physicists involved.

In the next decade, this symbiotic relationship is almost certain to undergo a severe test. Increasingly, nuclear physics research is being concentrated at a small number of expensive facilities, leading to a much more intense competition for beam time. This is a situation in which very low cross section experiments will have to compete especially hard in order to survive. Furthermore, it is not only the number of accelerators but also their nature that is changing. In the United States, for example, the most ambitious construction projects are either for electron accelerators, which have no obvious application to this field, or high energy heavy ion machines whose usefulness for this purpose is by no means clear. Thus, while proposals for such accelerators almost always emphasize their appropriateness for the study of nuclei far from stability, investigation of the basic reaction processes and construction of suitable apparatus is only just beginning.

For this investigation there are two straightforward approaches that can be taken. The first is to bombard a heavy target and search for spallation products exactly as is done with proton beams at isotope production facilities such as ISOLDE at CERN. In this application it is hoped that the greater excitation energy that can be deposited in the target nucleus by the heavy ion beam will lead to larger production cross sections for very exotic isotopes. At the present time it seems that the use of light nuclear beams such as ^{3}He may indeed by advantageous in certain applications. However, for heavier beams than this, there seems to be no clear advantage since any increase in cross section is more than compensated for by the lower beam intensities that are normally obtained.

The second application of high energy heavy ion accelerators is to invert the reaction process by accelerating the heaviest beam available and bombarding a light target. One then observes the projectile fragments. As we shall see, under favorable circumstances this method has kinematic advantages that can outweigh the problem of low beam intensity. Indeed, at the LBL Bevalac, we have already obtained significant results even though the beam intensity available is six orders of magnitude less than that obtained from a typical high energy proton accelerator.

In this paper, we shall discuss the fragmentation process and its application to production of neutron rich light nuclei. We shall then describe our recent development of the technique to measure β decay lifetimes and finally discuss some of the experiments that we may expect to be performed at the new accelerators.

2. Production Mechanisms

At low energies ($E/A \lesssim 20$ MeV/nucleon) many processes contribute to the total reaction cross section in heavy ion collisions. Of these, three that have found widespread application for production of unstable nuclei are fusion-evaporation reactions, deep inelastic scattering[3] and two body transfer reactions. However, as the bombarding energy is increased the cross section for all these processes decreases rapidly. There are many reasons for this: Firstly, the time scale of the reaction is much shorter, reducing the mean field effects and increasing the importance of nucleon-nucleon scattering. Secondly, as the relative velocity of the two ions increases, it is no longer possible to match the velocity of a nucleon or light cluster and transfer it from one nucleus to the other. Thirdly, in a central collision, so much energy is available that the two nuclei completely dissociate rather than fusing together.

For peripheral reactions much of the cross section goes instead into nuclear fragmentation[4] in which the nucleus breaks up into several pieces, usually one or two complex fragments and several nucleons and light clusters. The inclusive properties of this process have been extensively studied at high energies ($E/A \gtrsim 200$ MeV) and it is known that there is relatively little momentum transfer between target and projectile and that the fragments are produced moving close to the beam velocity at zero degrees in the laboratory. The exact nature of the reaction process, and in particular the importance of direct break up, is still controversial, but we should note that the abrasion-ablation model is able to make reasonable predictions of the cross sections.^{5}

3. Experimental Measurement of Production Cross Sections

The high velocity of the fragments leads to three particular experimental advantages of the fragmentation process. These have been discussed elsewhere but are of such importance that they can be restated here:

(i) Since both projectile and fragment are moving at high velocity in the laboratory, it is possible to use thick targets. For example a 1 gm cm^{-2} Be target is appropriate for the fragmentation of ^{48}Ca at 200 MeV/nucleon. This is between two and three orders of magnitude thicker than would be used in a typical deep-inelastic reaction. At higher energies than this even thicker targets would be appropriate.

(ii) Since the reaction products are produced in a narrow cone close to 0° in the laboratory, it is possible to collect almost the full reaction cross section in a spectrometer of quite modest acceptance. At 200 MeV/nucleon bombarding energy a spectrometer of 1 msr acceptance will accept greater than 30% of the cross section even in unfavorable cases.

(iii) Since they are all moving at the same velocity, magnetic analysis alone suffices to separate isotopes according to their A/Z values. This means that exotic species are readily separated from the more abundantly produced ones and that the detectors only have to handle relatively low count rates.

The experiments described here were carried out using the zero degree spectrometer^6 of the Lawrence Berkeley Laboratory Bevalac. Beams of ^{40}Ar and ^{48}Ca were accelerated to 205 and 220 MeV/nucleon respectively and used to bombard C and Be targets of 900 mg cm^{-2}. The arrangement of the apparatus is shown in figure 1 and comprises the target and then a spectrometer consisting of a quadrupole doublet and two dipole magnets followed by a large (~ 7m x 3m) vacuum tank. In all the experiments described here, the fragments were detected in air outside a thin vacuum window. The fragments were double focused by the quadrupole in the focal plane of the spectrometer and detected by a semi-conductor detector telescope.

This telescope comprised two 500 μ thick, 6 cm diameter, position sensitive Si(Li) detectors for horizontal and vertical position measurement followed by 12, 5 mm thick, 5 cm diameter, Si(Li) detectors for energy loss measurements. Finally, the telescope was backed by a plastic scintillator for rejection of light particles punching through the silicon.

The maximum beam intensity available was of the order of 4 x 10^7 particles/beam pulse (~10^7 particles/second) which is very small in comparison to a typical low energy nuclear physics experiment. Accurate beam monitoring was achieved with a variety of scintillators and an ion chamber. Two scintillators were mounted directly in the beam, one of which counted individual beam particles. For the other, the photomutiplier tube leakage current was digitized using a current to frequency converter. This is valuable at intensities greater than measureable by direct counting. For the very highest intensities, scintillator telescopes measured the flux of secondary particles scattered from the target. Unfortunately, the beam intensity can show considerable variations from pulse to pulse. For this reason, all the monitor scalers were read out via CAMAC and written to magnetic tape after every beam pulse.

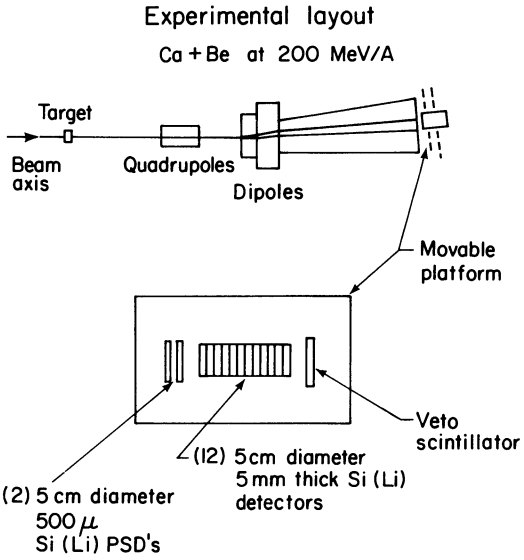

Fig. 1 Experimental layout for detection of fragments of 212 MeV/nucleon ^{48}Ca.

The combination of the spectrometer and focal plane telescope provides a system capable of two independent measurements of the particle mass and charge. First, the particles are identified by the energies deposited in the Si(Li) detectors. For each detector in the stack, a particle identification signal (PI) is calculated using the formula

$$PI_i = [(E_i + \Delta E_i)^n - E_i^n]/S_i \propto M^{n-1}Z^2$$

where ΔE_i is the energy that is lost in the i^{th} detector, E_i is the total energy deposited in subsequent detectors up to the stopping detector, S_i is the thickness of the i^{th} detector, n is a parameter which varies from element to element but is usually ∿1.78, and M and Z are the particle mass and charge respectively. The I_i signals are then combined to form a weighted mean and χ^2 function defined by

$$\chi^2 = \sum_{i=1}^{s-1} \left(\frac{I_i - \bar{I}}{\varepsilon_i^2} \right)$$

where ε_i is the area on each I_i. This error is derived by assuming a certain detector resolution and differentiating the identification function appropriately. The mass resolution is improved considerably by rejecting particles with large values of χ^2. This eliminates not only events that misidentify due to fluctuations in the energy loss, but, most importantly, those that react in the detectors. At these energies ∿ 30% of the incident particles will react in the silicon.

Secondly, the total energy, T, deposited in the telescope is combined with the particle deflection, D, in the spectrometer to form a second particle identification signal

$$PI = {}^{k}/_{TD^2} - {}^{T}/_{2Z^2} \propto {}^{M}/_{Z^2}$$

where k is the spectrometer calibration constant. These two functions may be combined to calculate the charge and mass of the fragment unambiguously.

The results obtained from such an analysis are shown in fig. 2, which contains the mass spectra for 8 elements produced in the ^{48}Ca bombardment.[2] In each case a 30% χ^2 cut and a total energy cut have been applied as well as a cut on charge. Fourteen new isotopes were identified from the data shown in this figure in addition to the two observed in our previous experiment using an ^{40}Ar beam.[1] The new isotopes observed in heavy ion fragmentation are

$$^{22}\text{N},\ ^{26}\text{F},\ ^{28}\text{Ne},\ ^{33,34}\text{Mg},\ ^{35,36,37}\text{Al},$$

$$^{38,39}\text{Si},\ ^{41,42}\text{P},\ ^{43,44}\text{S}\ \text{and}\ ^{44,45}\text{Cl},\ \text{for}$$

each of which at least 10 counts have been observed. In view of the very low beam intensities, these results are encouraging for the application of similar techniques at new accelerators such as the MSU and GANIL coupled cyclotron facilities. These machines will have very much larger beam intensities in just the energy range that we have been considering.

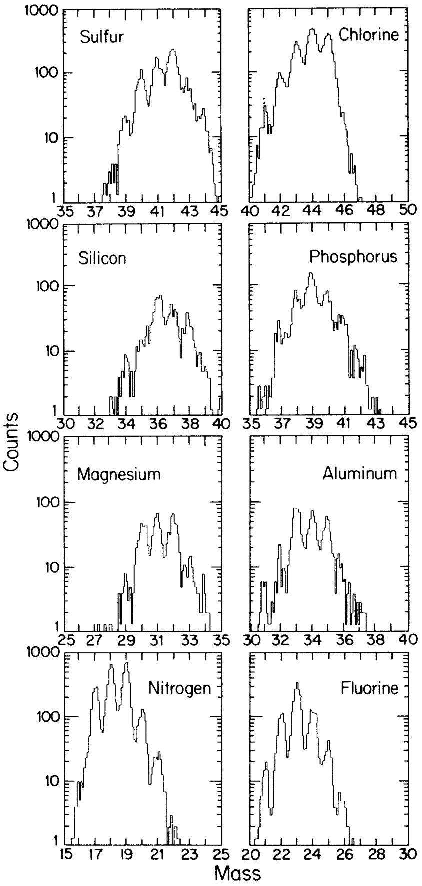

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Fig. 2 Mass spectra for elements produced in the fragmentation of 212 MeV/nucleon ^{48}Ca.

In figure 3, which shows the table of isotopes for the lighter elements, we see that we are already within one or two units of the limit of stability for all elements up to Neon. Whether this limit in fact can be reached with reasonable intensity is, of course, a sensitive function of the rate at which yield drops with increasing mass number. In figure 4, we compare the cross sections for the production of Sodium isotopes by heavy ion fragmentation and by spallation as measured by Klapisch and co-workers at CERN.[7] The first point to notice is that the trend of the cross section as a function of mass number is almost identical in the two cases even down to the pronounced odd-even effects that can be seen. This gives confidence that one can extrapolate from present heavy ion data to predict the yields for nuclei at the limit of stability. It is

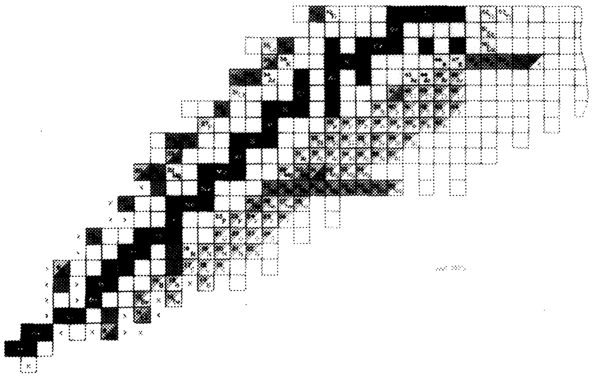

Fig. 3 Table of Isotopes for light nuclei.

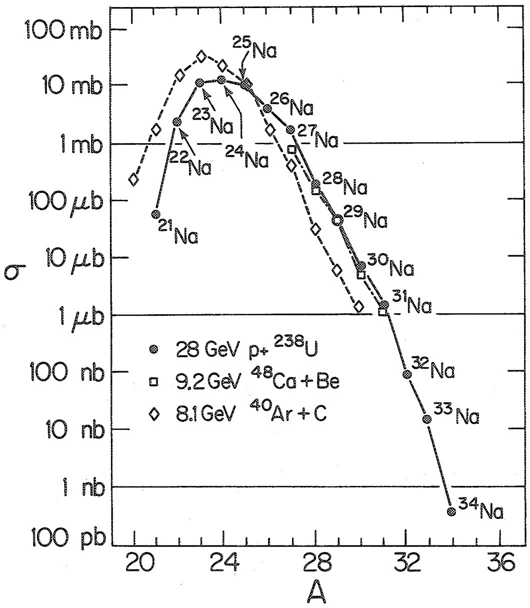

Fig. 4 Comparison of production cross sections for Ne isotopes produced in the ^{48}Ca + ^{9}Be, ^{40}Ar + C and p + ^{238}U reactions.

important, also, to note that the cross section for ^{48}Ca fragmentation is almost an order of magnitude greater than that for ^{40}Ar for the most neutron rich nuclei. This is obviously related to the larger neutron number in the former case and some further increase in cross section can be expected when heavier beams are used.

4. Half Life Measurements

Although identification of a new isotope is in itself a useful measurement, especially at the limits of stability, it is obviously desirable to measure the physical properties of the nucleus under consideration. For this reason we are now starting a program to measure the β decays of unstable nuclei formed via heavy ion fragmentation.

As we have discussed above, the isotopes produced in heavy ion fragmentation have a range of the order of several centimeters of silicon. They also have a considerable dispersion in range due to the spread in energies of the fragments. This makes the preparation of a β source a nontrivial matter since the isotopes are distributed through the stopping material. However, in our application the stopping material is itself an excellent β detector and this problem can be overcome by detecting the β electrons in delayed coincidence in the telescope stack. Furthermore, the great difference in range between different isotopes at the same magnetic ridigity then becomes an advantage since one has true isotope separation within the detector telescope.

In a test of this technique at the Bevalac we used a new telescope layout illustrated in figure 5. The 5 cm detectors used previously have been replaced by 6 7cm diameter position sensitive detectors also fabricated at LBL. The position sensitivity is valuable since it allows a correlation to be made between the position of the incident heavy ion and the decay electron. Two 800 μ thick trigger detectors were mounted in front of the stack. The complete detector stack is shown in figure 6.

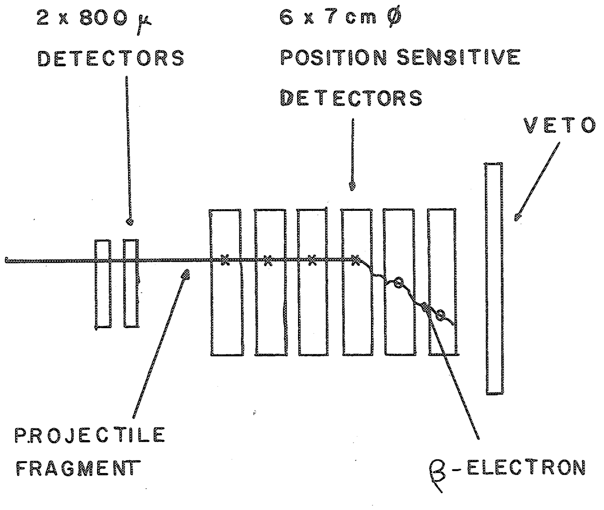

Fig. 5 Experimental layout for detection of delayed coincidences.

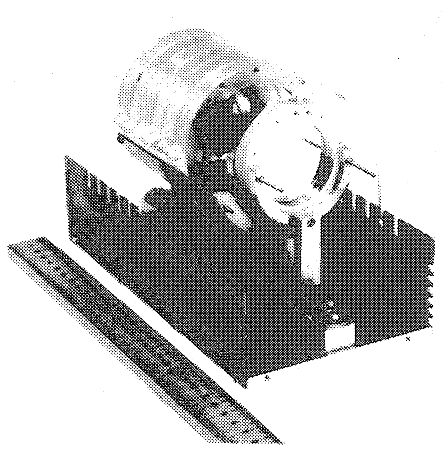

Fig. 6 Detector stack consisting of 2 800 μ detectors and 6 7 cm x 5 mm position sensitive detectors.

Since the energy deposited by the heavy ion in a detector is of the order of 1 GeV and that deposited by a β electron is of the order of 1 MeV some attention has to be paid to the electronics used as illustrated schematically in figure 7. The analog signals (3 per detector) from the position sensitive detectors are split after the preamplifier into low and high gain channels. All the analog channels are then fed to CAMAC ADCS for digitizations. In the test run a total of 38 amplifier channels were used. This could be considerably reduced by use of gain switching in the preamplifier.

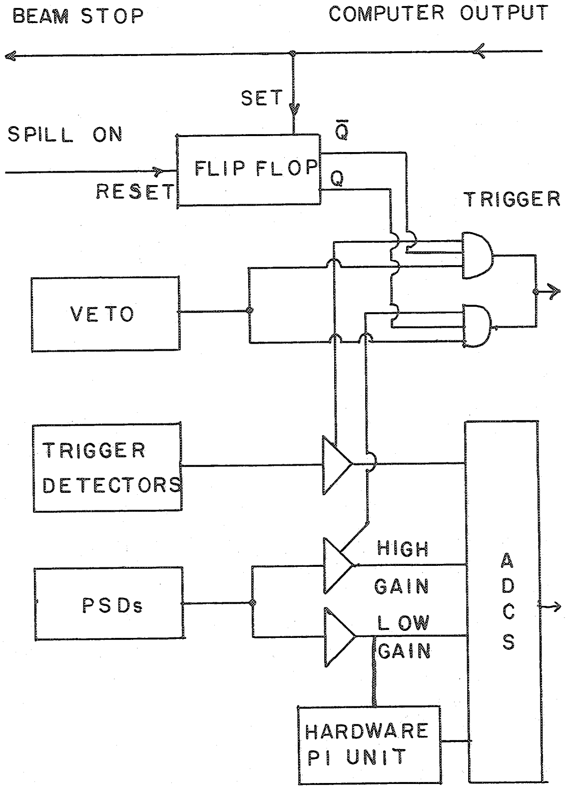

Fig. 7 Electronic scheme for detection of delayed β coincidences.

The low gain signals are also fed to a hardware particle identifier which produces an output using a power low approximation just as is done in analyzing the detector signals in the computer. The output of this identifier is also digitized and read into the computer. The CAMAC crate is connected to a microprogrammable branch driver (MBD) which passes data by direct memory access to a PDP 11/34 computer for analysis and storage on magnetic tape. When a low gain event is read from CAMAC, the program running in the MBD examines the ADC values and determines the stopping detector. It then compares this and the particle identifier signal with limits that are downloaded from the PDP 11/34, to determine whether the event represents a suitable stopping isotope; the read out and decision takes ∿ 600 μs. If the event is accepted as a valid stopping event then an output pulse is used to set a flip/flop which changes the trigger mode of the system to a twofold coincidence between any pair of position sensitive detectors in high gain. This pulse is also fed to the accelerator control room and interrupts the beam extraction for the remainder of the spill thereby reducing the beam background. This is accomplished within 2 ms allowing measurement of halflives as short as 5 ms. The high gain mode remains enabled until the system is reset at the start of the next spill.

In this first test, an ^{40}Ar beam of 250 MeV/nucleon was used. Unfortunately, the beam intensity available was only 10^6 particles/second so that the yield for a very neutron-rich isotope was reduced by approximately two orders of magnitude below that of the ^{48}Ca experiments described above. However, this beam intenisty was adequate to determine the feasibility of the experiment and to learn the technical problems involved.

Some preliminary analysis of a small subset of the data has now been carried out. In figure 8, we show the software PI spectrum for charge 13 events stopping in detector 5 in one of the runs. Two peaks can be resolved which are ^{31}Al and ^{32}Al respectively. The delay time until the first candidate β event is plotted for each of these peaks in figure 9. The decay curves are very different in the two cases. Preliminary analysis of the ^{31}Al curve shows a half life of 630±40ms, in good agreement withthe published value 644±25ms. In contrast, ^{32}Al shows a very much faster component with a half life of the order of 40 ms. This half life was

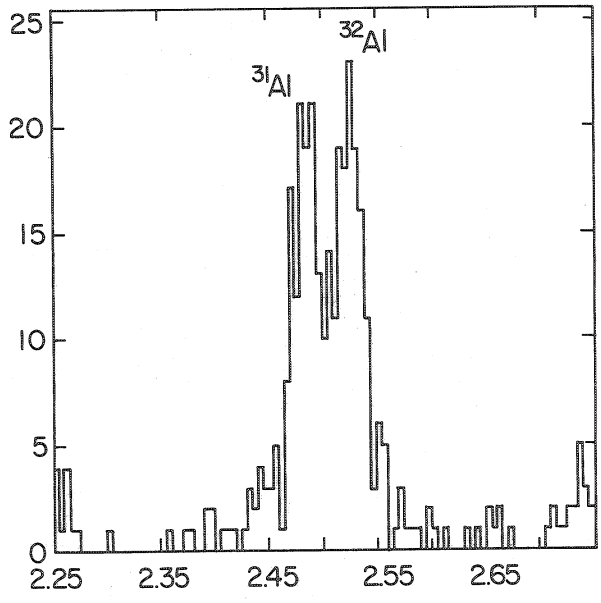

Fig. 8 Particle identification spectrum for Al isotopes produced by ^{40}Ar fragmentation at 250 MeV/nucleon.

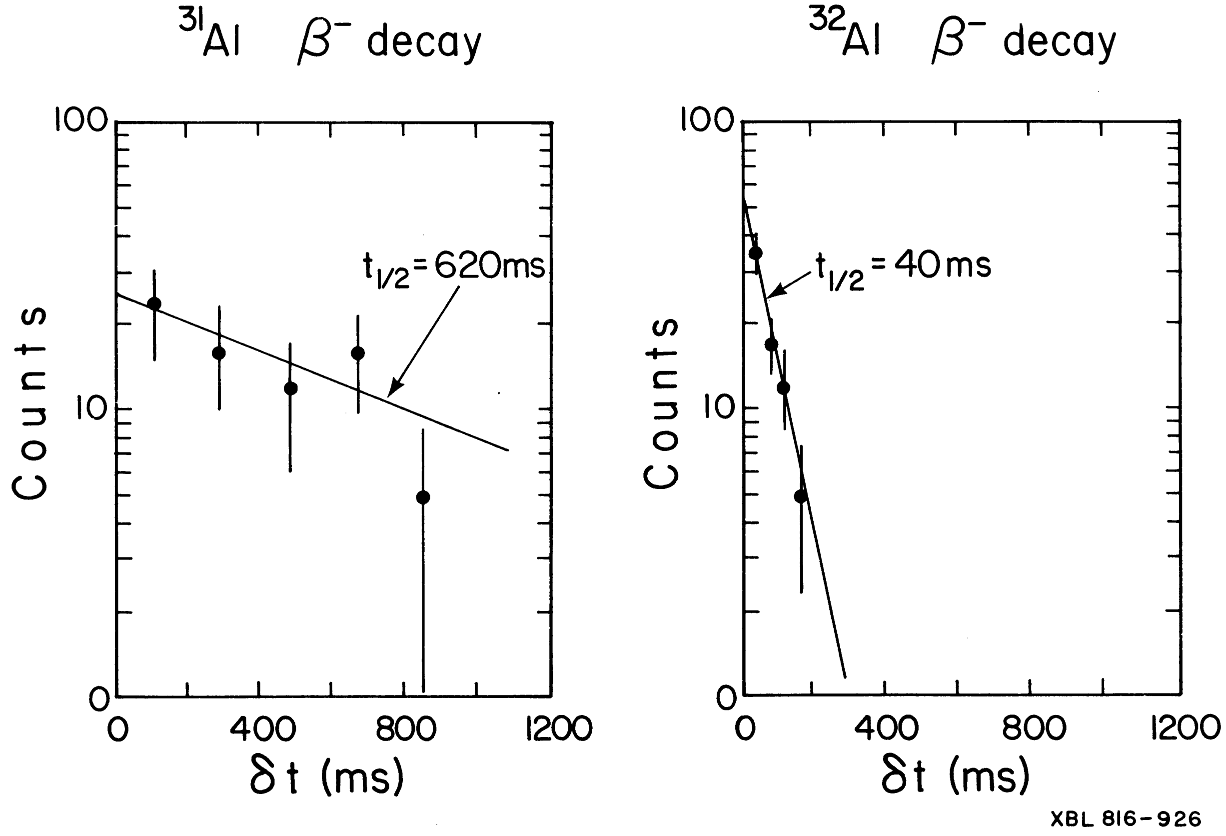

Fig. 9 Decay curves for β electrons in delayed coincidence with ^{31}Al and ^{32}Al.

previously unknown. In these spectra no attempt has been made to reduce background by demanding consistency between the positions of the heavy ion and β candidates, nor has any χ^2 cut been made on the PI spectrum, so some further background suppression can be expected in the final analysis. This preliminary experiment has produced very encouraging results and we believe that with larger beam intensities, the technique can be used to measure a large number of half lives in a relatively short time.

5. Conclusions

In the coming year the upgraded Bevalac, accelerating all ions up to Uranium and the MSU coupled cyclotron are expected to operate. We believe that fragmentation reactions to produce nuclei far from stability will play a role at these and other such facilities. First there will be experiments performed using secondary beams. At the highest Bevalac energies ($E/A \gtrsim 1$ GeV/nucleon) the fragments are so well focused that they can be prepared into a secondary beam thereby extending the study of heavy ion collisions to systems with unusual neutron to proton ratios. As one example the possibility of studying electromagnetic properties of nuclei in this way has already been discussed by Berman et. al.

Secondly, mass measurements will be attempted. A recoil mass spectrometer, incorporating a dipole and velocity filter is being constructed at Michigan State University and is expected to have a mass resolution of a few MeV.

For our own programme at the Bevalac, we hope to continue along two fronts exploiting the unique features of this machine namely the very high energies and heavy beams that will be available. If the Bevalac upgrade is successful, we believe that beam time for a further isotope search will be justifiable, this time using a broad range detection device at the HISS spectrometer. This would allow simultaneous measurement of isotopes with different A/Z values and would greatly increase the efficiency of our technique. We also plan to proceed with development of the half life measurements to make a systematic study of half lives in the mass 30-50 region. Systematic studies of many nuclei can yield useful information both for nuclear structure and for astrophysics.

In the introduction to this paper we questioned the applicability of high energy heavy ion accelerators to this field. Our experience at the Bevalac leads us to believe that this question does indeed have a positive answer. If the physics interest justifies it, then high energy heavy ion beams can certainly be expected to play a role in the study of nuclei at the limits of stability and experimental physicists will continue to exercise the ingenuity of experimental design that has served this field so well for the past 40 years.

6. Acknowledgements

The production cross section experiments were carried out by the authors of references 1 and 2, to all of whom this writer is greatly in debt for their advice and help.

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DISCUSSION

I. Bergström: In your first part of your talk you showed slides which indicated mass information but you did not comment about the possibility of getting Q-values? How do your measurements compare with the pion charge exchange measurements which is seldom talked about and which indeed gave Q-value information?

T.J.M. Symons: First, the mass information that we obtain from the Si(Li) detector telescope is only sufficient to resolve neighbouring isotopes, not to measure their masses. In this respect, our technique is inferior to the pion charge exchange measurements. However, our production cross-sections are very much higher enabling us to study nuclides further from stability.

W. Benenson: At what energy will the fragmentation process become useful, for example, for ^{40}Ar? Is it 25 MeV/A?

T.J.M. Symons: I believe that measurements with heavy ion beams can be made at any energy. However, at 25 MeV/nucleon one would probably not call it fragmentation. In order to have the very high efficiency that I have described, 100 MeV/nucleon is a minimum energy.

J.H. Äystö: Would it be possible to extract information on beta-decay energies with this technique?

T.J.M. Symons: Yes, of course. The only problem is the amount of beam time that will be required to make a useful measurement. I suspect that this is not justified at the Bevalac with our present beam intensities.

G. Herrmann: Would you expect that with this method one would have access to heavy, neutron-rich nuclei beyond the fission product region?

T.J.M. Symons: We would certainly have access to the fission product region. Whether we could go beyond it, I do not know. Also, rather different detection techniques would be required.