SECTION I

RESEARCH IN PROGRESS

New Reactions Leading to Exotic Nuclei

W. Benenson, E. Kashy, D. Mueller, and R.G.H. Robertson

Virtually all of the nuclei far from stability with A 55 which can be reached by the (^{3}He,^{6}He) (p,^{6}He) and (^{3}He,^{8}Li) reaction have now been observed and their masses measured. Besides the (^{3}He,^{8}B) reaction, which is described in another section, there are a number of reactions which reach new nuclei and make use of the exceptional properties of the 75 MeV ^{3}He beam. These are discussed in this section.

a) (^{3}H,^{9}Li): This reaction has been used successfully in a ^{14}N(^{3}He,^{9}Li)^{8}C experiment[1] which achieved a 50 keV accuracy for the mass of ^{8}C. In addition, one spectrum has been obtained for ^{58}Ni(^{3}He,^{9}Li)^{52}Co with a cross section of about 5 nb/sr. In the ^{8}C experiment a double-wire counter with a silicon stopping detector was used. Discrimination against unwanted particles with this detector is considerably better than with a plastic scintillator since both the linearity and the energy resolution are excellent. A 5 cm. long surface barrier detector was purchased for this purpose.

b) (^{3}He,^{8}He): This reaction has been observed at Princeton on ^{64}Ni--not a case which leads to a nucleus far from stability. Attempts to reach new nuclei far from stability have been unsuccessful so far because it appears that the cross section is extremely low. Whether this is due to the more negative Q-values or to the reaction dynamics favoring near to stability final states (as in compound nuclear reactions) is not known. We attempted to observe ^{22}Al and could not get a single true ^{8}He count for 0.5 coulombs of charge. The one event which came close to identifying as ^{8}He is equivalent to a cross section of 0.04 nb/sr. Similar results on the ^{58}Ni(^{3}He,^{8}He) reaction have been obtained at Princeton. It is now clear that the (^{3}He,^{8}He) reaction is not a powerful tool and also that the two-wire plus surface barrier detector on the focal plane is capable of reaching exceptionally low cross sections. If the ^{27}Al(^{3}He,^{8}He)^{22}Al cross section had been 1 nb/sr, we would have had a 25 count narrow peak without background--more than adequate for a 25 keV mass measurement.

c) (^{3}He,^{9}C): The identification system for the detection of this reaction has been checked by detecting the recoil ^{9}C particles from the ^{12}C(^{3}He,^{6}He)^{9}C reaction. A spectrum of ^{9}C particles is shown in Fig. 1. An attempt to reach the T_z=5 nucleus ^{58}Cr by the ^{64}Vi(^{3}He,^{9}C) reaction appears to have been unsuccessful. This attempt was made using a double-wire counter with a plastic scintillator stopping detector. We observed a background that identifies as ^{9}C particles. This background corresponds to a cross section of 1.1 nb/sr for the .5 MeV peak width expected from the target thickness. Use of the 5 cm. long silicon stopping detector mentioned above should allow us to reduce the background level substantially. If the cross section is about 1 nb/sr, we should be able to make a mass measurement with 100 keV accuracy in 2-3 days of beam time.

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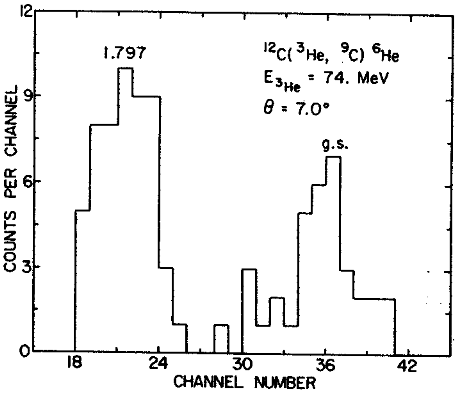

Fig. 1.--Spectrum of recoil ^{9}C ions from the ^{12}C(^{3}He,^{6}He)^{9}C reaction. The 0^+ and 2^+ levels of ^{6}He are clearly seen. The width of the peaks is due to target thickness.

T=2 Levels in T_z=-1 Nuclei

W. Benenson, E. Kashy, D. Mueller, H. Nann, and R.G.H. Robertson

Only one case of a T=2 level in a T_z=-1 nucleus has been experimentally determined. This is the T=2 state in ^{8}B, which was found by Robertson and Chien[1] using the (^{3}He,^{6}He) reaction. This state, which was needed to complete the first isobaric mass quintet (A=8), was identified easily because it produced a narrow peak lying very high in the continuum region of ^{8}B. Other examples of T=2 states in T_z=-1 nuclei will not be so simple since generally they lie in the region of discrete states. An attempt to find the T=2 state in ^{24}Al by searching for a peak in ^{27}Al (^{3}He,^{6}He) which is not observed in ^{24}Mg(^{3}He,t) was unsuccessful. This, however, was before the techniques for doing (^{3}He,^{6}He) with high resolution were developed.

^{20}Na is reasonable favorable case since the state lies in a region where one expects broadening of T=1 levels but not of T=2 levels. In addition, the other four members of the quintet are now accurately known[2], so one knows exactly where to look.

Figure 1 shows one of the spectra from the (^{3}He,^{6}He) reaction on a 50 μg/cm^2 Na target. Among the many new levels found for ^{20}Na, one is right at the predicted T=2, energy. Unfortunately the level is complex, perhaps consisting of a broad and narrow state at approximately the same position. The peak which is indicated by an arrow on the figure is very strong, however, and showed up at all angles measured. The next step is to measure the excitation energy of the peak accurately and to attempt to improve the resolution with the idea of resolving its components. A comparison run of ^{20}Ne(^{3}He,t) or ^{20}Ne(p,n) will also be made.

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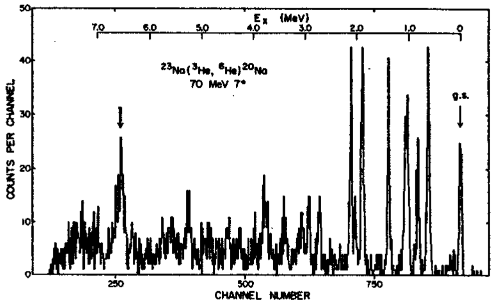

Figure 1. Spectrum of the ^{23}Na(^{3}He,^{6}He) reaction at 7° and 70 MeV.

T_z= -3/2 Nuclei and Mass Quartets

W. Benenson, E. Kashy, H. Nann, D. Mueller, and L. Robinson

The masses of T_z= -3/2 nuclei are required to complete isobaric mass quartets. Our project to measure these masses with high precision has been going on for several years, and now the p and s,d shells are practically complete. These sixteen far from stability nuclei range from ^{7}B to ^{37}Ca.

The situation approximately one year ago is summarized in the AMCO V conference proceedings[1]. At that time the missing T_z= -3/2 nuclei were ^{15}F, ^{27}P, ^{31}Cl, and ^{35}K. These nuclei are all accessible by the (^{3}He,^{8}Li) reaction, which we showed had enough yield to be a usable reaction in a paper on ^{19}Na and ^{23}Al[2]. Since that time we have measured ^{35}K[3], ^{31}Cl, and ^{27}P, and the one remaining case, ^{15}F, will be run soon. This nucleus is unbound, however, and it may prove difficult to give it a meaningful mass, as was the case for ^{11}N.

Figures 1. and 2. show the spectra from the mass measurements (and first observation) of ^{31}Cl and ^{27}P. These two experiments were made difficult by target problems. The ^{32}S(^{3}He,^{8}Li)^{27}P reaction had to be run with very low currents to prevent reevaporation of the S in a carbon foil sandwich target. The 150 nA, which the target would take is less than 1/10 of our usual currents, but luckily the cross section was relatively large ∿0.1 μb/sr. The ^{36}Ar(^{3}He,^{8}Li)^{31}Cl reaction was run on a gas target and consequently the resolution is not as good as in the other (^{3}He, ^{8}Li) experiments. Relatively high pressures (1/4 Atmosphere) were required by the low cross section ∿0.01 μb/sr.

To complete a mass quartet one also needs the T=3/2 state in the T_z= ±1/2 nuclei. For example, a quartet which has been completed since the Paris conference is the A=19 ground state which lacked the lowest ^{19}Ne, T=3/2 state. The A=35 quartet is still incomplete because the T=3/2 state in ^{35}Ar is not accurately measured. The ^{27}Si, T=3/2 state is unknown, and we are in the process of trying to identify it and measure its mass excess accurately with the ^{29}Si(p,t) reaction. Figure 3 gives the present status of mass quartets in a graphical form. A=9 ground state quartet remains the one slight disagreement with the prediction of a quadratic form for the Isobaric Multiplet Mass Equation.

Our present work on this project centers on improving the accuracy of the less well measured T_z= -3/2 nuclei and on completing more quartets by finding excited T=3/2 levels in T_z= ±1/2 nuclei. With wire counters, we now have much higher resolution (∿30 keV) for (^{3}He,^{6}He) than when the project first started, and this makes more work on ^{21}Mg, ^{25}Si, ^{29}S and ^{37}Ca worthwhile.

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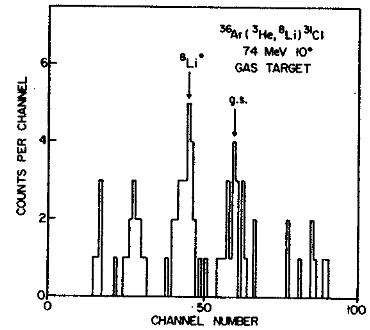

Fig. 1. Spectrum from the mass measurement and first observation of ^{31}Cl.

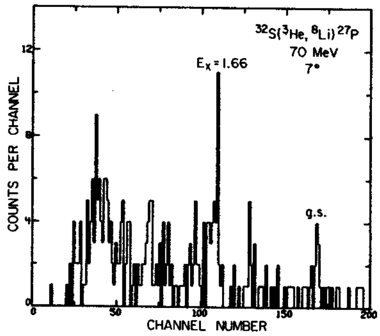

Fig. 2. Spectrum from the mass measurement and first observation of ^{27}P.

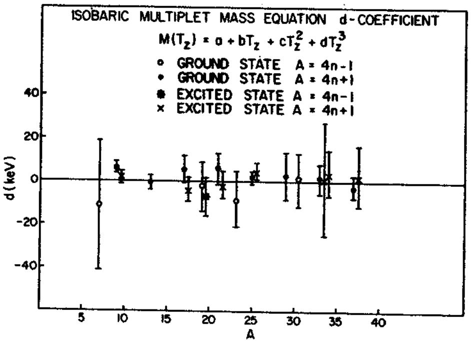

Fig. 3. The present states of the agreement between mass quartets and Wigner's mass multiplet equation as measured by the d-coefficient.

Neutron-Rich Nuclei via the (^{3}He,^{8}B) Reaction

E. Kashy, W. Benenson, D. Mueller, H. Nann and L. Robinson

We have begun a series of measurements of the 5-nucleon pickup reaction (^{3}He,^{8}B) on neutron-rich targets. So far, the T_z=9/2 nuclei ^{43}Cl and ^{59}Mn have been observed and their masses have been measured.[1,2] The particle identification was provided by combining the time of flight information, light output in a thin plastic scintillator and two measurements of the specific ionization in the focal plane of our magnetic spectrograph. Spectra of ^{8}B ions from targets of ^{64}Ni and ^{27}Al are shown in Fig. 1; the ^{27}Al(^{3}He,^{8}B)^{22}Ne reaction served in this case as the energy calibration needed for the mass of ^{59}Mn. The result for ^{43}Cl indicate a mass somewhat greater than predicted by mass equations such as that of Garvey-Kelson[3], although it is possible that the transition observed was to an excited level of ^{43}Cl. The main difficulty in that measurement was the background of ^{8}B ions in the region of interest caused by the ^{12}C(^{3}He,^{8}B)^{7}Li reaction to unbound levels of ^{7}Li which could have hidden a very weak peak corresponding to ^{43}Cl.

Targets of ^{46}Ca, ^{70}Zn and ^{76}Ge are now being obtained to search for ^{41}Cl, ^{65}Co and ^{71}Cu by this reaction. While the cross sections are expected to be extremely small, they are still well within the capability provided in part by our intense ^{3}He beam (2-3μa).

Since little is now known on the reaction mechanisms responsible for 5-nucleon pick-up, we have measured angular distributions of ^{8}B ions from ^{27}Al target bombarded by 74 MeV He^3's, for transitions corresponding to the lowest 0^+, 2^+, 4^+, and 2^+ levels of ^{22}Ne. These are shown in Fig. 2, where it is seen that the differential cross sections are slightly forward peaked and with magnitudes of 100-400 nb/sr. It would be of interest to see if these results are reproduced by calculations made under various assumptions for the reaction process.

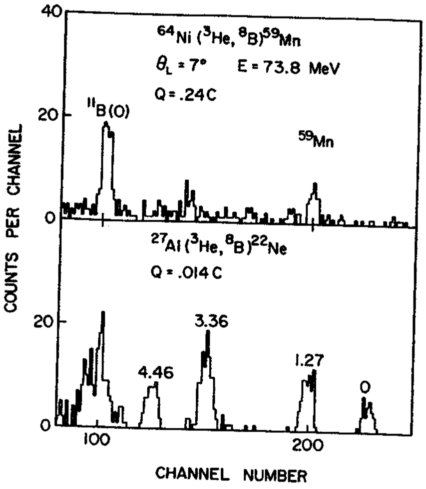

Figure 1

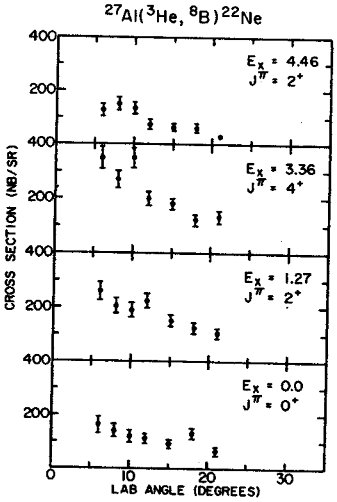

Figure 2

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Coulomb Displacement Energies of T = 1/2 Mirror Nuclei in the $1f_{7/2}$ Shell

D. Mueller, E. Kashy and W. Benenson

The $(^3He,^6He)$ reaction on targets of ^{46}Ti, ^{50}Cr, ^{54}Fe, and ^{58}Ni has been employed to determine the masses and excitation energy of levels in the final nuclei, ^{43}Ti, ^{47}Cr, ^{51}Ni. Angular distributions from these reactions to a few of the more strongly excited states have been taken between 4.5 and 27 degrees in the laboratory. These measurements allow the extraction of Coulomb displacement energies for both the ground and excited states. The remeasurement of the ground state masses allows the use of a mass relationship to improve predictions of the masses of very proton-rich nuclei. A beam of 70 MeV ^3He particles from the MSU cyclotron was employed. Two sets of targets were used. One set consisted of approximately 1 mg/cm^2 thick self-supporting isotopically-enriched metal foils which were used in obtaining the angular distributions. The others were metal foils evaporatively deposited on carbon foils. This set ranged in thickness from 40. to 99. μg/cm^2 ± 10% and was used for the accurate determination of the mass excesses and excitation energies of the final nuclei. The Q-values were determined by comparison of the magnetic rigidity of the ^6He particles from the reactions of interest to those from the $^{27}Al(^3He,^6He)^{24}Al$ and $^{25}Mg(^3He,^6He)^{22}Mg$ reactions in the spectrograph.

The results of the Q-value measurements and the deduced mass excesses are compared in Table 1 to previous measurements [1,2]. The primary differences between the present and previous measurements at MSU are that thinner targets and an additional calibration were employed in the present measurement, while a greater number of measurements were employed in obtaining the previous results. High resolution spectra are shown in Fig. 1 and 2.

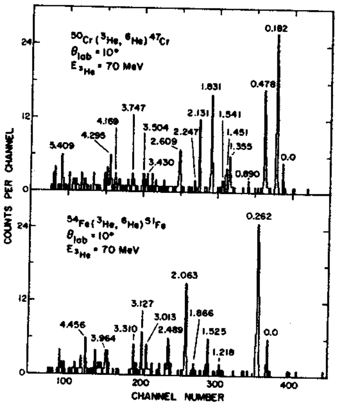

Fig. 1 High resolution spectra of ^6He particles from the $^{50}Cr(^3He,^6He)$ and $^{54}Fe(^3He,^6He)$ reactions.

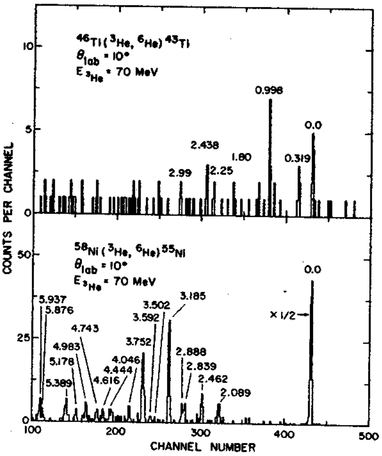

Fig. 2 High resolution spectra of ^6He particles from the $^{46}Ti(^3He,^6He)$ and $^{58}Ni(^3He,^6He)$ reactions.

The spin and parity assignments for some levels in the $T_z = -1/2$ nuclei have been made primarily by comparison to their $T_z = 1/2$ mirror levels. These assignments are further supported by comparison of the angular distributions from the states of interest to those from the $^{42}Ca(^3He,^6He)^{39}Ca$ reaction, where the spin and parities of the states in the final nucleus are known. This empirical comparison is shown in Fig. 3. Recently Delic and Kurath performed a finite-range distorted-wave Born approximation which was successful in describing the qualitative features of the $^{13}C(^3He,^6He)^{10}C$ reaction[3]. However, no attempt has been made here to undertake a DWBA analysis of these results since the $(^3He,^6He)$ reaction is not yet well understood.

The results of the mass measurements and the determination of excitation energies allow

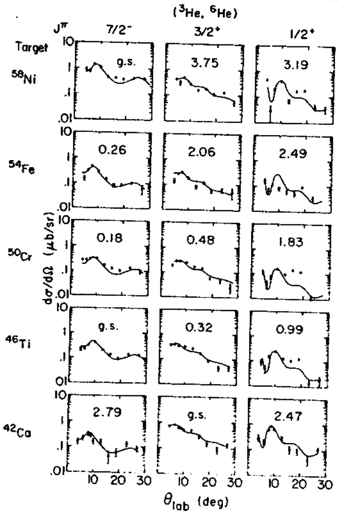

Fig. 3 Angular distributions of the $(^3He,^6He)$ reaction at 70 MeV.

the extraction of Coulomb displacement energies for the $J^{\pi} = 7/2^{-}, 3/2^{+}$, and $1/2^{+}$ levels in the $A = 4n + 3$, $T = 1/2$ mirror nuclei. Recently Sherr and Bertsch employed the Bansal-French-Zamick model to calculate the Coulomb displacement energies of excited particle-hole states in light nuclei and reported that the level shifts are reproduced to within 50 keV[4]. Using this model, the Coulomb displacement energy of the lowest $J^{\pi} = 3/2^{+}$ state in 43 Ti and ^{43}Sc is given by

$$\Delta E_c(43, 3/2^{+}) = \Delta E_c(39,3/2^{+}) + 2c(3/2^{+}, 7/2^{-})$$

where $E_c(39,3/2^{+})$ is the Coulomb energy difference of the $3/2^{+}$ levels in ^{39}Ca and ^{39}K, and $c(3/2^{+}, 7/2^{-})$ is the Coulomb interaction of a $d_{3/2}$ proton with an $f_{7/2}$ proton. The 2 reflects the greater number of $d_{3/2} - f_{7/2}$ proton interactions in ^{43}Ti compared to ^{43}Sc. The results of predictions using this model for both the $1/2^{+}$ and $3/2^{+}$ states in the $A = 4n + 3$, $T = 1/2$ mirror nuclei are indicated by the solid lines in Fig. 4. The values $c(3/2^{+}, 7/2^{-}) = 296$ keV and $c(1/2^{+}, 7/2^{-}) = 302$ keV used were obtained by performing a least squares fit to the data which is indicated by the points. Recently, we pointed out that ^{39}Ca - ^{39}K has an anamolously large Coulomb displacement energy resulting from the large binding energy of these nuclei[5]. Hence, it is reasonable to ignore the A = 39 points. The results of a fit to the data excluding the A = 39 values are indicated by the dashed lines in Fig. 4. It is then found that $c(3/2^{+}, 7/2^{-})[c(1/2^{+}, 7/2^{-}] = 316$ keV [321 keV] and that the predicted Coulomb displacement energy of the $3/2^{+}$ [$1/2^{+}$] states in ^{39}Ca - ^{39}K is 126 keV [117 keV] below the experimental values. This is consistent with results obtained from the systematics of the series of analogue states in Ca - K[5]. Finally, calculations of the $d_{3/2} - f_{7/2}$ and $s_{1/2} - f_{7/2}$ proton-proton Coulomb interactions were performed using both harmonic oscillator and Woods-Saxon wave functions. Table 2 shows the excellent agreement between the results obtained in the calculations and the experimentally determined values.

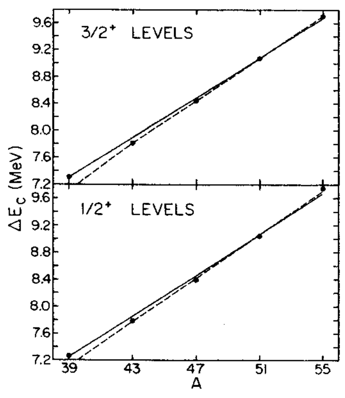

Fig. 4 Coulomb displacement energies versus mass number for $A = 4n + 3$, $T = 1/2$ mirror nuclei in the $1f_{7/2}$ shell. The points represent the experimental data while the lines connect the predictions discussed in the text.

Table 2. Coulomb Interaction Between Protons in Different Shells

	Exp. (keV)	H.O. (k3V) [a]	W.S. (keV)	
			Direct	Exchange
$f_{7/2}-d_{3/2}$	316	308	338	-16
$f_{7/2}-2s_{1/2}$	321	294	328	- 6

a) Calculation made using th oscillator parameter = .258 fm^{-2}.

Table 3 lists the results of mass predictions made using the Garvey-Kelson symmetric mass relation[6] and the most recent results for the masses involved in the relation.

We plan to extend our investigation of Coulomb energies by employing the (^{3}He, ^{8}Li) reaction to reach excited states in the $A = 4n + 1$, $T_z = -1/2$ nuclei in the $1f_{7/2}$ shell, as well as to remeasure those masses which we have already observed using the (p, ^{6}He) reaction[1].

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Table 1

		Mass Excess (MeV)	
Nucleus	Previous[a]	Present	Average
^{43}Ti	-29.328±0.012	-29.305±0.014	029.319±0.008[b]
^{47}Cr(g.s.)	-34.608±0.040[c]	-34.553±0.015	-34.561±0.012[c]
($7/2^-$)	-34.386±0.012	-34.371±0.013	-34.379±0.010
^{51}Fe(g.s.)	-40.219±0.017	-40.200±0.015	-40.201±0.012[d]
($7/2^-$)	-39.940±0.013	-39.938±0.013	-39.939±0.010
^{55}Ni	-45.337±0.011[e]	-45.327±0.013	-45.333±0.010

	Q-Value (MeV)	
Reaction	Previous[a]	Present[f]
^{46}Ti(^{3}He,^{6}He)^{43}Ti	-17.463±0.012	-17.486±0.014
^{50}Cr(^{3}He,^{6}He)^{47}Cr(g.s.)	-18.313±0.040	-18.368±0.014
($7/2^-$)	-18.535±0.012	-18.550±0.013
^{54}Fe(^{3}He,^{6}He)^{51}Fe(g.s.)	-18.698±0.017	-18.697±0.015
($7/2^-$)	-18.969±0.013	-18.971±0.013
^{58}Ni(^{3}He,^{6}He)^{55}Ni	-17.555±0.011	-17.565±0.013

a) Ref. 1.

b) The average mass excess of ^{43}Ti includes the measurement of Ref. 2 (-29.321±0.010 MeV).

c) In the previous measurement, the ^{47}Cr g.s. was not resolved. The separation of the $7/2^-$ and the ground state was taken from the present measurements.

d) The relative excitation of the $7/2^-$ and $5/2^-$ ground state from the present measurement was employed to deduce the ^{51}Fe and ^{47}Cr ground state masses.

e) This value represents an 8.2 keV increase in the mass of ^{55}Ni from the previous value[1] due to the measurement of the ^{58}Ni mass of Jolivette *et al.*[7]

f) Q-values measured relative to the ^{27}Al(^{3}He,^{6}He)^{24}Al(g.s.) and ^{25}Mg(^{3}He,^{6}He)^{24}Mg (3.3082) reaction Q-Values of -19.812±0.003 MeV[8,9] and -18.7656±0.004 MeV[9,10,11,12], respectively.

Table 3 -- Predicted mass excess using Garvey-Kelson symmetric mass relation.[a]

Nucleus	Mass excess (MeV)	Separation energy[b] (MeV) One proton	Two protons
		$T_z=-1$	
^{44}V	-23.83	1.81	6.31
^{46}Cr[c]	-29.56	5.02	6.64
^{48}Mn	-29.31	2.03	6.81
^{50}Fe	-34.50	4.13	6.22
^{52}Co	-34.38	1.48	6.34
^{54}Ni	-39.27	3.92	5.53
		$T_z=-\frac{3}{2}$	
^{43}V	-17.92	0.10	3.87
^{45}Cr	-19.64	3.14	4.95
^{47}Mn	-22.65	0.32	5.34
^{49}Fe	-24.76	2.76	4.79
^{51}Co	-27.40	0.19	4.32
^{53}Ni	-29.66	2.59	4.07
		$T_z=-2$	
^{42}V	- 8.02	-0.37	2.09
^{44}Cr	-13.54	2.96	3.06
^{46}Mn	-12.62	0.22	3.36
^{48}Fe	-18.17	2.82	3.14
^{50}Co	-17.73	0.26	3.02
^{52}Ni	-22.68	2.58	2.77
		$T_z=-\frac{5}{2}$	
^{41}V	0.08	-1.81	0.43
^{43}Cr	- 2.14	1.45	1.08
^{45}Mn	- 5.17	-1.14	1.82
^{47}Fe	- 7.15	1.84	2.06
^{49}Co	- 9.95	-0.93	1.89
^{51}Ni	-12.02	1.59	1.85
		$T_z=-3$	
^{42}Cr	6.17	1.25	-0.56
^{44}Mn	6.35	-1.26	0.19
^{46}Fe	0.53	1.60	0.46
^{48}Co	0.97	-0.84	1.00
^{50}Ni	- 4.13	1.49	0.56
		$T_z=-\frac{7}{2}$	
^{45}Fe	13.58	0.08	-1.18
^{49}Ni	7.61	0.67	-0.17
		$T_z=-4$	
^{48}Ni	16.43	0.50	-1.31

a) Masses used in the relation are the present experimental results, Mass 71 mass values[9]. For ^{55}Co the mass excess used is -54,0275 ± 0.0022 MeV from Ref. 7, and for ^{49}Cr, the mass excess used is -45,327 ± 0.0029 MeV from Ref. 13.

b) Negative binding energy indicates nucleus unbound to particle emission.

c) Experimental mass excess is -29.46 ± 0.03, Ref. 14.

A Determination of the Mass and Some Energy Levels of the Nuclide ^{44}Ar[*]

G.M. Crawley, W.F. Steele, J.N. Bishop, P.A. Smith, and S. Maripuu[+]

The lifetime of the nucleus ^{44}Ar has been reported,[1,2] but until now its mass and energy levels were unknown. We have measured the mass of ^{44}Ca(^{3}He,^{7}Be)^{44}Ar reaction at 70 MeV ^{3}He bombarding energy. The reaction products were analyzed by the Enge split-pole magnetic spectrograph and detected in a plastic scintillator photomultiplier unit behind a 25 cm single wire charge division gas proportional counter.[3] The counter measures both position along the focal plane and differential energy loss of an ion, while the scintillator is used to measure time-of-flight of an ion through the spectrograph.

Contamination by carbon and oxygen is particularly severe because they are commonly present on calcium targets and the (^{3}He,^{7}Be) reaction on these nuclides has a relatively large cross section.[4] Consequently, an effort was made to minimize the amount of carbon and oxygen to come into contact with the ^{48}Ca target. Targets were prepared by evaporating a layer, approximately 200 μg/cm^2 thick, of 97.16% isotopically enriched ^{48}Ca onto both gold and silver foils of between 100 and 200 μg/cm^2. The metal was evaporated after reduction of calcium carbonate mixed with zirconium powder in a zirconium tube. The silver backing foils gave a smoother target presumably because the coefficient of expansion of silver is closer to that of calcium than is the expansion coefficient of gold. The targets were prepared, stored and transfered to the target chamber under vacuum. Nevertheless, as can be seen from Fig. 1, peaks arising from carbon and oxygen are still larger than the peaks corresponding to levels in ^{44}Ar.

To help minimize the effect of the oxygen impurities in the ^{44}Ar ground state region, 1.5 mm diameter pins were placed in front of the proportional counter at the positions where ^{7}Be ions from the oxygen contaminent in the target would focus. This reduced the size of the peaks due to the 4.4 MeV state of ^{12}C arising from the oxygen impurity by about a factor of ten. In addition to contaminants, the ^{7}Be spectra are complicated by those outgoing ^{7}Be ions which are in the .429 MeV particle stable first excited state. Thus each level in the residual nucleus produces two peaks in the ^{7}Be spectrum which are separated by about .4 MeV. The experimental resolution (FWHM), due primarily to target thickness, of the spectrum measured at 7° laboratory angle (Fig. 1) is about 66 keV, which allows discernment of these peak pairs, including those of impurities.

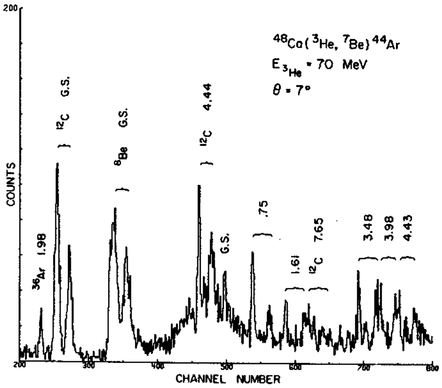

FIG. 1.--The 7° spectrum from the ^{48}Ca(^{3}He,^{7}Be)^{44}Ar reaction at 70 MeV. Brackets are used to indicate the pair of peaks corresponding to the two states of ^{7}Be excitation for each level in the final nucleus.

Ten independent spectra were measured at angles ranging from 5° to 15°. Small angles were chosen because the cross sections are larger at forward angles and to maximize the separation of the peaks corresponding to ^{44}Ar from the contaminant peaks. The pair of peaks corresponding to the 4.4 MeV state of ^{12}C together with the background produced by the broad 2.9 MeV level of ^{8}Be, could obscure peaks from potential lower levels of ^{44}Ar. In order to check this possibility, a spectrum was taken at 15°, where any lower energy peaks due to ^{44}Ar would be placed between the peaks due to the ^{8}Be ground state and the 4.4 MeV state of ^{12}C. No such peaks were observed. A further check on the possibility that the peak identified as the ground state of ^{44}Ar is really not from the 0.429 MeV first excited state of ^{7}Be, is provided by the width of the peak. The peak observed has a width of only 54 keV, which is consistent with this peak corresponding to the ground state of ^{7}Be but is too narrow to correspond to the first excited state. Peaks corresponding to the first excited state of ^{7}Be, which decays by emission in flight, are broadened by about 76 keV due to the recoil effect. The average width of ^{44}Ar peaks in Figure 1 corresponding to the 0.429 MeV state of ^{7}Be is 110 keV which is consistent with folding the recoil contribution into the average ground state width (66 keV). Finally both the kinematic shift with angle and previous measurements of spectra from a natural calcium target[4] and from plain silver and gold backings ensured that the states observed were from the ^{48}Ca(^{3}He,^{7}Be)^{44}Ar reaction.

Table 1 presents the experimental value of the mass excess of ^{44}Ar together with a number of theoretical predictions. The Garvey-Kelson prediction,[5] which is based on an extrapolation from known ground state masses assuming an

TABLE I.--^{44}Ar Mass Excess

	Mass Excess (MeV)	Dif. (MeV)
Experimental Value	-32.27±.02	
Theoretical Predictions		
Garvey-Kelson[5]	-32.76	0.49
Janecke[6]	-32.41	-0.14
Comay-Kelson[6]	-32.25	-0.02
Jelley, et al.[8]	-32.35	0.08
Gloeckner, et al.[9] Set A	-32.21	-0.06
Set B	-32.17	-0.10

TABLE II.--Energy Levels of ^{44}Ar.

Experiment		Shell Model[9]	
Ex (MeV)	$d\sigma/d\Omega(7°)$ (μb/sr)	Ex (MeV)	Predicted J^{π}
0.0	1.0	0.0	0^+
0.75 .03	2.0	0.832	0^+
1.61 .03	1.0	1.25	2^+
3.48 .03	1.3		
3.98 .05	0.7		
4.43 .04	0.8		

independent particle model, disagrees with the experimental value by 490 keV. This is more than twice the average deviation of the Garvey-Kelson mass prediction. The calculation by Janecke,[6] shown in Table I, is basically a Garvey-Kelson model calculation but uses more recent mass values.[7] This value is much closer to the measured value differing only by 140 keV. The Comay-Kelson calculation[6] uses a statistical technique to extrapolate from known masses and is very close to the measured mass. However, they quote an uncertainity of 640 keV on their calculated value. An alternative approach using a j-j coupled shell model description for the ground states of even-even and even-odd nuclei is also quite successful and the prediction by Jelley, et al.[8] differs by only 80 keV from the measured value which compares favorable with the r.m.s. deviation of 85 keV for this model. Detailed shell model calculations which include particles in the d 3/2, f 7/2, and p 3/2 shells by Gloeckner, et al.[9] also give mass values quite close to the experimental mass excess. The energy levels observed in ^{44}Ar are shown in Table II together with the shell model calculations of Gloeckner, et al.[9] In general the agreement for the first few levels is very good. Of particular interest is the prediction that the first excited state of ^{44}Ar is a 0^+ state at 832 keV, consisting of 2 proton and 2 neutron holes in the d 3/2 shell. Such a state would readily be formed by the ^{48}Ca(^{3}He,^{7}Be) reaction by simply picking up four particles from the d 3/2 shell. The state observed at 750 keV excitation is the strongest state in the spectrum.

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Mass of ^{57}Ni

H. Nann, D. Mueller, A. Saha and E. Kashy

During the course of our systematic study of (p,t) and (^{3}He,^{6}He) reactions in the fp shell we found that the mass of ^{57}Ni deviates from the Wapstra-Gove mass table[1] value by several standard deviations. We determined the mass of ^{57}Ni by measuring the Q-values of the ^{59}(p,t)^{57}Ni and ^{58}Ni(^{3}He,α)^{57}Ni reactions.

In the ^{59}Ni(p,t)^{57}Ni experiment, we used a 40 MeV proton beam. The ^{59}Ni target (37.4% ^{58}Ni. 43.0% ^{59}Ni, 15.2% ^{60}Ni, 1.0% ^{61}Ni, 2.1% ^{62}Ni and 1.2% ^{64}Ni) was a rolled foil of about 230 μg/cm^{2} thickness and was made by S. Raman, Oak Ridge National Laboratory. The reaction products were detected in the focal plane of the Enge split-pole spectrograph by a position sensitive proportional counter. The resolution obtained was about 15 keV FWHM. Fig. 1 shows an example of the spectra obtained. As one can see, the ground and 0.769 MeV state transitions of the ^{59}Ni(p,t) reaction fall in the same region as the ground and 1.454 MeV state transitions of the ^{60}Ni(p,t) reaction and the ground state transition of the ^{58}Ni(p,t) reaction. These three transitions thus served as calibration lines for the ^{59}Ni(p,t) Q-value determination. Using the most recent mass excess values of the Jolivete, et al.[2] we obtain -12738.2±3.3 keV for the Q-value of the ^{59}Ni(p,t)^{57}Ni ground state transition.

The ^{58}Ni(^{3}He,α)^{57}Ni experiment was performed with a 70 MeV ^{3}He beam using a similar setup as described before. The target was prepared by vacuum evaporation of ^{58}Ni (isotopically enriched to 99.9%) onto a carbon backing and had a thickness of about 90 μg/cm^{2}. In this experiment the magnetic rigidities of the α-particles from the calibration reaction ^{52}Cr(^{3}He,α)^{51}Cr. The Q-value obtained for the ^{58}Ni(^{3}He,α)^{57}Ni reaction is +8360±4.0 keV.

From the two Q-values a mass excess for ^{57}Ni of -56078.4±3.0 keV reported in the 1971 mass table.

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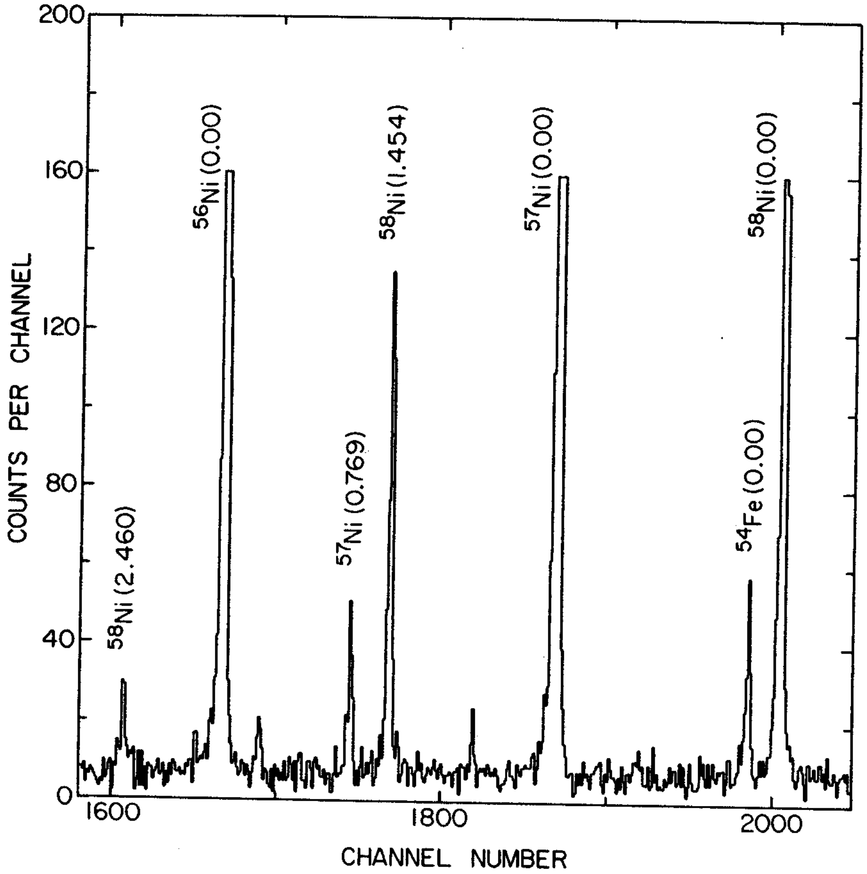

FIG. 1.--Triton spectrum from the ^{58,59,60}Ni(p,t)^{56,57,58}Ni reaction. The peaks are labelled by the final nucleus and its excitation energy.

Mass Measurements Near ^{208}Pb

F.M. Bernthal, J.A. Nolen, Jr., P.A. Smith, C.H. King, and T.L. Khoo

Various workers have attempted to develop from nuclei near doubly closed-shells an appropriate effective interaction between nucleons. In particular, a great deal of experimental and theoretical effort has been devoted to the question of whether a three-body interaction exists and is important in the nuclear force, and, if so, to set limits on the size of such an interaction.

The region near the ^{208}Pb doubly closed shell provides an unusually attractive laboratory for precision tests of the nuclear shell model. The interaction energies of one or two valence particles or holes with the ^{208}Pb core are well-known experimentally. In an elegant series of experiments over the past several years, Linden, Bergstrom, Blomquist and coworkers in Stockholm have identified a large number of relatively pure high-spin two- and three-particle configurations in ^{206}Pb and ^{205}Pb, respectively. Their data provide a convenient empirical basis for exploring the effective 3-body interaction among the valence nucleons in ^{205}Pb. The approach is described in Ref. 1, and the results can be summarized as follows:

Shell model calculations for three neutron holes in the ^{208}Pb closed shell are remarkably accurate. For those states in ^{205}Pb where the calculations are based on firm empirical evidence (^{207}Pb and ^{206}Pb), the rms deviation between experiment and theory is only 6 keV. For <u>all</u> known experimental levels (about 30), the authors of Ref. 1 find an rms deviation of only 20 keV. Their experiments and calculations show in convincing fashion that the average potential experienced by three holes in the ^{208}Pb shell is determined by one- and two-body effective interactions, and that the effective valence three-body interaction in ^{205}Pb must be <5 keV.

Similar calculations should be applicable to other 3-particle nuclei based on the ^{208}Pb core. Moreover, if proton particles or holes are introduced, one has the opportunity to test for an isospin-dependence of the 3-body interaction. The Stockholm group has extended their calculations to the ^{207}Bi and ^{211}At nuclei, and find the agreement with experiment in these cases not to be so good as for ^{205}Pb. The primary uncertainty in the calculations, however, is the less well-known ground-state masses of these nuclei relative to ^{208}Pb. In particular, if one assumes the accepted ^{207}Bi mass to be about 15 keV too small, quite good agreement is obtained for ^{207}Bi and ^{211}At as well. Following a related series of experiments, Bergstrom, <u>et al.</u>[2] have extended their calculations to ^{208}Po and ^{209}At in an attempt to determine the form and magnitude of two-nucleon core-polarization effects on the ^{206}Pb core. Again, the mass of ^{207}Bi seems to be the major difficulty in comparing experiment with calculations.

In hopes of eliminating the mass of ^{207}Bi as a possible source of the deviation between theory and experiment in the Stockholm calculations, we have carried out the (p,t) reaction on a mixed ^{209}Bi-^{208}Pb target. The target was approximately 100 μgm/cm^2 and was on a 20 μgm/cm^2 carbon backing. Beams of 35-MeV protons were used to obtain triton spectra on nuclear emulsions at 10° and 15° in the Enge split-pole spectrograph. The mixed ^{207}Bi-^{206}Pb spectrum taken at 15° is shown in Fig. 1, together with a spectrum taken under identical conditions with a pure ^{209}Bi target. Preliminary analysis of these data indicates

$$S_{2n}(^{209}\mathrm{Bi}) - S_{2n}(^{208}\mathrm{Pb}) = (241\pm2)\ \mathrm{keV}.$$

The 1971 mass tables give (250±8 keV) for this difference. Thus, we find the ^{207}Bi mass to be 9 keV <u>smaller</u> relative to ^{208}Pb than previously assumed. This increases the discrepancy between theory and experiment in the Stockholm work to about 25 keV, a number which must be viewed as significant when compared with the remarkably good agreement obtained for ^{205}Pb. A similar conclusion applies to the ^{211}At case,[1] since its ground-state mass is directly related by α-decay to the ^{207}Bi mass.

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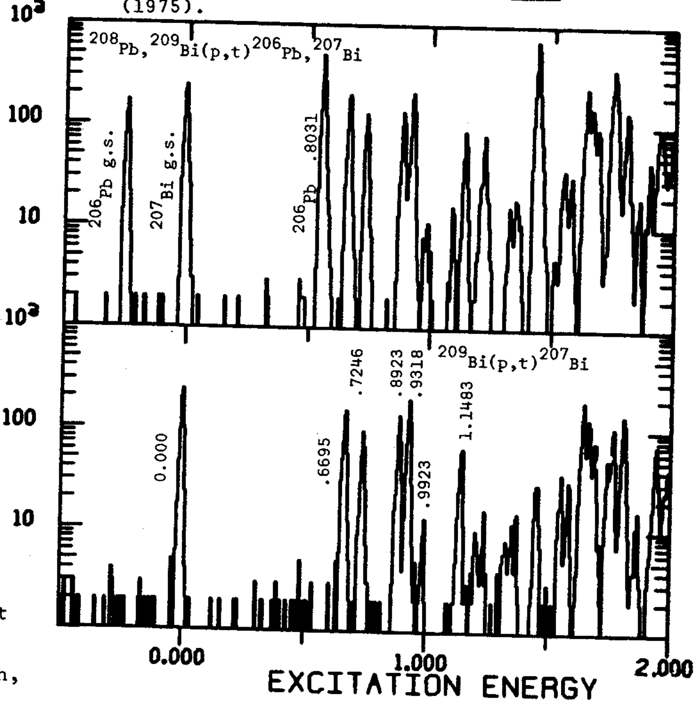

Search for Delayed-Proton Emitter ^{24}Si[+]

R.G.H. Robertson*, T. Bowles**, and S.J. Freedman***

The detection of T_z=2 nuclides (a proton excess of 4) as radioactivities has not been reported despite a number of efforts to produce them. Not only are they of intrinsic interest as the most proton-rich nuclei, but they also may provide a means of precisely locating the T=2 state in the daughter nucleus through Fermi β-decay and delayed proton emission. A search for ^{24}Si has been initiated using the Princeton University Cyclotron.

The β^+ decay of ^{24}Si will populate the 0^+ T=2 state in ^{24}Al as well as 1^+ T=1 states. The results of a shell-model calculation[1] combined with experimental data on the β^- decay of ^{24}Ne, and the isobaric multiplet mass equation lead to the decay scheme given in Ref. 1. About 6% of the decays of 100 ms-^{24}Si should populate the 0^+ T=2 state in ^{24}Al. This state, and several 1^+ T=1 states, lie above the proton emission threshold. It is difficult to predict reliably which states in ^{23}Mg will be populated in the isospin-forbidden proton decay of the 0^+, 2 state, but the ground state transition of (4084 ± 14) keV c.m. lies fortuitously in a region which is clear of proton lines from ^{25}Si(β^+)^{25}Al(p)^{24}Mg.

The method adopted to search for ^{24}Si involves coincident measurement of proton energy E_p and recoil fragment time-of-flight, τ. The recoil mass is then given by

$$M \sim \tau\sqrt{E_p(\text{lab})}$$

Determination of the recoil mass serves not merely to reduce background and interference from uninteresting species, but, more importantly, to identify conclusively the mass of the parent nuclide associated with each proton group.

A schematic diagram of the apparatus is shown in Fig. 1. Activities produced in a helium jet system are transported to a thin catcher foil (~20 μg cm^{-2} of Formvar) via a skimmer cone which removes much of the helium gas. Protons pass through the foil to a Si detector and recoils from proton decay pass through a converter foil (about 30 μg cm^{-2} of Formvar, supported on a Ni mesh) 8 cm away. Secondary electrons from the foil are accelerated to a two-stage microchannel plate assembly which provides the timing information. This procedure has two advantages over direct detection of the recoil ions - it permits compensation of geometrical time dispersion by appropriately curving the foil, and it allows the channel plates to operate in a clean, high vacuum (provided by a turbomolecular pump). The efficiency for detecting recoil ions in the 100-200 keV range under consideration appears to be of order unity, and by recording signals from the interface between the first and second channel plates, some discrimination can be obtained between recoils and β-particles, as the latter give much smaller pulses.

The mass resolution is limited entirely by the effects of β-recoil for all transitions of interest in this work. While the electronic time resolution is less than 1 ns, it is not possible with any flight path to achieve better than about 7% mass resolution (or 2 mass units) for the main transitions in ^{24}Si and ^{25}Si. The transitions of interest are both Fermi decays, for which the electron-neutrino correlation is peaked at zero degrees, and the velocity spread caused by recoil is at a maximum. Nevertheless, this resolution is adequate to remove all activities (such as ^{21}Mg, ^{20}Na) from the ^{24}Si mass band, with the exception of ^{25}Si. It is also, of course, adequate for mass identification.

An example of 2-D data from this apparatus is shown in Fig. 2. Beams of ^{3}He ions (degraded to 62 MeV) from the Princeton Cyclotron were used to bombard a 99.8% enriched ^{24}Mg target for about 8 hours at 2.5 μA. Sharp lines from ^{25}Si can be seen readily and some are identified at the left of the figure. Also visible are some broad lines from ^{21}Mg. The rectangles indicate the expected positions of proton groups from the 0^+,2 state in ^{24}Al feeding the ground and first excited state of ^{23}Mg. There is no indication of any significant peak above background at either location.

Recently several changes have been made in this apparatus. The activity is now collected on eight foils mounted on a stepper wheel which can be stepped in 35-40 ms. A cryogenic He jet system has been developed, and is described elsewhere in this report. Some data have been taken with the new system, but are still in the preliminary stages of analysis.

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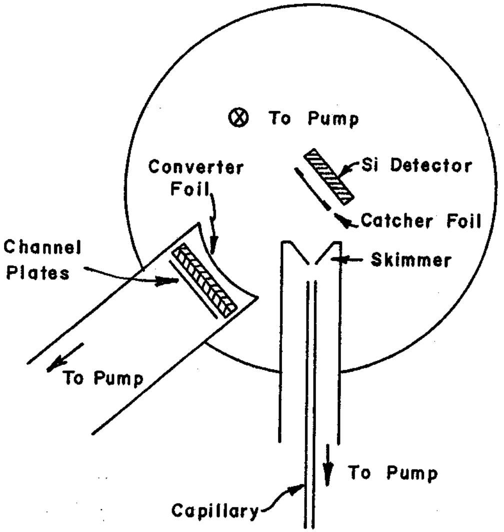

Fig. 1 Schematic diagram of recoil time-of-flight apparatus.

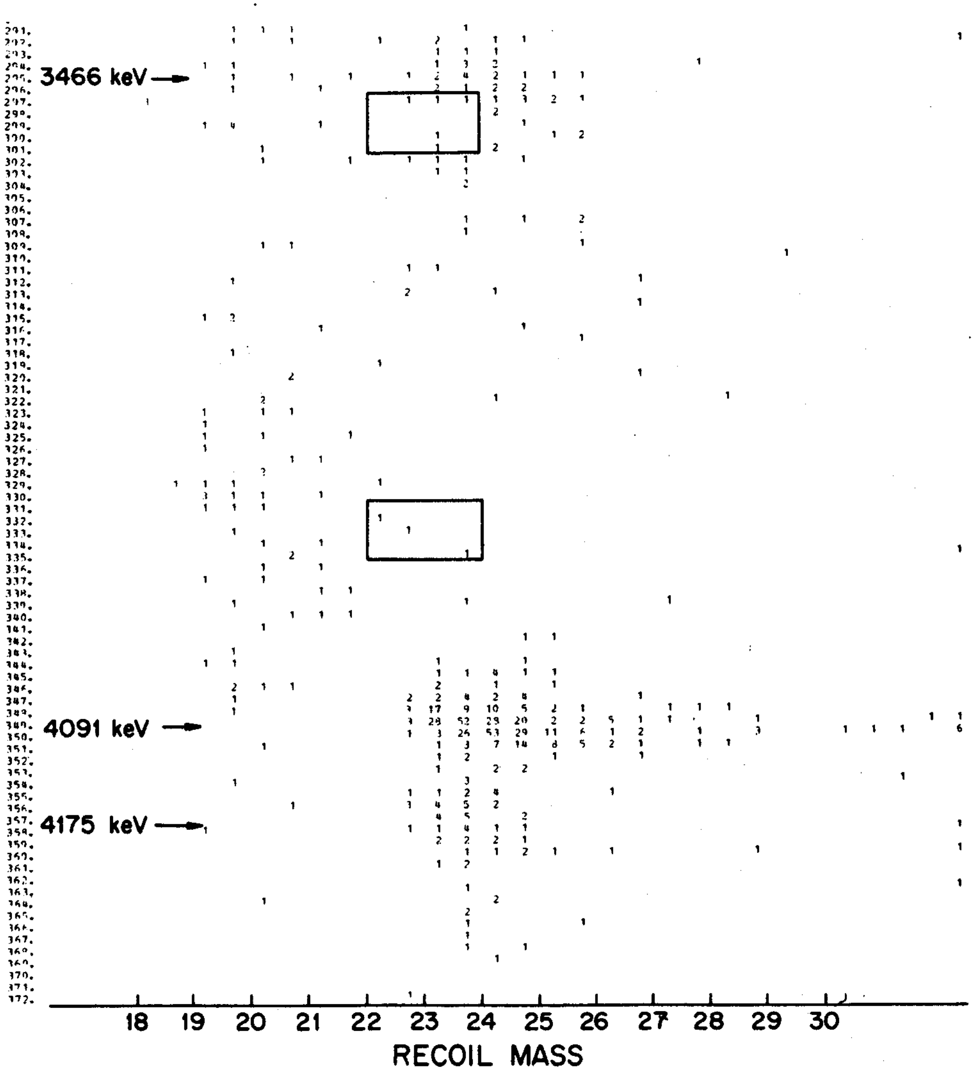

Fig. 2 Portion of 2D data showing region of proton energy and recoil mass where decay of T=2 state in ^{24}Al might be seen.