Title
USING A CYCLOTRON PLUS ECR SOURCE FOR DETECTOR EVALUATION AND CALIBRATION

Author
McMahan, M.A.

Publication Date
1986-06-01

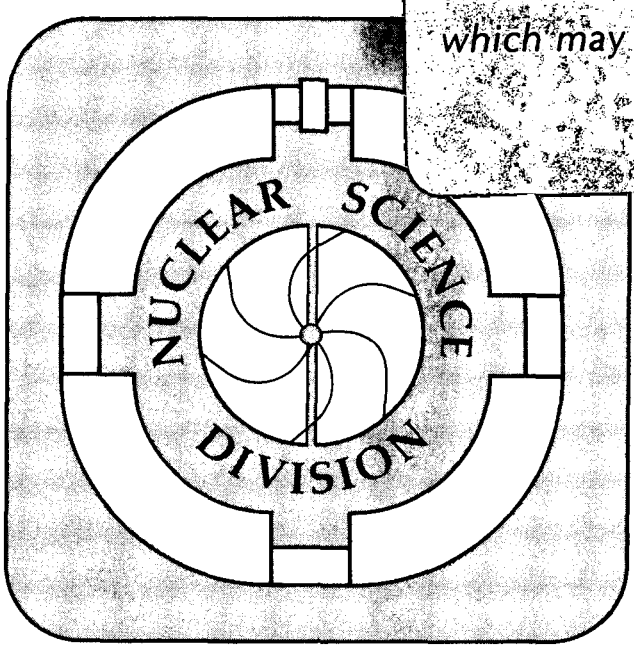
Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Nuclear Instruments and Methods

USING A CYCLOTRON PLUS ECR SOURCE FOR DETECTOR EVALUATION AND CALIBRATION

M.A. McMahan, G.J. Wozniak, C.M. Lyneis,
D.R. Bowman, R.J. Charity, Z.H. Liu, L.G. Moretto,
W.L. Kehoe, A.C. Mignerey, and M.N. Namboodiri

June 1986



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

LBL-21538

Using a Cyclotron plus ECR Source for Detector Evaluation and Calibration

by

M.A. McMahan, G.J. Wozniak, C.M. Lyneis, D.R. Bowman,
R.J. Charity, Z.H.Liu, and L.G. Moretto
Nulcear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

and

W.L. Kehoe and A.C. Mignerey
Department of Chemistry
University of Maryland
College Park, MD 20742

and

M.N. Namboodiri
Nuclear Chemistry Division
Lawrence Livermore National Laboratory
University of California
Livermore, CA 94550

June 1986

6/4/86
LBL-21538

Using a Cyclotron plus ECR Source for Detector Evaluation and Calibration

by

M.A. McMahan, G.J. Wozniak, C. M. Lyneis, D.R. Bowman, R.J. Charity, Z.H. Liu, and L.G. Moretto
Nuclear Science Division, Lawrence Berkeley Lab, Berkeley, CA 94720

and

W.L. Kehoe and A.C. Mignerey
Dept. of Chemistry, Univ. of Maryland, College Park, MD 20742

and

M.N. Namboodiri
Nuclear Chemistry Div., Lawrence Livermore Natl. Lab, Livermore, CA 94550

Abstract:

A technique is described to quickly measure the response of detectors to intermediate-energy heavy ions. An ECR source was utilized to produce ions as heavy as krypton. A series of ions with the same charge-to-mass ratio was accelerated in a cyclotron to a constant velocity or energy/nucleon. Different ion species were extracted by adjusting the resonant frequency a few kHz. Detectors were directly exposed to the extracted beams. For a charge-to-mass ratio of one-quarter, over seventeen ion species from $^{4}He^{+1}$ to $^{84}Kr^{+21}$ were observed in a two hour period.

I. Introduction

Electron cyclotron resonance (ECR) sources[1] have become increasingly popular replacements to the Penning Ionization Gauge (PIG) as the source of positive ions for injection into a cyclotron. This is because the ECR source is able to create more highly ionized species, allowing the acceleration of higher energy and heavier beams. In the present paper, we describe a technique utilizing properties unique to the cyclotron + ECR source combination which is applicable to a wide range of detector development projects. This technique allows one to obtain data for a large variety of heavy ions over a substantial energy range in a short amount of time. Over seventeen different beams, ranging from A=4 to A=84, were extracted from the cyclotron in a single two hour period.

We illustrate the technique with some initial studies of the response of a plastic scintillator to heavy ions. Although they have become increasingly important as intermediate energy heavy ion detectors, little quantitative information exists in the literature on the response of scintillator materials to heavy ions, particularly with energies greater than 100 MeV. In order to evaluate whether they would make adequate detectors for intermediate-energy heavy ions, we have studied the response of several different scintillator materials to heavy ions in the energy range of 8-30 MeV/nucleon. Detailed results of our measurements on the response of several kinds of scintillating material to a wide variety of heavy ions will be presented in a subsequent paper.[2]

II. Experimental Method

The technique requires an accelerator which will accelerate all ions having the same charge/mass (q/A) ratio and an ion source capable of producing many different ion species with the same q/A ratio. Because most isotopes have near integer masses, certain values of q/A are allowed for a whole series of isotopes. Although a traditional PIG source can be used to produce a limited number of ion species with the same q/A, an ECR source can produce a much larger number because it produces more highly ionized species. Thus an ECR source with the appropriate source feed can simultaneously produce a large number of ion species with the same q/A, allowing the acceleration of an entire series of isotopes to a constant velocity, or E/A, since in a cyclotron, [3]

$$E/A = K\,(q/A)^2\,,$$

where K is the characteristic cyclotron constant. For example, at the 88-Inch cyclotron at Lawrence Berkeley Laboratory, K ranges from 1 to 160 depending on the ion being accelerated and its extraction properties. The maximum possible beam energies are shown in Figure 1 for several values of q/A which have been accelerated at K = 140. For q/A = 1/2, beams of 35 MeV/u are possible. It is clear from this figure that a large range of beam energies is available from <2 to 35 MeV/nucleon.

Tables 1-3 list three simple q/A series that have been produced in the LBL ECR source and accelerated in the 88-Inch cyclotron. The isotope, charge state, natural abundance, beam energy, and the resonant frequency of the cyclotron are listed. The frequencies and energies were calculated using the cyclotron optics code.[4,5] Except for the q/A = 1/2 series, which is terminated at an upper mass of A = 40 by the line of beta stability, the series are limited only by the charge states produced in the ECR source. For the q/A = 1/3 and 1/4 series, beams up to A ≅ 200 are possible if one had an ion source which could produce ions with charge states of +50-66. In fact, for the q/A = 1/8 series, not shown here, one should be able to produce beams from $^{16}O^{+2}$ to $^{232}Th^{+29}$ at 2 MeV/nucleon. The tables include only ions through the krypton isotopes, since they are the heaviest species seen thus far using this technique. Additional series with q/A = 3/8 and 7/20 have also been accelerated.

Although the circulating ions have the same nominal q/A and E/A, their resonant frequencies differ slightly due to small differences in their q/A ratios. This is because the actual masses are not exactly integer due to nuclear binding energy effects. The frequency difference for the three series is given in Figure 2. The frequencies increase with mass, first quickly, and then more slowly. Above A=30, all ion species are coresonant within a few kHz. Since the width of the resonance frequency of the cyclotron is also a few kHz, all of the heavier frequencies are accelerated and extracted at the same frequency setting. For lighter ions, the separation is somewhat larger and only two or three ion species are observed at a single frequency. In some cases even for lighter

ions, the resonant frequencies are very close. For example, Ne and O at q/A = 1/2 are coresonant within 0.7 kHz. It is virtually impossible to obtain a "clean" fully stripped Ne beam if any oxygen is present in the source. A clean neon beam can be obtained by either using a different isotope, for instance ^{22}Ne, or running at a lower energy using a charge to mass ratio that is not allowed for ^{16}O. However, the bane of experimentalists trying to run a reaction or spectroscopy experiment can be a blessing for detector development, as will be shown below.

III. Experimental Results

The setup for the detector tests was quite simple, and is shown schematically in Figure 3. The ECR source was run on a gas or gas mixture and tuned to maximize the output for a particular ion species with or near to the desired charge to mass ratio. The ECR beam was then injected into the cyclotron, which was tuned on a "model" beam, generally a light ion present in large concentrations at the given q/A ratio. Typical model beams used are those in boldface in Tables 1-3. The model beam was tuned, extracted and focussed on a phosphor in the target position. In order to directly expose the detectors to the beam, the injection line was "detuned" and the exit collimators closed so as to attenuate the beam several orders of magnitude. The detector counting rate was limited to less than 10 kHz. To extract other beams of the same approximate q/A without retuning the machine, the resonance frequency was varied slightly. As beams of higher charge state and thus lower abundance in the source plasma were needed, the injection line and collimators, etc. were gradually brought back to their values for maximum transmission. Because the magnetic rigidity of all the ion species at one q/A value is identical, it was not necessary to retune the cyclotron or the beam line.

The detectors to be tested were set up in a 60" scattering chamber on a movable arm which could be rotated into zero degrees. In addition to directly exposing the detector to the different beams, degraders were placed before the detector in order to decrease the beam energy without retuning the cyclotron. The detector signals were run through a pre-amp, amplifier, and ADC into a Modcomp computer where they were recorded on magnetic tape for offline analysis.

The ions actually observed for the three different q/A series are given in the final column of Tables 1-3. In general, most ion species were seen, many of which were due to impurities in the ECR source. Sample composite spectra are shown in Figure 3-5 for q/A = 1/2 (30 MeV/u), 1/3 (15.5 MeV/u), and 1/4 (8.75 MeV/u). The spectra were obtained by summing over runs taken at different cyclotron frequency settings. A 7.6 cm. diameter by 7.6 cm. cylindrical plastic scintillator (Bicron B-400) and RCA photomultiplier tube was used, designed and packaged by Bicron Inc. The energy resolution of this detector was determined to be approximately 1-2% in the above energy range for all ions.

Figure 4, at q/A = 1/2, or 30 MeV/u, shows a wide range of fully stripped light ions, up to $^{36}Ar^{+18}$, at 1.08 GeV. Because of restrictions on extraction for ^{4}He, the K in this case was 120. The gas used was a mixture of ^{4}He and ^{20}Ne, and the cyclotron was tuned for $^{4}He^{+2}$. In addition, small amounts of deuterium and ^{36}Ar were introduced into the ECR source. The H^{+} peak was obtained by passing the H_2^{+} beam through a thin degrader in order to breakup the molecular ion. It can be seen that eleven out of the fourteen possible ions listed in Table 1 were seen, with the exceptions of ^{6}Li, ^{32}S, and ^{40}Ca. In later tests, small amounts of SO_2 were leaked into the source and a strong sulphur peak observed. Li has also been observed. The heaviest stable isotope of A=2Z, allowing a q/A ratio of 1/2, is ^{40}Ca. During a later test, this 1.2 GeV beam was also observed from impurities introduced into the source during a previous long run with a calcium oven.

To measure the detector response for ions heavier than ^{40}Ca, one can use other series of ions such as q/A = 1/3 or 1/4. The q/A = 1/3 beams were produced in three steps. First, the ECR source was tuned up on O^{+7} using only oxygen gas, in order to optimize high charge state production. Second, the cyclotron and beamline were tuned using 186.5 Mev C^{+4} from carbon impurities in the source. Third, a very small amount of Kr gas was introduced into the ECR source and the scintillator signal for Kr^{+28} was used to optimize the Kr concentration. Figure 5 shows thirteen such beams obtained at a q/A of 1/3, or 15.5 MeV/u. In addition, several other beams were produced at low intensities which are not shown here (see Table 2). The observed beams include a

very strong ^{63}Cu peak. The $^{12}C^{+4}$ and $^{63}Cu^{+21}$ beams were the two strongest of the many impurity beams observed. The carbon and the copper probably come from the diffusion pump oil in the ECR vacuum system and the walls of the plasma chamber in the ECR source, respectively. Beams of $^{78}Kr^{+26}$, at .35% natural abundance, and $^{84}Kr^{+28}$ were both clearly observed, the latter giving a maximum energy of 1.3 GeV.

A sample spectrum is shown in Figure 6 for q/A= 1/4, at 8.75 MeV/u. The cyclotron was tuned on $^{16}O^{+4}$, using a gas mixture of Ne and Kr. This figure illustrates the sensitivity of the technique to trace impurities in the ECR source. Over seventeen different beams were observed, almost every possible ion species from $^{4}He^{+1}$ up to $^{84}Kr^{+21}$, except for a gap around mass 60-70.

IV. Discussion

One can see from looking at the tables and figures the wide range of ion species available with this technique. We have seen ion species from hydrogen to krypton at energies ranging from 9 to 30 MeV/u. Lower energies are readily available by choosing lower magnetic fields, smaller q/A values, or by placing degraders in front of the detector. With this technique, calibration of detectors or studies of their response to heavy ions can be done very easily. For example, we have so far evaluated more than ten different samples of scintillating material at five different q/A ratios (1/4, 3/8, 1/3, 7/20, 1/2) in six runs averaging sixteen hours each, including tuning.

A set of aluminum degraders was used to measure the energy dependence of the scintillator response for each beam. Conversely, once the detector response was calibrated, the energy loss measurements were very useful for verifying the existence of a degenerate doublet. Since all the ions of a given charge-to-mass ratio are accelerated to the same velocity, two ions with identical charge states and atomic masses will have the same beam energy, thus will appear degenerate in the detector. This is shown for the case of ^{40}Ar and ^{40}Ca in Figure 7. The calcium beam is about half the intensity of the argon beam. In Figure 7a) at 17.0 MeV/u (no degrader), the two beams are degenerate in energy. However, with a degrader of 13.7 mg/cm^2 in the beam (Fig. 7b)), the two peaks begin to separate due to the different energy losses in the degrader. With a degrader thickness of 34.0 mg/cm^2, the two ions are well separated (Fig. 7c)). This degrader produces an energy difference of 1.7 MeV/u between the two species. Such degenerate beams can be used to study the charge dependence as well as the mass dependence of a detector's response to heavy ions.

The number of ions that can be accelerated by this technique is limited by 1) the natural termination of a q/A series by the path of the line of beta stability, as in the case of q/A = 1/2 (at ^{40}Ca), or 2) the increasingly low concentrations in the ECR source of ions with high charge states as the mass of the ion is increased. Exposing the scintillator detectors to low intensity beams after they have been accelerated by the cyclotron can give in some cases more sensitive diagnostics of the ECR source output than the analyzing magnet that is generally employed. This is especially true for very heavy ions such as Kr and Xe where there are a large number of isotopes and charge states so that different ions can have very similar or even the same charge to mass ratio. The charge state distributions out of the ECR source have been measured using an analyzing magnet for O, Ar, Kr, and I (iodine) ions, as shown in Fig. 8. The maximum charge states observed in these tests were O^{+7}, Ar^{+14}, Kr^{+22}, and I^{+30}. These maximum charge states correspond to a sensitivity limit of about 10 particle-nanoamps, or 6×10^{10} particles/sec for I^{+30}. The sensitivity is predominantly limited for heavy species by the background produced by other isotopes and charge states. Using the present technique, however gives the measured intensities in the cyclotron and the estimated intensities on target shown in Table 4 for C^{+4}, Cu^{+21}, and Kr^{+28}. The intensities on target were calculated using typical values for the transmission through the cyclotron of 4% for light beams and 5% for heavier ions, and assuming a transmission through the beam line of 50%. The estimated intensity on target for $^{84}Kr^{+28}$ is 3×10^5 particles/sec of oxygen-like krypton. For copper, it is an order of magnitude higher. With this technique, one can measure not only heavy species of interest but also the impurity levels in the ECR source plasma at concentration levels well below those detectable with the normal analyzing magnet. Such measurements clearly show residual concentrations of various elements which have been previously introduced into the ECR source. The short term negative effects on the performance of the source due to elemental solids such as Mg, Si, S, and Ca have already been observed, but little is known about the rate at which the contamination is removed.

The ratio of the beam intensities of two isotopes with the same q/A can be used to estimate the probability in the ECR source of stripping additional electrons from an already highly ionized species. This would be true if the isotopic abundance for an element in the ECR source plasma is the same as the naturally occuring abundance, and if all ions with the same charge to mass ratio

have the same transmission through the cyclotron. Estimates for these probabilities are given in Table 5 for the cases of $^{84}Kr/^{78}Kr$ at q/A = 1/3 and, $^{84}Kr/^{80}Kr$ and $^{40}Ar/^{36}Ar$ at q/A = 1/4. The ratio of the natural abundances are given in the second column and the experimental ratio of total peak counts, averaged over all runs, in the third. The ratio of these quantities, (Column 4) , should reflect, for example in the argon case, the probability of pulling an additional electron off of an ion of charge +10 to make an ion of charge +11. The probabilities thus obtained are 51% for the Ar^{+11}, 39% for Kr^{+21}, and only 0.4% for pulling two electrons off of Kr^{+26} to make Kr^{+28}. The square root of this last ratio, 6.5%, gives the average probability of removing one electron in this charge state region, indicating that the probability of producing Kr ions with a charge state greater than +28 is extremely small.

The uncertainty in the above calculations are larger for the $^{84}Kr/^{78}Kr$ case because the measured isotope ratios varied for small changes in the extraction frequency, indicating that the two isotopes may not have been accelerated and extracted equally at all frequency settings. The numbers reported in the table were taken at the nominal machine setting for Kr and should be considered an upper limit on the probability for additional stripping. In the case of the $^{84}Kr/^{80}Kr$ ratios taken at q/A = 1/4, these experimental variations were not observed.

V. Conclusions

We have demonstrated that an ECR source can be utilized to ionize an entire series of ion species having the same q/A, for example $^{4}He^{+1}$ to $^{84}Kr^{+21}$. Any such series can be accelerated to a constant velocity or energy/nucleon in a cyclotron. This series of beams can be easily extracted and delivered for detector testing without retuning the cyclotron or the beamline optics. Thus one can expose several different detectors to a large number of different beams in a very short period of time. The ability to simultaneously accelerate many different ions to the same velocity makes it ideal for detector calibration or development projects in which one wants data for many different ion species.

This technique also can be used to provide diagnostics for the high charge state production of an ECR source. Typically, very high charge states of heavy species have intensities so low that they cannot be readily measured with a current meter or are obscured by contaminants or neighboring isotopes. This method is particularly useful for very heavy ions (Kr, Xe), where the several naturally occuring isotopes and the different charge states can generate ion species with very similar q/A ratios. These species cannot be separated at the rigidity of the analyzing magnet but can be distinguished after acceleration in the cyclotron.

Although the present results are restricted to the range of energies (up to 35 MeV/nucleon) and ion species that can be covered by the present ECR source and the K of the 88" cyclotron, the technique itself is quite general. Plans to install ECR sources in conjunction with many higher K cyclotrons (for instance, the K=800 superconducting cyclotron at Michigan State University) will allow this technique to be extended to higher energies and heavier species. A K=800 machine will give q/A=1/2 species at 200 MeV/nucleon and q/A=1/4 species at 50 MeV/nucleon. Future improvements in ECR source technology should also provide higher intensities of very heavy ions with large charge states. Such beams will extend even further the possibilities for systematically evaluating heavy ion detectors.

This work was supported by the Director, Office of High Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

References:

1) C.M. Lyneis and D.J. Clark, LBL-18980, Proceedings of 1985 Particle Accelerator Conference, Vancouver, May, 1985.

2) M.A. McMahan, R.J. Charity, G.J. Wozniak, D.R. Bowman, Z.H. Liu, L.G. Moretto, W.L. Kehoe, A.C. Mignerey, and M.N. Namboodiri, preprint 1986, and Bull. Am. Phys Soc. 30, 1250(1985).

3) G. Friedlander, J.W. Kennedy, E.S. Macias, J.M. Miller, *Nuclear and Radiochemistry,* (John Wiley & Sons, New York), 1981, Chapter 15, pg 562.

4) D.J. Clark, R.A. Gough, and W.R. Holley, Nucl Instr and Methods 154, 1(1978).

5) R.A. Gough and L. Chlosta, LBL-12793, (1981).

Table 1. Possible beams of q/A = 1/2 (30 MeV/u)

ION	CHARGE STATE	% NATURAL ABUNDANCE	ENERGY[5] (MeV)	FREQUENCY[5] (MHz)	OBSERVED
H_2	1^+	99.98	59.6	11.9682	Y
D	1^+	0.015	59.6	11.9754	Y
^{4}He	2^+	100.	120.0	12.0474	Y
^{6}Li	3^+	7.5	179.7	12.0263	Y
^{10}B	5^+	19.8	299.8	12.0401	Y
^{12}C	6^+	98.9	360.2	12.0547	Y
^{14}N	7^+	99.6	420.2	12.0522	Y
^{16}O	8^+	99.8	480.5	12.0583	Y
^{20}Ne	10^+	90.5	600.6	12.0590	Y
^{24}Mg	12^+	79.0	720.9	12.0618	Y
^{28}Si	14^+	92.2	841.2	12.0641	Y
^{32}S	16^+	95.0	960.0	12.0651	Y
^{36}Ar	18^+	0.34	1081.6	12.0650	Y
^{40}Ca	20^+	96.9	1201.8	12.0653	Y

Table 2. Possible beams of q/A = 1/3 (15.5 MeV/u)

ION	CHARGE STATE	% NATURAL ABUNDANCE	ENERGY[5] (MeV)	FREQUENCY[5] (MHz)	OBSERVED
^{3}He	1^{+}	0.00014	46.4	8.7272	N
^{6}Li	2^{+}	7.5	93.0	8.7510	Y
^{9}Be	3^{+}	100.	139.7	8.7608	Y
^{12}C	4^{+}	98.9	186.5	8.7723	Y
^{15}N	5^{+}	0.37	233.1	8.7722	Y
^{18}O	6^{+}	0.20	279.8	8.7727	Y
^{21}Ne	7^{+}	0.27	326.5	8.7748	Y
^{24}Mg	8^{+}	79.0	373.2	8.7776	Y
^{27}Al	9^{+}	100.	419.9	8.7781	Y
^{30}Si	10^{+}	3.1	466.7	8.7797	Y
^{33}S	11^{+}	0.75	513.3	8.7796	N
^{36}S	12^{+}	0.02	560.0	8.7801	N
^{36}Ar	12^{+}	0.38	560.0	8.7800	N
^{39}K	13^{+}	93.3	606.7	8.7802	N
^{42}Ca	14^{+}	0.65	653.4	8.7807	N
^{45}Sc	15^{+}	100.	700.0	8.7806	N
^{48}Ti	16^{+}	73.8	746.7	8.7807	N
^{48}Ca	16^{+}	0.19	746.7	8.7807	N
^{51}V	17^{+}	99.8	793.5	8.7816	N
^{54}Fe	18^{+}	5.8	840.2	8.7818	Y
^{54}Cr	18^{+}	2.36	840.2	8.7819	Y
^{57}Fe	19^{+}	2.2	886.9	8.7819	Y
^{60}Ni	20^{+}	26.1	933.6	8.7821	Y
^{63}Cu	21^{+}	70.0	980.2	8.7818	Y
^{66}Zn	22^{+}	27.9	1026.9	8.7818	Y
^{69}Ga	23^{+}	60.1	1073.5	8.7815	N
^{72}Ge	24^{+}	27.4	1120.2	8.7815	N
^{75}As	25^{+}	100.	1166.8	8.7812	N
^{78}Se	26^{+}	23.5	1213.5	8.7810	N
^{78}Kr	26^{+}	0.35	1213.5	8.7810	Y
^{81}Br	27^{+}	49.3	1260.2	8.7810	N
^{84}Kr	28^{+}	57.0	1306.9	8.7812	Y
^{84}Sr	28^{+}	0.56	1306.9	8.7812	N
⋮					
⋮					

Table 3. Possible beams of q/A = 1/4 (8.75 MeV/u)

ION	CHARGE STATE	% NATURAL ABUNDANCE	ENERGY[5] (MeV)	FREQUENCY[5] (MHz)	OBSERVED
^{4}He	1^{+}	100.	34.9	6.6091	Y
^{12}C	3^{+}	98.9	104.9	6.6133	Y
^{16}O	4^{+}	99.8	139.9	6.6154	Y
^{20}Ne	5^{+}	90.5	174.8	6.6158	Y
^{24}Mg	6^{+}	79.0	209.9	6.6174	Y
^{28}Si	7^{+}	92.2	244.9	6.6187	Y
^{32}S	8^{+}	95.0	279.9	6.6190	Y
^{36}S	9^{+}	0.015	314.9	6.6191	N
^{36}Ar	9^{+}	0.34	314.9	6.6192	Y
^{40}Ar	10^{+}	99.6	349.9	6.6194	Y
^{40}Ca	10^{+}	96.9	349.9	6.6194	Y
^{44}Ca	11^{+}	2.1	384.8	6.6192	Y
^{48}Ti	12^{+}	73.7	419.8	6.6197	Y
^{48}Ca	12^{+}	0.19	419.8	6.6189	Y
^{52}Cr	13^{+}	83.8	454.8	6.6200	Y
^{56}Fe	14^{+}	91.7	489.8	6.6202	Y
^{60}Ni	15^{+}	26.1	524.8	6.6201	N
^{64}Zn	16^{+}	48.9	559.8	6.6198	N
^{64}Ni	16^{+}	0.9	559.8	6.6199	N
^{68}Zn	17^{+}	18.6	594.7	6.6198	Y
^{72}Ge	18^{+}	27.4	629.8	6.6201	N
^{76}Ge	19^{+}	7.8	664.8	6.6200	N
^{76}Se	19^{+}	9.0	664.8	6.6200	N
^{80}Se	20^{+}	49.8	699.8	6.6201	N
^{80}Kr	20^{+}	2.25	699.8	6.6201	Y
^{84}Kr	21^{+}	57.0	734.8	6.6202	Y
⋮					
⋮					

Table 4. Intensities (q/A = 1/3)

	$^{12}C^*$	$^{63}Cu^*$	Kr
from Cyclotron (ena)	300.	0.061	0.0028
on target (ena)	18.0	0.031	0.0014
on target (part/sec)	$3x10^{10}$	$8.5x10^6$	$3x10^5$

* from impurities in ECR source

Table 5. Isotopic Ratios

	Charge State	% Natural Abundance	Ratio of Counts	Efficiency
$^{40}Ar/^{36}Ar$	11/10	292.7	148.2	0.51
$^{84}Kr/^{80}Kr$	21/20	25.33	9.87	0.39
$^{84}Kr/^{78}Kr$	28/26	162.8	0.70	0.0043

Figure Captions:

1) The maximum energy/nucleon at K = 140 which is available from the LBL 88-inch cyclotron for various values of $(q/A)^2$. The symbols denote some of the typical q/A series that are discussed in the text.

2) The difference between cyclotron resonance frequencies for a species of mass A and a ^{12}C beam for q/A = 1/2, 1/3, and 1/4. The hatched area denotes the width of the resonance frequency of the cyclotron.

3) Schematic diagram of the experimental setup. The ECR source injects the cyclotron with a series of ions of a given charge to mass ratio. Individual ionic species are then accelerated, extracted, and transmitted through the beam line into a 60-inch scattering chamber and directly into the detector being tested.

4) Composite spectrum of some of the undegraded beams observed at q/A = 1/2 (30 MeV/nucleon). The isotope and charge state of the detected beams are listed in Table 1. The cyclotron was tuned on ^4He. He, Ne, Ar, and H_2 gases were fed into the source. Spectra were obtained with a plastic scintillator.

5) Composite spectrum of some of the undegraded beams observed at q/A = 1/3 (15.5 MeV/nucleon). The isotope and charge state of the detected beams are listed in Table 2. The cyclotron was tuned on ^{12}C. Kr gas was fed into the source.

6) Composite spectrum of some of the undegraded beams observed at q/A = 1/4 (8.75 MeV/nucleon). The isotope and charge state of the detected beams are those listed in Table 3. The cyclotron was tuned on oxygen. Kr gas was fed into the source.

7) A = 40 (Ca and Ar) spectra after passing through aluminum degraders: a) is the spectrum with no degrader (17.0 MeV/u), b) with a 13.7 mg/cm^2 thickness of aluminum , and c) with a 34.0 mg/cm^2 thick aluminum degrader.

8) Normalized charge state distributions of oxygen, argon, krypton, and iodine ions as measured with an analyzing magnet at the exit of the ECR source.

88" CYCLOTRON: AVAILABLE ENERGIES
K = 140

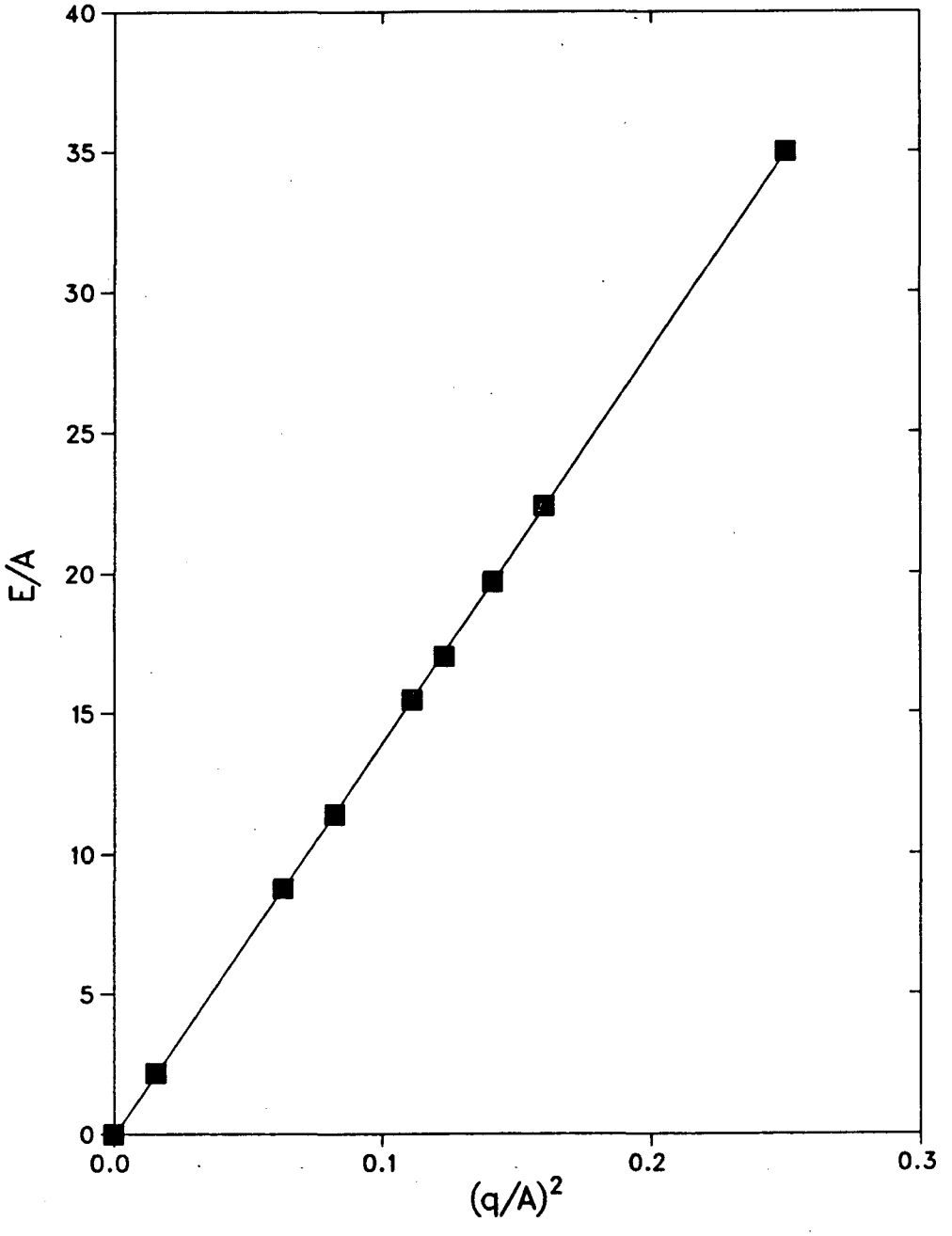


Fig. 1

XBL 865-2114

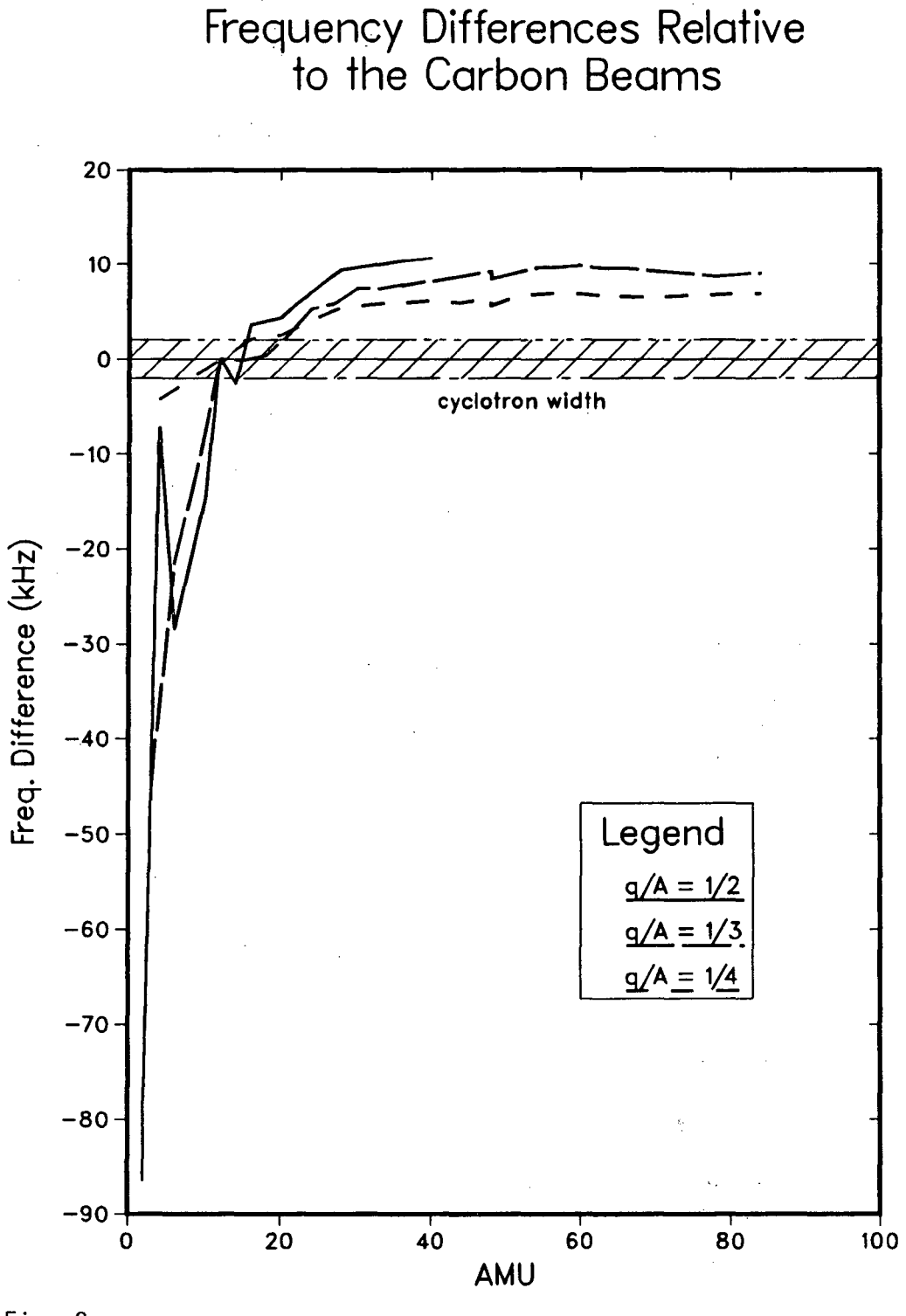
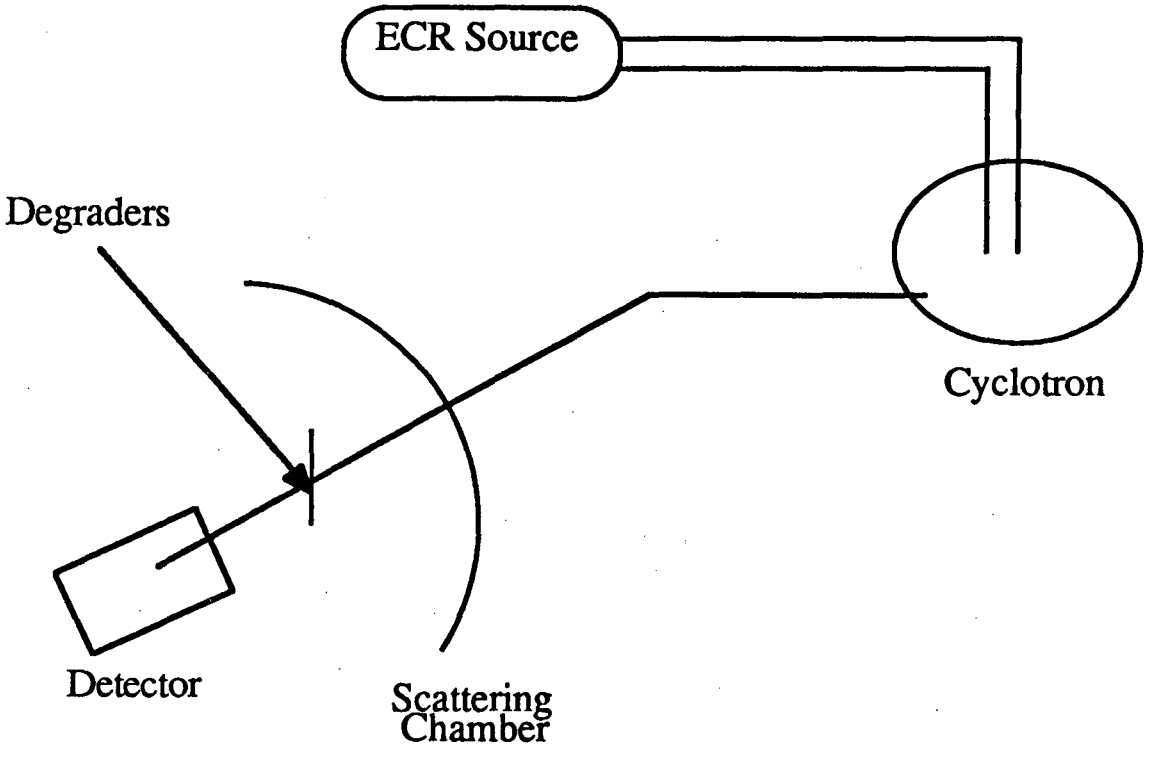


Fig. 2

XBL 865-2113



XBL 865-2110

Fig. 3

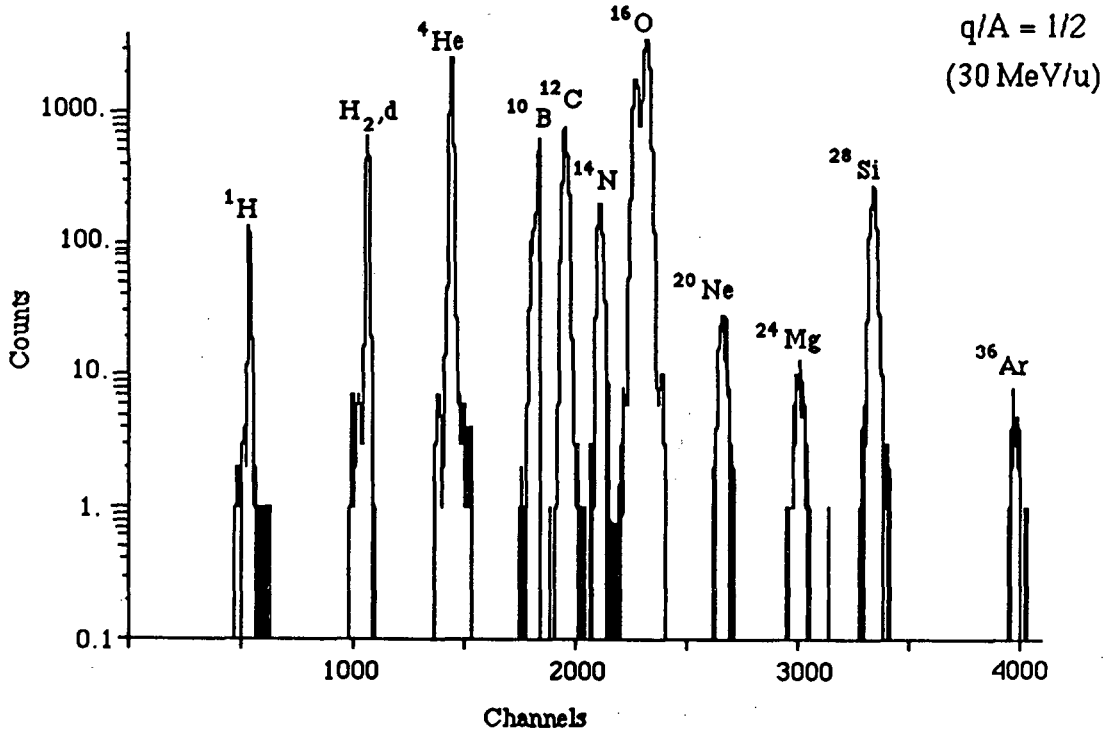


Fig. 4

XBL 865-2111

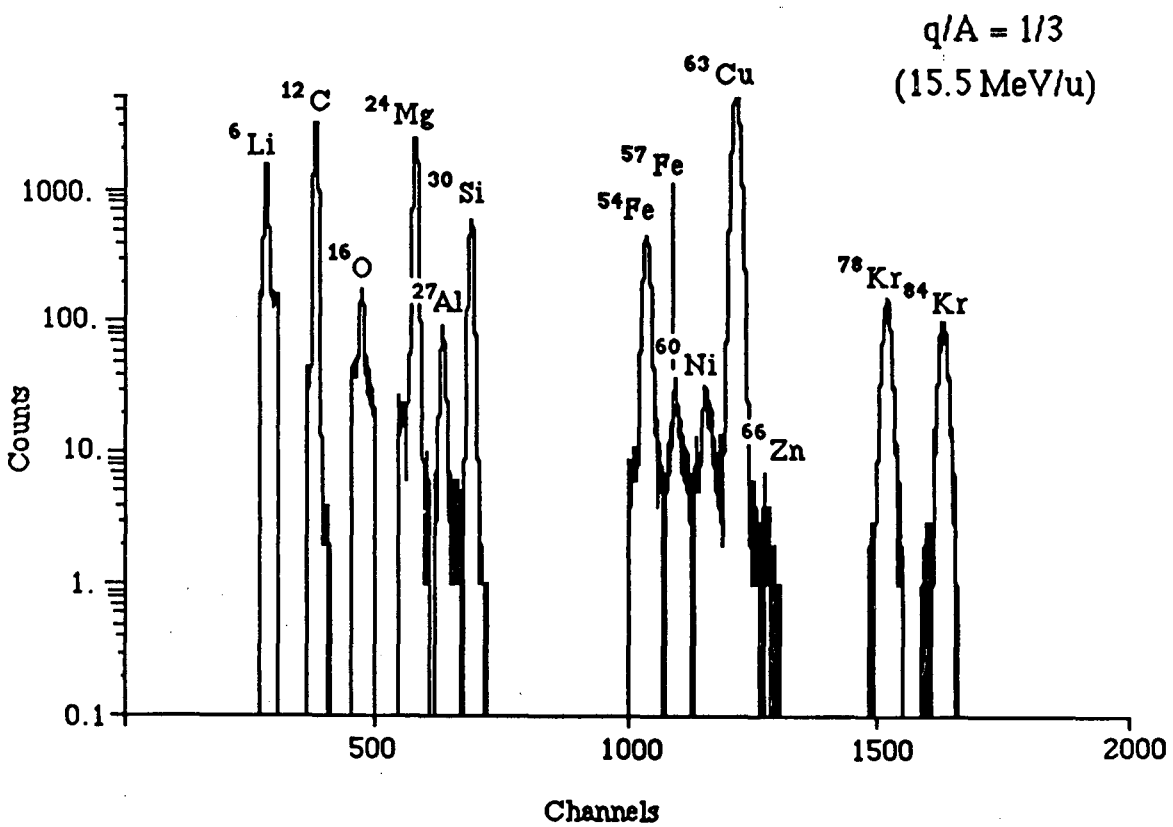


Fig. 5

XBL 865-2112

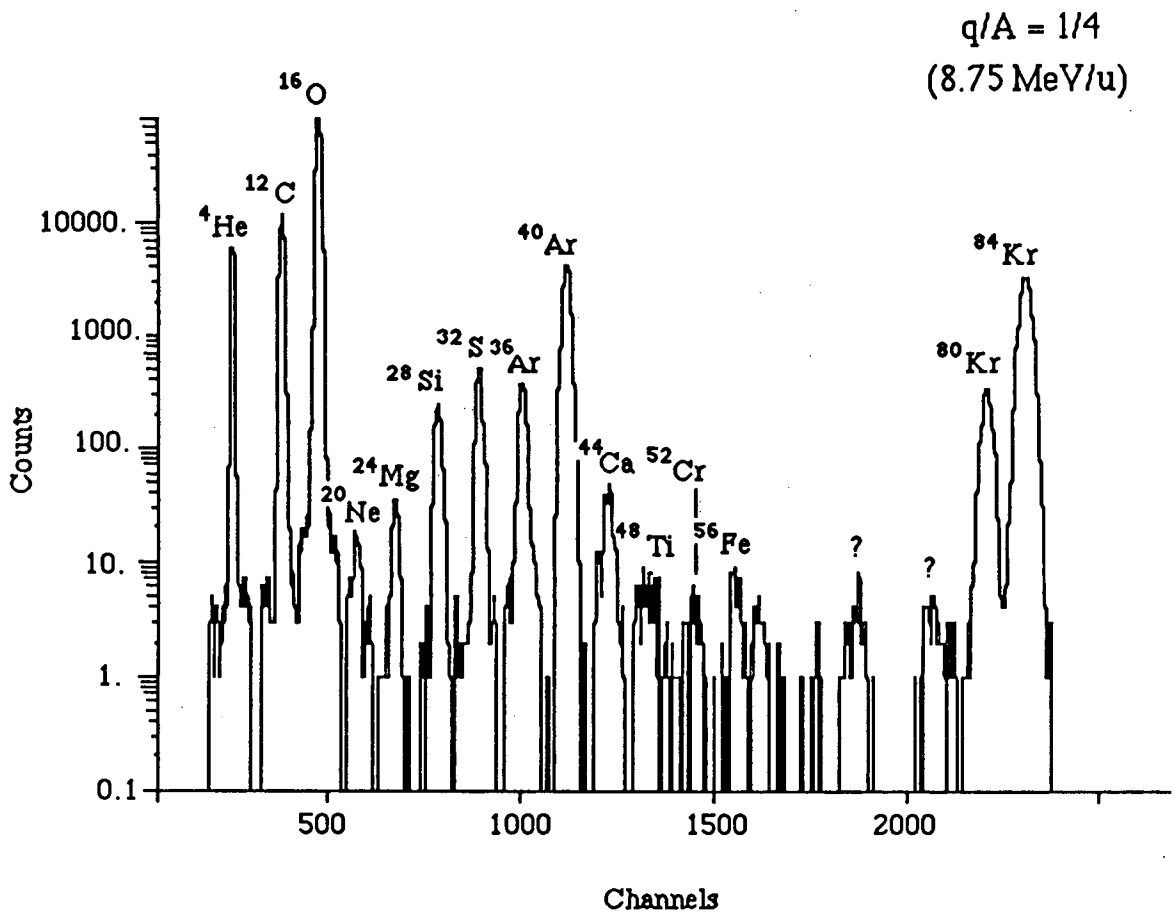


Fig. 6

XBL 865-2109

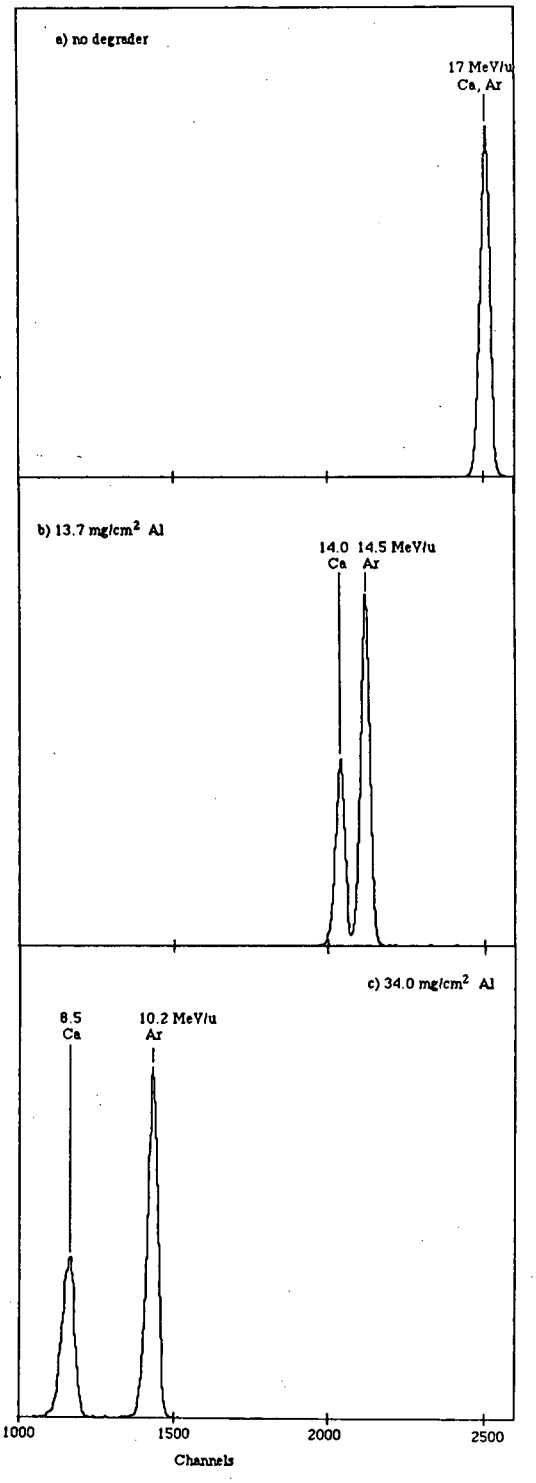


Fig. 7

XBL 865-2115

Charge State Distributions from LBL ECR Source

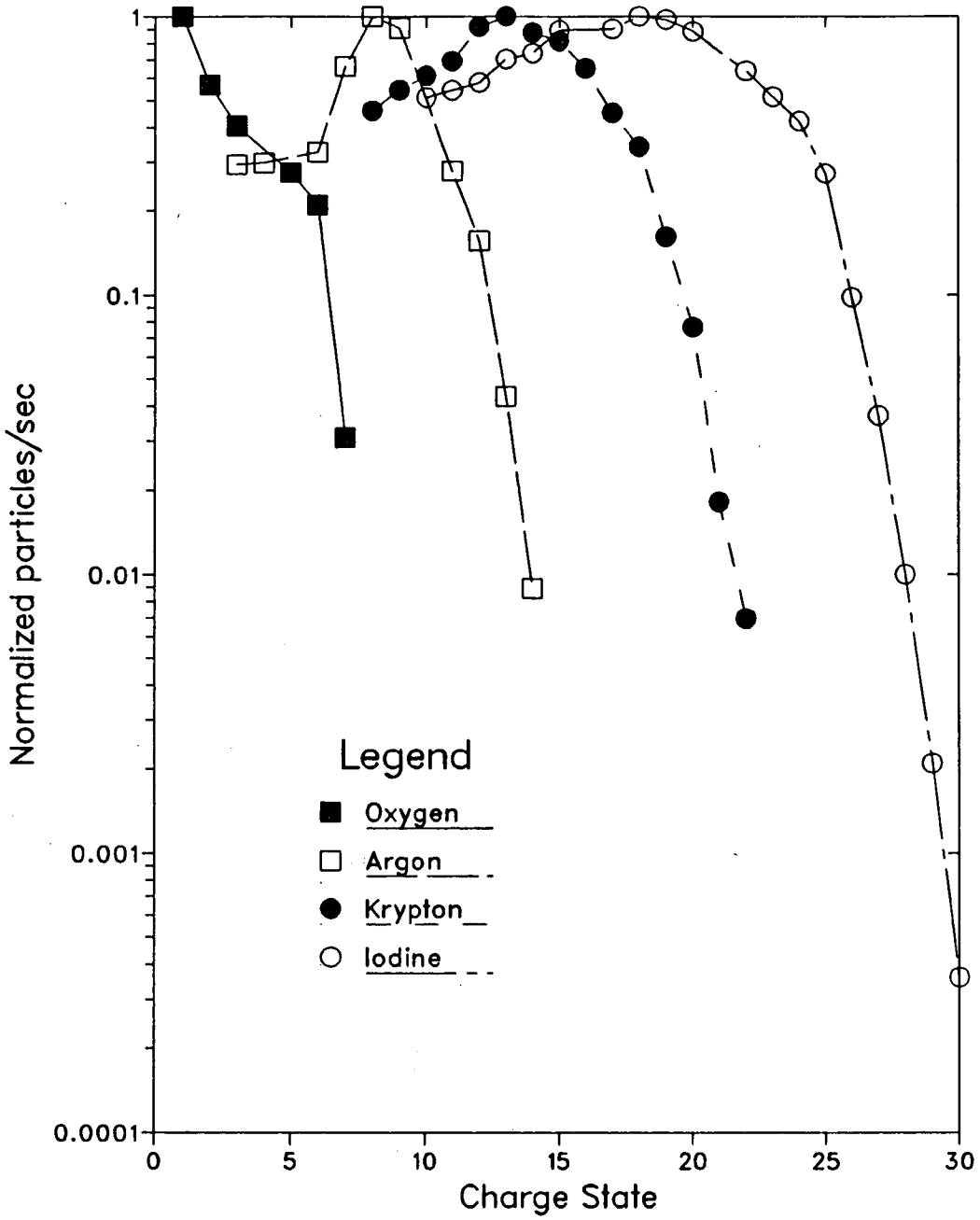


Fig. 8

XBL 865-2108

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720