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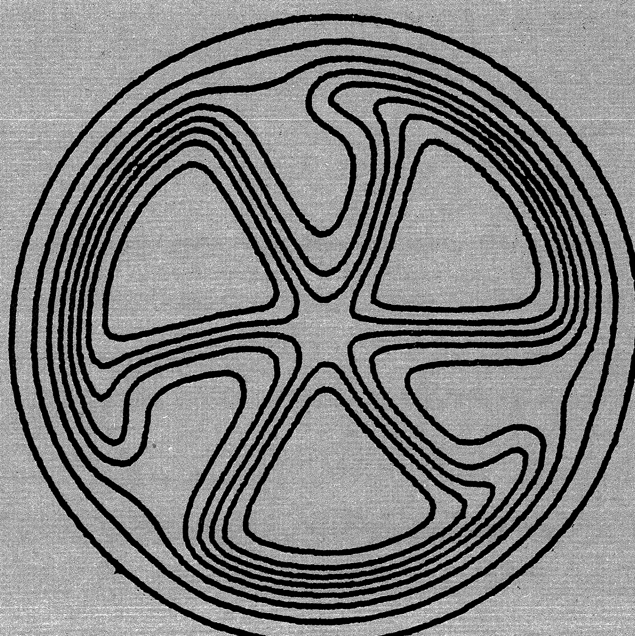
EXOTIC NUCLEI WITH Z > N

WALTER BENENSON



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Exotic Nuclei with Z>N*

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ABSTRACT

The use of multinucleon transfer reactions to measure the mass and energy levels of nuclei far from β-stability is discussed. The results are compared to the predictions of the isobaric multiplet mass equation, Garvey-Kelson mass formulas and shell model calculations.

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I. INTRODUCTION

In this lecture I will discuss the techniques, results and interpretation of a series of experiments performed over a period of five years in collaboration primarily with Prof. Edwin Kashy. The object of these experiments is to use two-body final state nuclear reactions to measure the masses and energy levels of exotic nuclei and in many cases to record their initial observation. An exotic nucleus has been defined as one at least three nucleons away from a stable nucleus. These nuclei, for example ^{9}C, are much more difficult to reach than non-exotic nuclei, and therefore special techniques are required. In the first part of the lecture I will discuss the particular technique we have employed, and then I will discuss the results and their interpretation.

Three transfer reactions which lead to exotic nuclei as final states are (^{3}He,^{6}He), (p,^{6}He) and (^{4}He,^{8}He). Typical parameters for these reactions are given in Table I. The (^{3}He,^{8}He) reaction has not been observed at the time of this lecture but is a very promising method of reaching very proton rich nuclei. The cross sections for all the reactions are very low and the Q-values extremely negative, but these characteristics do not in themselves make the experiments difficult since many sector focussed cyclotrons have adequate energy and beam current. ^{6}He and ^{8}He particles are not difficult to identify since neighboring He-nuclei are unstable and would not reach a detector. The key experimental problem is eliminating or discriminating against the other particles which are produced 10^5 to 10^{10} times more prolifically. The scattering angles used in these measurements are always less than 12° so elastically scattered particles must be kept off the detector. This can easily be accomplished by a magnetic field, and a spectrograph automatically achieves and desired result provided there is not an accidental equality between the rigidity of elastic-particles and the ones of interest. A typical contaminant is from α-particles, which can be 10^6 times more numerous than the particles of interest. The spectrograph-time-of-flight combination described below was found to be the most satisfactory solution to the problem.

II. EXPERIMENTAL TECHNIQUES

The apparatus illustrated[1] in Fig. 1. is used in conjunction with the Michigan State University Cyclotron. It consists of an Enge split-pole spectrograph and a focal plane detector. The focal plane detector provides position, energy loss, total energy and time-of-flight information. It consists of a charge-division proportional counter and a plastic scintillator. The principle of operation of a charge-division position-sensitive proportional counter is illustrated schematically in Fig. 2. Since charge sensitive preamps are essentially at ground for pulses, the fraction of the total charge flowing to each end depends on the resistance between the place where the charge was

produced and the end. The operation then relies only on the wire itself having a relatively uniform resistance. The plastic scintillator is coupled to a photomultiplier tube, which provides a fast signal from the anode for timing and a slow signal from the dynode for crude total-energy information. The time-of-flight is measured relative to the cyclotron rf voltage. The beam burst from the Michigan State University Cyclotron is very narrow (∿0.25 ns) and stable with respect to the applied rf voltage so the time resolution is dominated by the time spread due to the angular acceptance of the spectrograph. This effect can be clearly seen in the time-of-flight spectrum of Fig. 3. Changing the angular acceptance from 1° to 2° doubles the time spread for each particle type. Using time-of-flight along with the total energy signal from the plastic scintillator and the energy loss in the wire counter, the background level has been reduced to the level of about 1 nb/sr.

Some of the spectra recorded during this series of (^3He,^6He) experiments are given in Figs. 4, 5 and 6. Figure 6 also illustrates the mass measuring technique, which involves a comparison of the magnetic rigidity of the ^6He-particles produced in the reaction of interest to that of ^6He-particles from known reactions with higher and lower Q-values. In each run the magnetic field is adjusted to put the ^6He peak at the same location on the focal plane. Thus the measurement is essentially a comparison of three magnetic fields. The experimental errors, which range from 10 to 50 keV, are usually dominated by target thickness corrections. These are large because relatively thick targets are needed. Other errors are minimized by various techniques. For example, angles forward of 12° are always used to keep kinematic effects small. Dependence on the beam energy is minimized by choosing calibration reactions with as similar a Q-value as possible.

III. RESULTS

a) The sd- and p-shells.

When the target is a $T_z=0$ nucleus, the transfer reactions discussed above lead to nuclei with $T_z=3/2$[2] and -2.[3] This is only possible for nuclei in the s-d and p-shell since there are no $T_z=0$ targets above ^{40}Ca. Nuclei with $T_z=-3/2$ and -2 are of particularly interest to studies of isobaric multiplets. $T_z=-3/2$ nuclei, for example, usually complete a mass quartet of the type illustrated for A=9 in Fig. 7. Not only is the ground state of ^{9}C a member of a quartet, but so is also every state in ^{9}C. In other words each state in ^{9}C has a mirror in ^{9}Li and two analogs which lie very high in ^{9}Be and ^{9}B. Very often the location of the T=3/2 level in the $T_z=\pm 1/2$ nucleus is required to complete a quartet. An example[4] is the analog of the first excited states of ^{9}C and ^{9}Li which was found in ^{9}B by looking for a narrow peak in the ^{11}B(p,t)^{9}B reaction (see Fig. 8) at the energy predicted by a symmetry relation for the masses of a multiplet. This relation was first given by Wigner[5] in 1957 and is called the

isobaric multiplet mass equation (IMME). It says that the masses of a multiplet are no more than a quadratic function of T_z.

$$M(T_z) = a + bT_z + cT_z^2$$

Two-body forces which do not conserve isospin, like the Coulomb force, do not break this relation. What is required is something which produces a change in the spatial wave function as a function of the charge (T_z). As examples one can sight the expansion of the wave function due to the greater charge of the most proton rich member or mixing with T=1/2 levels in the $T_z=\pm 1/2$ nuclei.

As a measure of the deviation of the predictions of the equation from the experimental masses, one can quote either X^2 or a coefficient of a cubic term dT_z^3. This is illustrated for the A=9 system in Table 2. The ground state A=9 quarter is the most accurately known and also has the most significant deviation from the prediction of the IMME. A positive d-coefficient of 3-4 keV is theoretically accounted for, but beyond this level there is no explanation available except that the ^{9}Li ground state mass may be slightly wrong. Preliminary results[6] of a mass measurement of ^{9}Li indicate that the d-coefficient for both the ground and first excited A=9 quartets should be reduced by 1-2 keV. The d-coefficients of all the known mass quartets is given in Table 3 and in Figure 9.

In order to reduce the errors of the d-coefficients, one must look to the T=3/2 levels in the $T_z=\pm 1/2$ nuclei. This arises because the d-coefficient is three times more sensitive to their errors than the errors of $T_z \pm 3/2$ nuclei. The d-coefficient can be expressed in terms of the masses by the following equation.

$$d = 1/6[M(3/2)-M(-3/2)]-1/2[M(1/2)-M(-1/2)]$$

where $M(T_z)$ is the mass of the T_z member of the quartet. Thus, in order to reduce the error of the d-coefficient to a few keV, one must measure the mass excesses of the T=3/2 levels to an accuracy of a few keV. This has been done for the ground state A=9 quartet[7] only. In some case, however, the large error is due to the width of the states involved and can not be reduced. Examples are the A=4n-1 quartets in which the T_z=-3/2 nucleus is unbound in every case.

The IMME works so well that it is not necessary to complete a mass quartet in order to study the Coulomb energies between members. The information on the Coulomb energies is in the b- and c-coefficients. Several shell model calculations of these quantities have been made as can be seen in Table 4. The shell model calculations of McGrory and Wildenthal[8] involve the use of neutrons and protons separately in the Oak-Ridge-Rochester code. Single particle energies were taken from ^{17}O and ^{17}F. The resulting agreement is good in general but fails to reproduce the small differences between adjacent levels. The calculations of

Auerbach, et al.[9] were carried out in perturbation theory using shell model wave functions. They predict c only because they used b to adjust the radius.

Very recently Robertson and co-workers used transfer reactions to complete the first isobaric quintet.[10] The mass of the T_z=-2 nucleus ^{8}C was measured with the (^{4}He,^{8}He) reaction and the analogs of this nucleus were located in ^{8}Be,^{8}B and ^{8}Li. The ^{8}B level was located by simply looking for a narrow peak in the $^{11}B(^{3}He,^{6}He)^{8}B$ reaction at the energy predicted by the IMME. The results of this series of experiments is summarized in Table 5. Once again the IMME gives satisfactory agreement with the experimental masses. Using all five masses one obtains $d = 18 \pm 14$ and $e = 13 \pm 7$ keV.

b) The $f_{7/2}$ shell

The (p-^{6}He) and (^{3}He,^{6}He) reactions on ^{50}Cr, ^{54}Fe and ^{58}Ni give six T_z=-1/2 nuclei as their final states. Practically nothing was known about these nuclei before these measurements,[11] and they are key nuclei in extending nuclear mass relationships to the region of Z>N nuclei. It is the knowledge of these masses, for example, which permits the use of the Garvey-Kelson[12] charge symmetric mass relation labelled (a) in Fig. 10 to distinguish it from the transverse relation (b). The spectra shown in Fig. 11 were used to determine the masses of ^{45}V, ^{49}Mn and ^{53}Co. These masses were then used with the Garvey-Kelson mass formulas to predict the masses of Z>N up to A=28. The results of this study are given in Table 6. The predictions show that we have quite a way to go before we reach the proton drip line since it lies near ^{48}Ni and ^{45}Fe.

The Coulomb energies in the $f_{7/2}$ shell show quite an interesting A dependence. For these studies the $7/2^-$ T=1/2 states were used. In some of the nuclei this is an excited state which is much more strongly excited than the seniority 3 ground state. ^{49}Mn is such a case and was therefore the hardest nucleus to observe in its ground state. The cross section for ^{54}Fe(p,^{6}He)^{49}Mn(g.s.) was 7 nb/sr. The results for the Coulomb energies of the $7/2^-$ mirror pairs are plotted in Fig. 12. The Coulomb energy difference, ΔE_c, has been divided by $Z_<$ to remove the trivial Z-dependence which is like a uniformly charged sphere. The experimental points are shown with their error bars, and the solid curve is a shell model calculation by Wildenthal and Chung.[11] The two-particle Coulomb interaction of Shlomo and Bertsch[13] was used with a constant radius pure $f_{7/2}$ configuration. There is good agreement in both the general trend and the amount of Coulomb pairing. Also shown is the same plot for the $d_{5/2}$ shell to demonstrate how much smaller the pairing effect is in the $f_{7/2}$ shell.

Future work will be devoted to completing the (α-^{8}He) and (p,^{6}He) reactions on the T_z=0 nuclei. These reactions have Q-values that are so negative that the use of much higher energy accelerators (>100 MeV) will be required.

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Table 1-- TRANSFER REACTIONS USED TO STUDY EXOTIC PROTON-RICH NUCLEI

Reaction	$^3He,^6He$	$p,^6He$	$^4He,^8He$	$^3He,^8He$
Typical Q-Values (MeV)	-20 to -40	-25 to -50	-50 to -70	-50
Cross Section μb/sr	0.05 to 4.0	0.005 to 0.100	0.020	<0.004
final nucleus T_z	-3/2 -1/2	-3/2 -1/2	-2 -3/2	-5/2 -2 -3/2

Table 2.--Parameters of the two A=9 quartets for a quadratic and cubic fit to the IMME (in keV).

^{9}Li Excitation Energy	J^π	a	b	c	d	χ^2
Ground State	$3/2^-$	26337.9±1.6	-1320.1±1.6	265.6±1.6	---	19
2.691 MeV	$1/2^-$	28846.2±2.1	-1162.2±3.1	244.6±3.1	---	1.8
Ground State	$3/2^-$	26339.2±1.6	-1332.4±3.2	266.6±1.6	7.6±1.6	---
2.691 MeV	$1/2^-$	28848.2±2.6	-1167.3±4.9	242.6±3.4	4.2±3.1	---

s,d Shell

Table 4.--Isobaric Multiplet Mass Equation Coefficients (keV)

$$M = a + bT_z + cT_z^2$$

A	J^{π}	Experiment b	Experiment c	Shell Model b	Shell Model c	Lev, Auerbach and Kashy c
21	$5/2^+$	-3667	237	-3570	208	239
	$1/2^+$	-3628	228	-3528	208	
25	$5/2^+$	-4382	221	-4382	221	240
	$3/2^+$	-4371	216	-4417	214	
29	$5/2^+$	-5025	200			224
37	$3/2^+$	-6200	200	-6390	184	199
	$1/2^+$	-6172	203	-6251	197	

Table 3.-- Isobaric Multiplet Mass Equation

$$M = a + bT_z + cT_z^2 + [dT_z^3]$$

$T_z=-3/2$ Nucleus	J^{π}	E_x	d(keV±keV)
^{7}B	$3/2^-$	0.0	-11 ±30
^{9}C	$3/2^-$	0.0	7.6±1.6
	$1/2^-$	2.62	4.2±3.1
^{13}O	$3/2^-$	0.0	- 0.5± 2.9
^{17}Ne	$1/2^-$	0.0	5.8± 6.3
	$3/2^-$	1.32	- 4.2± 7.4
^{21}Mg	$5/2^+$	0.0	6.3± 6.9
	$1/2^+$	0.21	- 2.4± 7.0
^{23}Al	$5/2^+$	0.0	-11.2±18.5
^{25}Si	$5/2^+$	0.0	1.9± 2.9
	$3/2^+$	0.040	4.8± 3.6
^{29}S	$5/2^+$	0.0	3 ±11
^{33}Ar	$1/2^+$	0.0	2.0± 5.5
	$3/2^+$	1.34	1.0±26.0
	$5/2^+$	1.79	3.8±11.0
^{37}Ca	$3/2^+$	0.0	- 2.4± 4.9
	$1/2^+$	1.61	2.4±15.0

Table 5.-- FIRST COMPLETE MASS QUINTET

A=8

T_z	Nucleus	ME	Ex	Reactions
-2	^{8}C	35.36(17)	G.S.	$^{12}C(\alpha,{}^{8}He)$
-1	^{8}B	33.542(9)	110.619	$^{11}B({}^{3}He,{}^{6}He)$
0	^{8}Be	32.434(27)	27.492	$^{10}Be(p,t)$
1	^{8}Li	31.770(54)	10.822	$^{10}Be(p,{}^{3}He)$
2	^{8}He	31.597(13)	G.S.	$^{26}Mg(\alpha,{}^{8}He)$

Table 6.--Predicted mass excess using GKS, new mass measurements, mass 71 mass values[11] and Ref. 7.

Nucleus	Mass Excess (MeV)	Binding energy (MeV)[a] One proton	Two protons
		T_z=-1	
^{44}V	-23.82	1.79	6.30
^{46}Cr[b]	-29.59	5.01	6.62
^{48}Mn	-29.28	1.96	6.79
^{50}fe	-34.46	4.15	6.22
^{52}Co	-3439	1.44	6.34
^{54}Ni	-39.26	3.92	5.51
		T_z=-3/2	
^{43}V	-17.91	.08	3.85
^{45}Cr	-19.67	3.14	4.92
^{47}Mn	-22.60	.30	5.32
^{49}Fe	-24.76	2.77	4.73
^{51}Co	-27.34	.17	4.32
^{53}Ni	-29.69	2.59	4.04
		T_z=-2	
^{42}V	- 8.01	- .39	2.07
^{44}Cr	-13.58	2.95	3.03
^{46}Mn	-12.58	.19	3.33
^{48}Fe	-18.15	2.84	3.14
^{50}Co	-17.71	.24	3.01
^{52}Ni	-22.63	2.58	2.75

Nucleus	Mass Excess (MeV)	Binding energy (MeV)[a] One proton	Two protons
		$T_z=-5/2$	
^{41}V	.09	1.82	.41
^{43}Cr	-2.17	1.45	1.06
^{45}Mn	-5.13	-1.16	1.79
^{47}Fe	-7.14	1.85	2.05
^{49}Co	-9.91	- .95	1.89
^{51}Ni	-12.01	1.59	1.83
		$T_z=-3$	
^{42}Cr	6.14	1.24	- .58
^{44}Mn	6.40	-1.28	.17
^{46}Fe	.55	1.61	.46
^{48}Co	1.01	- .86	1.00
^{50}Ni	-4.11	1.49	.54
		$T_z=-7/2$	
^{45}Fe	13.60	.09	-1.19
^{49}Ni	7.63	.67	- .19
		$T_z=-4$	
^{48}Ni	16.45	.49	-1.33

[a] Negative binding energy indicates nucleus unbound to particle emission.

[b] Experimental mass is -29.46 .03 (Ref. 10).

FIGURE CAPTIONS

Figure 1.--Schematic of the spectrograph-time-of-flight combination.

Figure 2.--Equivalent circuit of a charge division position sensitive proportional counter.

Figure 3.--Time of flight spectrum taken during a (p-^{6}He) experiment. The ^{6}He-particles have the same time-of-flight as the tritons and are distinguished by energy loss information.

Figure 4.--First observation of ^{55}Ni.

Figure 5.--Energy levels of ^{33}Ar.

Figure 6.--Spectra taken during a measurement of the mass of ^{37}Ca.

Figure 7.--The A=9 isobaric quartets.

Figure 8.--Observation of the analog of the first excited state of ^{9}C in ^{9}B.

Figure 9.--Summary of the d-coefficient of all the known mass quartets. The data on the A=4n-1 quartets is from the review article of J. Cerny (Ann. Rev. of Nuc. Science 18, 27(1968).

Figure 10.--Two of the Garvey-Kelson mass formulas. The one labelled (a) is the charge symmetric and the one labelled (b) is the transverse mass relation.

Figure 11.--Spectra at 10.5° from the (p,^{6}He) reaction on three $T_z=1$ nuclei in the $f_{7/2}$ shell.

Figure 12.--Reduced Coulomb energies $\Delta Ec/Z_<$, in the $f_{7/2}$ and $d_{5/2}$ shell.

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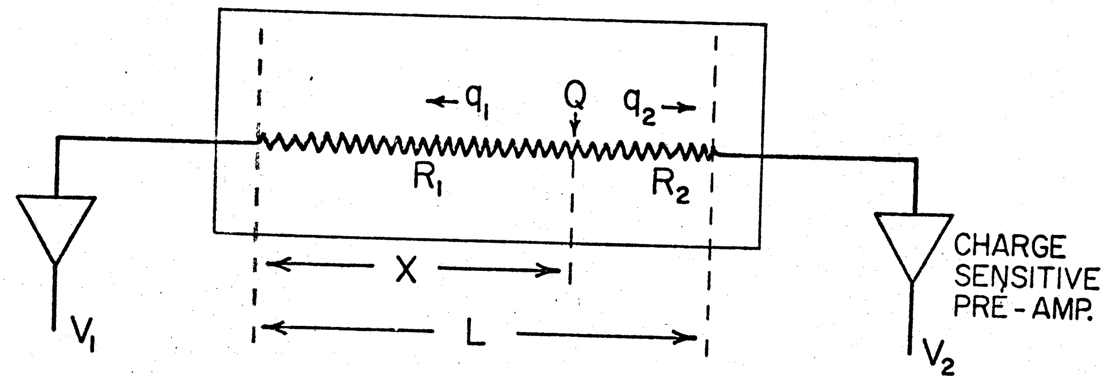
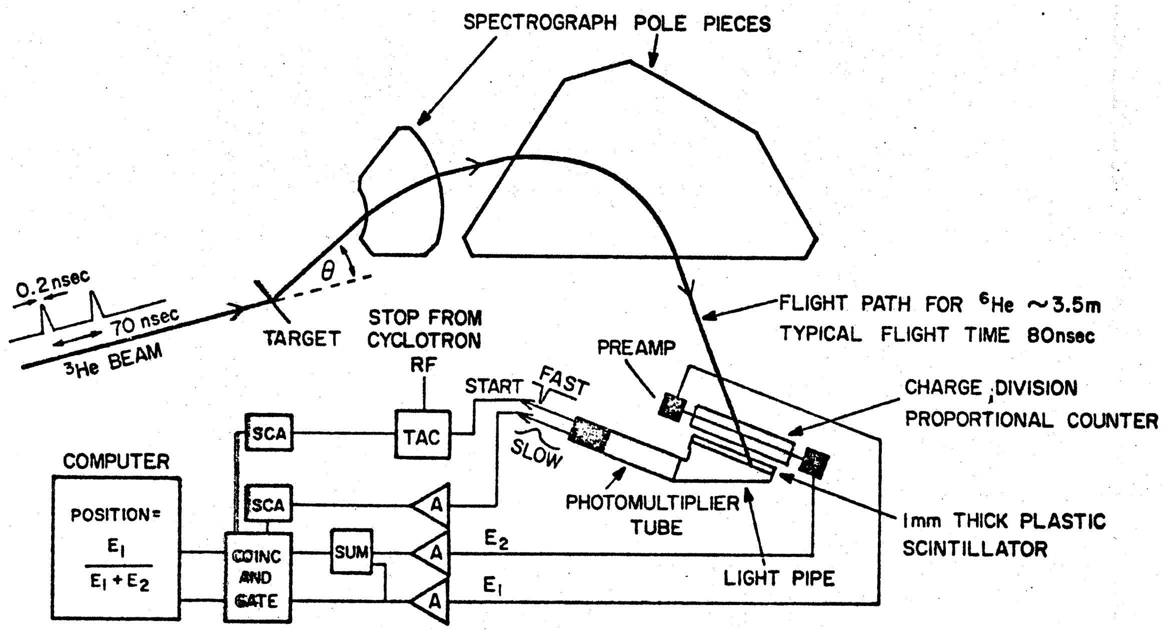
CHARGE DIVISION POSITION SENSITIVE
PROPORTIONAL COUNTER



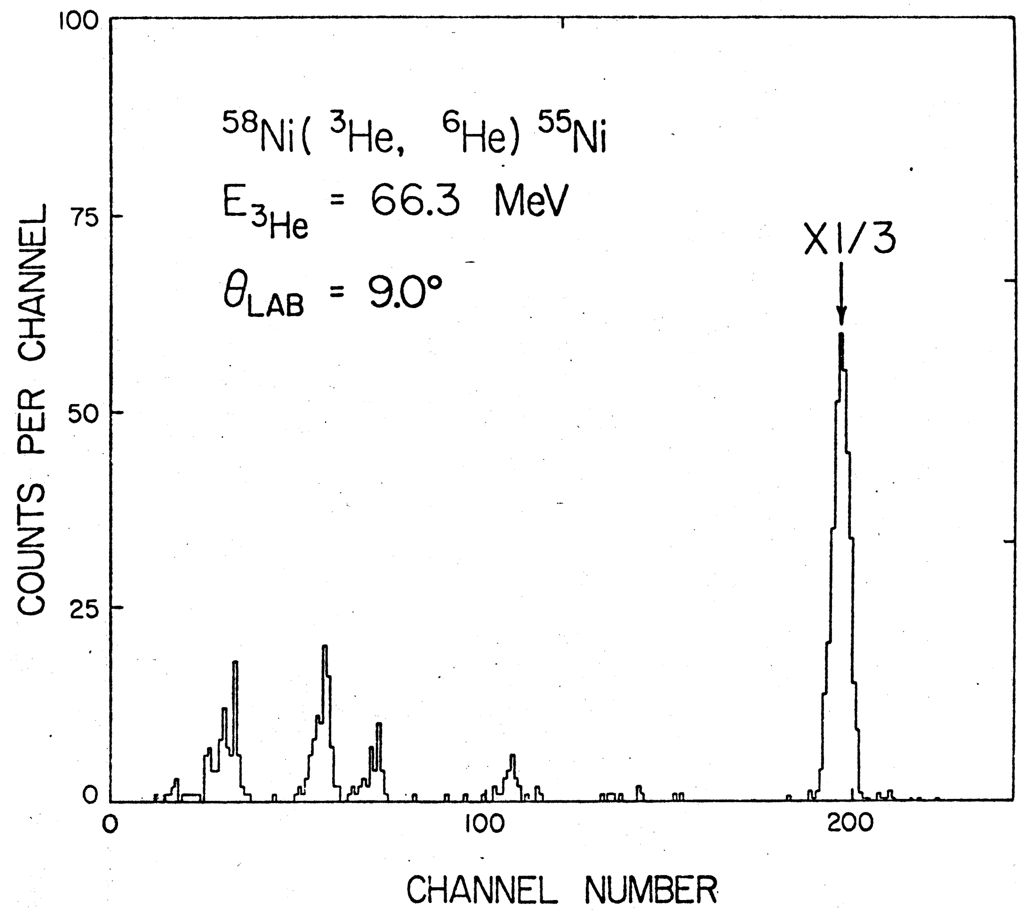
$$X = \frac{q_2}{q_1 + q_2} L = \frac{V_2}{V_1 + V_2} L$$

19



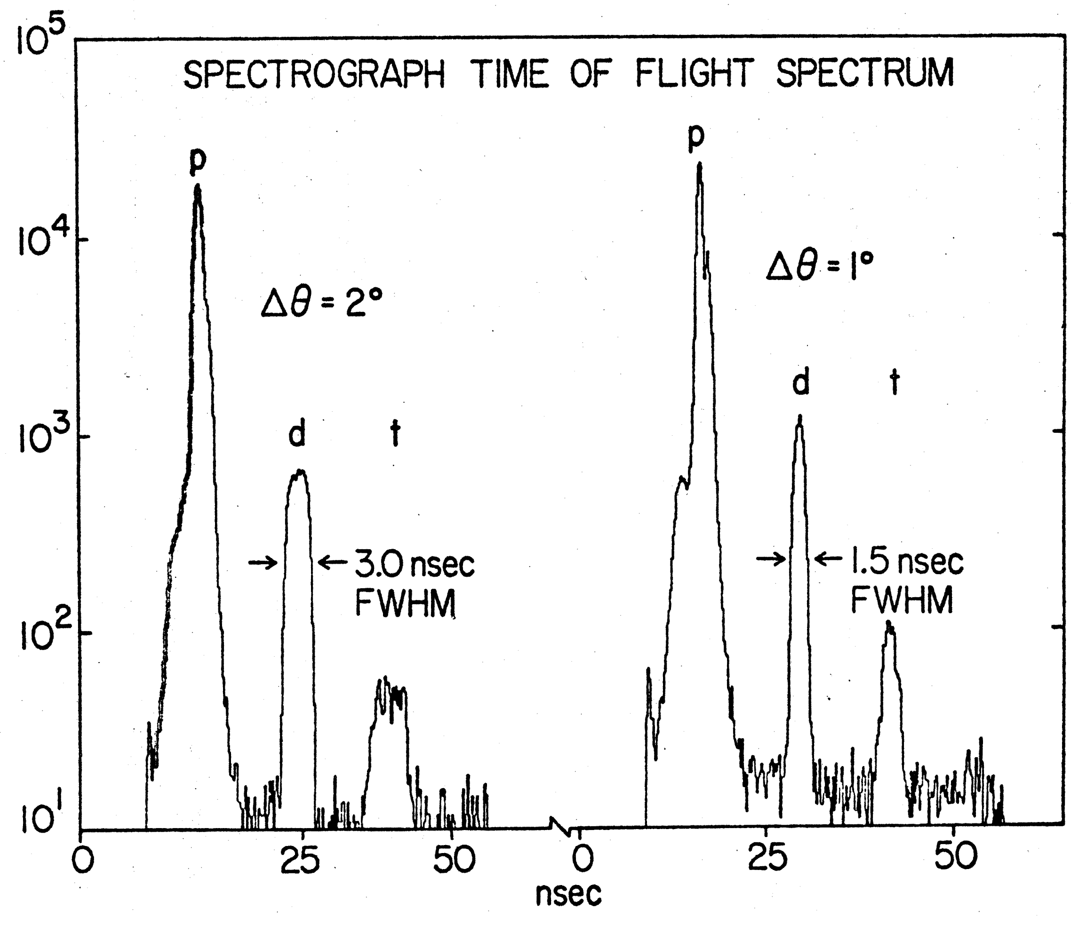
TIME OF FLIGHT PARTICLE IDENTIFICATION IN THE SPECTROGRAPH

22

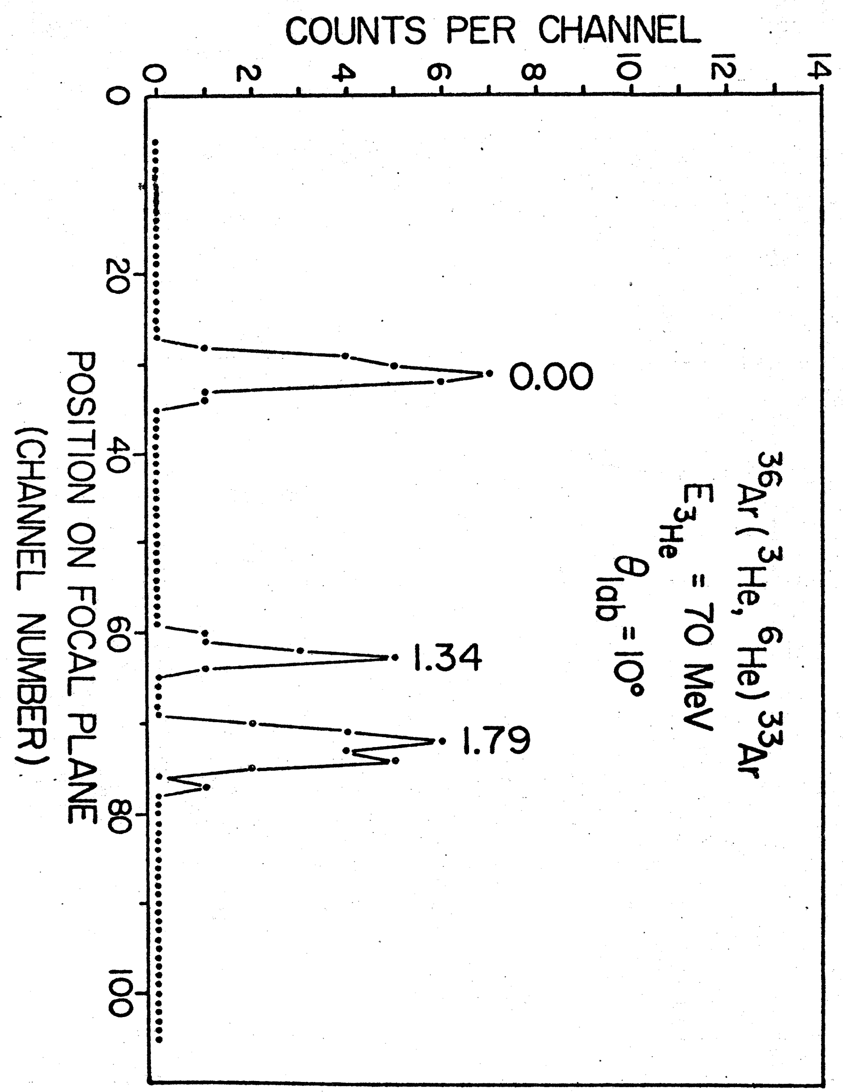


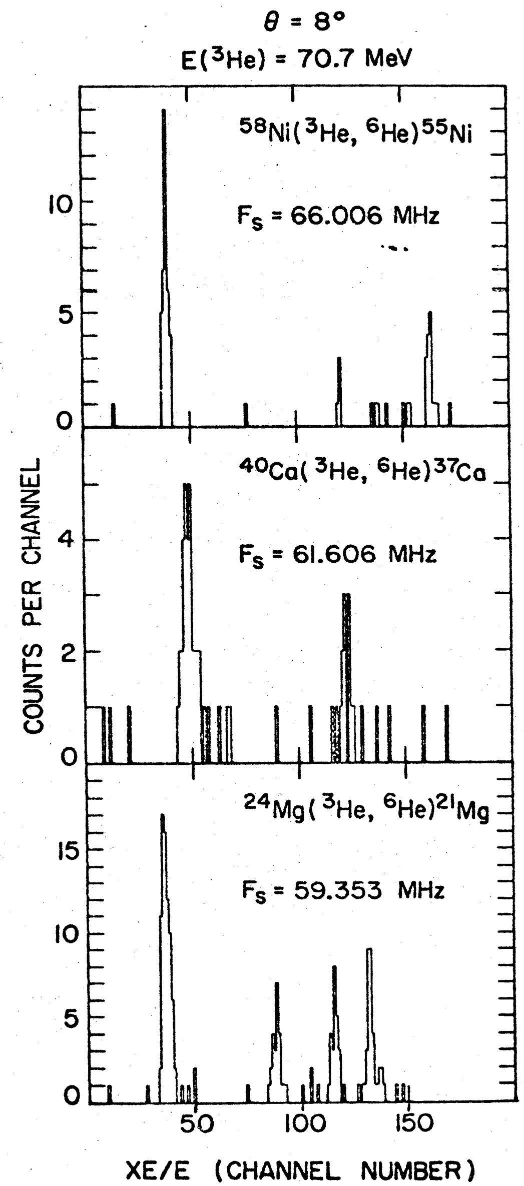
$^{58}Ni(^{3}He, ^{6}He)^{55}Ni$
$E_{^3He}$ = 66.3 MeV
θ_{LAB} = 9.0°
X1/3
COUNTS PER CHANNEL
CHANNEL NUMBER
0
25
50
75
100
0
100
200

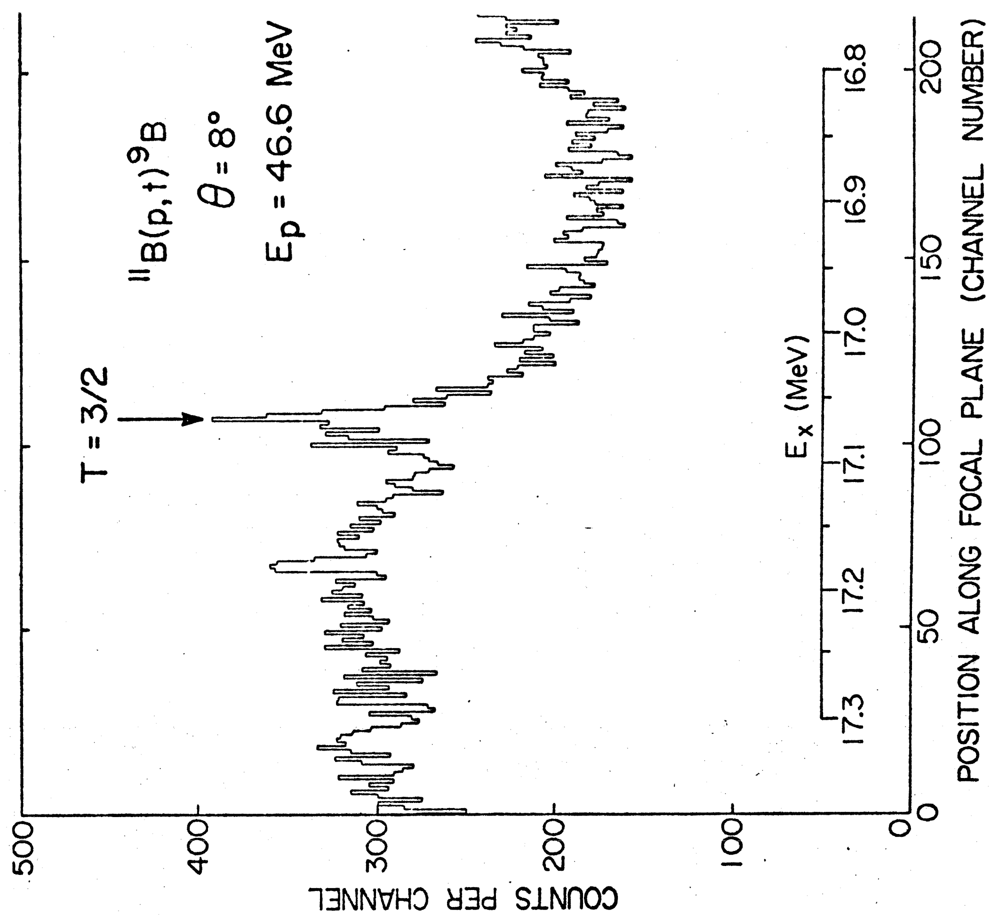
21



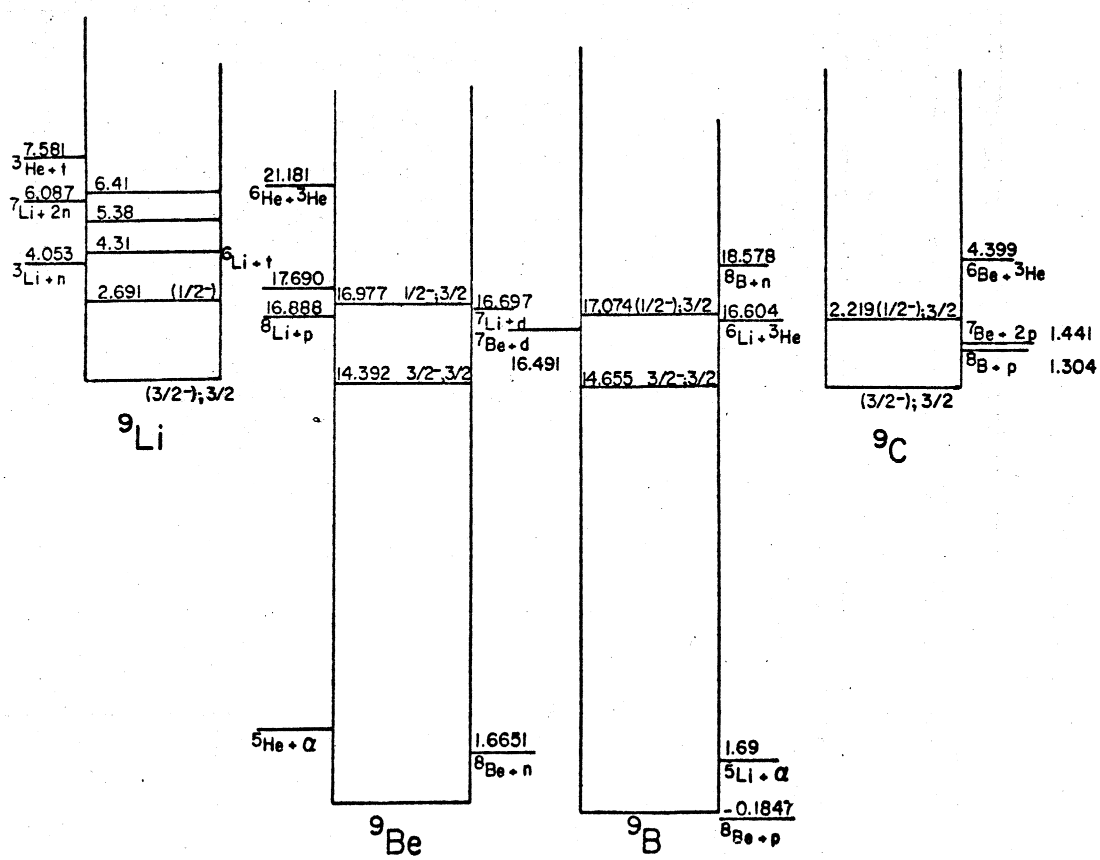
SPECTROGRAPH TIME OF FLIGHT SPECTRUM
p
d
t
$\Delta\theta$ = 2°
$\Delta\theta$ = 1°
3.0 nsec FWHM
1.5 nsec FWHM
10^1
10^2
10^3
10^4
10^5
0
25
50
0
25
50
nsec


COUNTS PER CHANNEL
POSITION ON FOCAL PLANE
(CHANNEL NUMBER)
0.00
1.34
1.79
$^{36}Ar(^{3}He, ^{6}He)^{33}Ar$
$E_{^{3}He}$ = 70 MeV
θ_{lab} = 10°

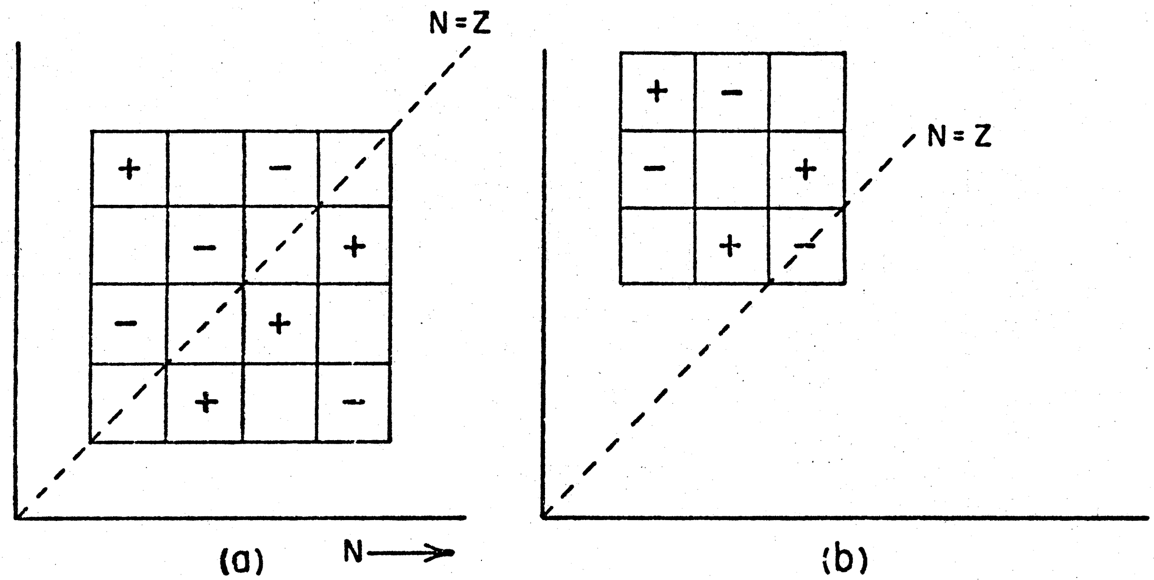

θ = 8°
E(^{3}He) = 70.7 MeV
$^{58}Ni(^{3}He, ^{6}He)^{55}Ni$
F_s = 66.006 MHz
$^{40}Ca(^{3}He, ^{6}He)^{37}Ca$
F_s = 61.606 MHz
$^{24}Mg(^{3}He, ^{6}He)^{21}Mg$
F_s = 59.353 MHz
COUNTS PER CHANNEL
XE/E (CHANNEL NUMBER)



A = 9 T = 3/2 LEVELS

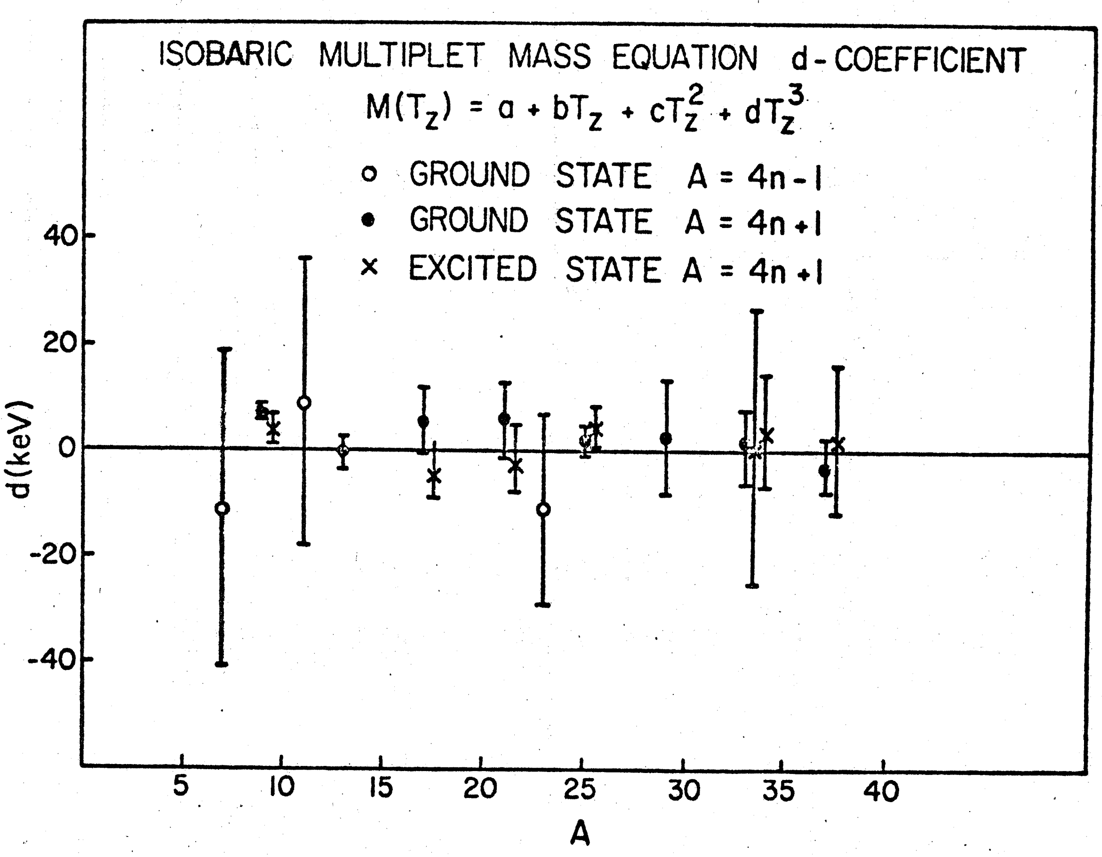


28

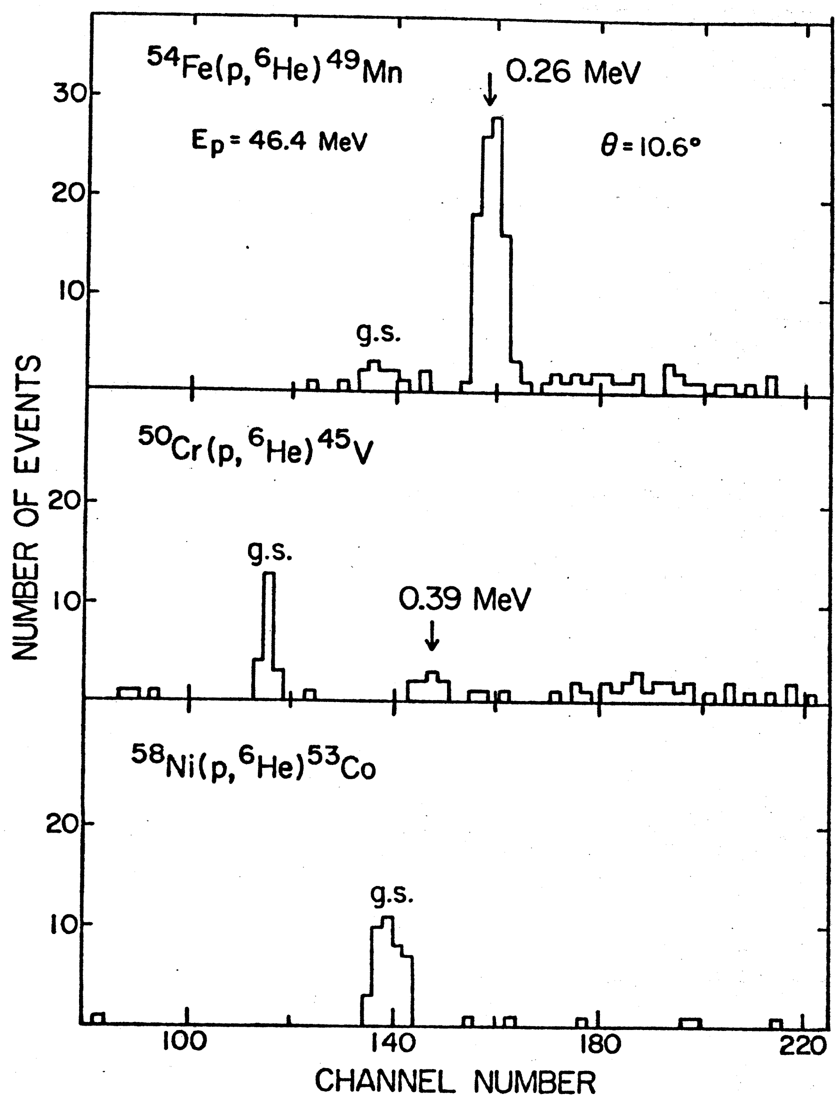


N = Z
Z
N
+
−
(a)
(b)

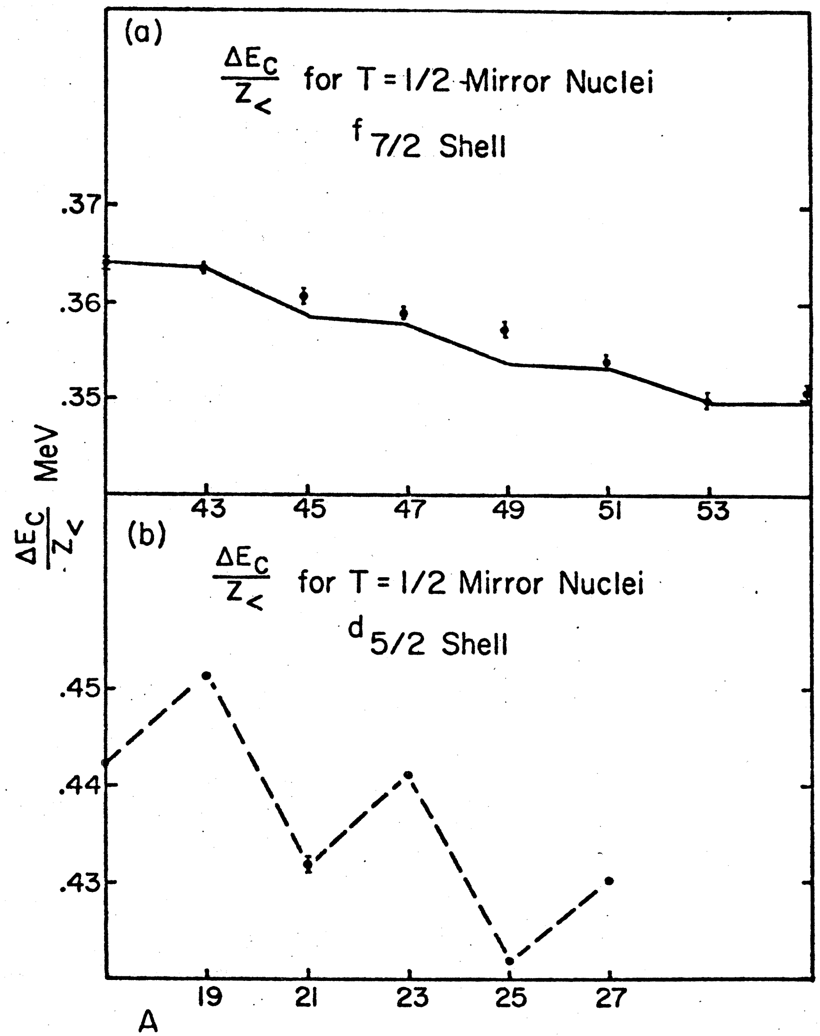
27



ISOBARIC MULTIPLET MASS EQUATION d-COEFFICIENT
M(T_Z) = a + bT_Z + cT_Z^2 + dT_Z^3
GROUND STATE A = 4n-1
GROUND STATE A = 4n+1
EXCITED STATE A = 4n+1
d(keV)
40
20
0
-20
-40
5
10
15
20
25
30
35
40
A



54Fe(p,6He)49Mn
Ep = 46.4 MeV
θ = 10.6°
0.26 MeV
g.s.
50Cr(p,6He)45V
g.s.
0.39 MeV
58Ni(p,6He)53Co
g.s.
NUMBER OF EVENTS
30
20
10
100
140
180
220
CHANNEL NUMBER



(a)
ΔEC/Z< for T = 1/2 Mirror Nuclei
f 7/2 Shell
.37
.36
.35
43
45
47
49
51
53
(b)
ΔEC/Z< for T = 1/2 Mirror Nuclei
d 5/2 Shell
.45
.44
.43
19
21
23
25
27
A
ΔEC/Z< MeV