SECTION I

RESEARCH IN PROGRESS

Proton Rich Nuclei

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

We have now made the first measurements of the ground state masses of the nuclei ^{45}V, ^{49}Mn, and ^{53}Co, and new measurements of the masses ^{43}Ti, ^{47}Cr, ^{51}Fe, and ^{55}Ni. The nucleus ^{45}V was observed for the first time, whereas ^{53}Co has been detected previously in a proton emitting isomeric state.[1] The observation of ^{49}Mn has been reported in the ^{40}Ca(^{12}C,t)^{49}Mn reaction.[2] The Q-value of this heavy ion reaction was consistent with the prediction for the mass of ^{49}Mn under the assumption of equal population of ground and first excited states which were unresolved. The present precision mass measurements employed the (p,^{6}He) and (^{3}He,^{6}He) reactions on relatively thin targets. These results complete the series of T=1/2 mirror nuclei in the $f_{7/2}$ shell and allow comparison of Coulomb energies within a nuclear subshell to a shell model prediction.[3] The results of the present measurements also permit the prediction of the masses of proton-rich nuclei far from the N=Z line by means of the symmetric mass relation (GKS) of Kelson and Garvey.[4]

The determination of the new masses was made by comparing the ^{6}He particles from the (p,^{6}He) reaction on ^{50}Cr, ^{54}Fe and ^{58}Ni targets to the ^{6}He particles from the calibration reaction ^{27}Al(p,^{6}He) ^{22}Mg in a magnetic spectrograph. The new measurements of the masses of ^{43}Ti, ^{47}Cr, ^{51}Fe and ^{55}Ni were made by comparing the ^{6}He particles from the (^{3}He,^{6}He) reaction on ^{46}Ti, ^{50}Cr, ^{54}Fe and ^{58}Ni targets to the ^{6}He particles from the ^{27}Al(^{3}He,^{6}He) ^{24}Al reaction. The elimination of a window between the gas of the wire counter and the scintillator facilitated detection in the scintillator of the low energy ^{6}He from the (p,^{6}He) reactions. The method and electronics have been previously described.[5] In addition, in the (p,^{6}He) measurements, a pulsing system was used to allow only one-in-three cyclotron beam bursts to reach the target.

Figure 1 shows the spectra obtained in the (p,^{6}He) reactions. A single state dominates each spectrum and is identified by comparison to the mirror nuclei as the lowest $J^{\pi}=7/2^{-}$ level. In ^{49}Mn the $7/2^{-}$ level is not the lowest level, but an excited state at 0.263 MeV. The ground state is expected to have $J^{\pi}=5/2^{-}$ which is the ground state J^{π} value of its mirror ^{49}Cr. This seniority 3 state is very weakly excited relative to the $7/2^{-}$ level with a cross-section of only ~7 nb/sr. Table 1 lists results for the mass excesses from the present, as well as previous measurements.

For a homogeneously charged spherical model of radius R, the Coulomb energy, E_c is 3/5 x $\frac{Z(Z-1)e^2}{R}$. The (Z-1) reflects the self-energy of the proton which is included in the mass of the proton. Thus using $Z_<$ to denote the charge of the T_z=+1/2 member of the T=1/2 mirror pair, the Coulomb energy difference is $\Delta E_c=6/5\ \frac{Z_< e^2}{R}$. Then by dividing ΔE_c by $Z_<$, the principal Z dependence is removed, and we can look at the systematics in finer detail. Table 2 lists the experimental Coulomb energy difference (ΔE_c= $M(T_z=-1/2)-M(T_z=1/2)-\Delta Hn$ where ΔHn is the mass difference between ^{1}H and a neutron) and the reduced Coulomb energy difference $\Delta E_c/Z_<$ for the lowest $J^{\pi}=7/2^{-}$ level of the T=1/2 mirror pairs. Figure 2a shows a plot of measured $\Delta E_c/Z_<$ for T=1/2, $J^{\pi}=7/2^{-}$ mirror states in the $f_{7/2}$ shell. The experimental results are indicated by the points with error bars. The solid line is a prediction made by Chung and Wildenthal[3] who used the two-particle Coulomb interaction of Shlomo.[9] The calculation assumed a pure $f_{7/2}$ configuration and a constant radius for the nuclei from A=41 to 55. There is good agreement between the prediction and experiment for both the size of the Coulomb pairing interaction and the general dependence of the reduced Coulomb energy on A. Experimentally, the average Coulomb pairing interaction is 29±10 keV, only 14 keV less than found in the calculation. Interestingly the 44.3 keV pairing calculated for the mirror pairs above, is significantly smaller than 70 keV pairing entered in the two body-matrix elements. For comparison a similar plot is shown in Figure 2b for the lowest $5/2^{+}$ level in the $1d_{5/2}$ shell. It is clearly seen that the $f_{7/2}$ mirror states do not show the large Coulomb-pairing variations seen in the $1d_{5/2}$ shell. Another interesting feature of the $f_{7/2}$ data is the symmetry about the mean value of $\Delta E_c/Z_<$, i.e., the sum of the A=47 plus 49 $\Delta E_c/Z_<$ is the same as for A=45 plus 51, for 43 plus 53, etc., allowing for experimental error. This symmetry is also seen in the $d_{5/2}$ shell (see Figure 2b) and in the $d_{3/2}$ shell where the masses and, therefore, Coulomb energies are much more accurately determined. This symmetry appears to be the result of a smooth variation of the Coulomb interaction with A.

Since we now have preliminary results for the masses of all T_z=-1/2 nuclei up to ^{55}Ni, we can use the method of Kelson and Garvey[4] to predict the masses of proton-rich nuclei with atomic numbers ≤28. This method based upon an independent particle model, takes into account size, shell, and pairing effects. In the cases where prediction and experiment can be compared, agreement at the 150 keV level is found. Table 3 lists the calculated mass excesses of $T_z=-1\rightarrow-4$ isotopes from V through Ni which are predicted to be stable to both one and two-proton emission as well as for alpha emission. Also listed are the first two isotopes of each element that are predicted to be unbound to one or two-proton emission. In view of the predicted particle stability of $^{48}_{28}\mathrm{Ni}_{20}$ and $^{45}_{26}\mathrm{Fe}_{19}$, it appears that the experimental observation of nuclei all the way out to the proton drip line will require some rather exotic heavy ion reactions and pose quite a challenge to the experimentalists.

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TABLE 1.--Experimental results and comparison with previous measurements.

	Mass Excess (MeV)	
Nucleus	Present	Previous[a]
Ti^{43}	-29.327 ±.012	-29.341 ±.015 -29.321±0.010[b]
V^{45}	-31.862 ±.017	
Cr^{47}(gs)[c]	-34.604 ±.040	-34.625 ±.028
($7/2^-$)	-34.382 ±.012	
Mn^{49}($5/2^-$gs)	-37.597 ±.024	
($7/2^-$)	-37.334 ±.018	
Fe^{51}($5/2^-$gs)	-40.217 ±.017	-40.232±.017
($7/2^-$)	-39.938±.013	-39.962±.020
Co^{53}	-42.631±.018	
Ni^{55}	-45.348±.011	-45.369 ±.015

[a] Previous Measurements from Ref. 6, except as noted.

[b] Measurement from Ref. 7.

[c] The $3/2^-$ ground and the $5/2^-$ excited state of $^{47}\mathrm{Cr}$ are not resolved.

TABLE 2.--Coulomb energies and reduced Coulomb energies for the T=1/2 mirror pairs in the $f_{7/2}$ shell.

A	E_c(MeV)[a]	E_c/Z
41	7.2781±.005	.3639±.0002
43	7.6339±.001	.3635±.0005
45	7.9206±.018	.3600±.0008
47	8.2566±.012	.3590±.0005
49	8.5658±.020	.3569±.0008
51	8.8438±.014	.3538±.0006
53	9.0928±.023	.3497±.0009
55	9.4615±.012[b]	.3504±.0004[b]

[a] Coulomb energies calculated using present measurements.

[b] A value of -54.0275 .0022 MeV for the mass excess of $^{55}\mathrm{Co}$ was used, Ref. 8.

TABLE 3.--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	Binding energy (MeV)[a] 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	-34.39	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
	$T_Z=-5/2$		
^{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).

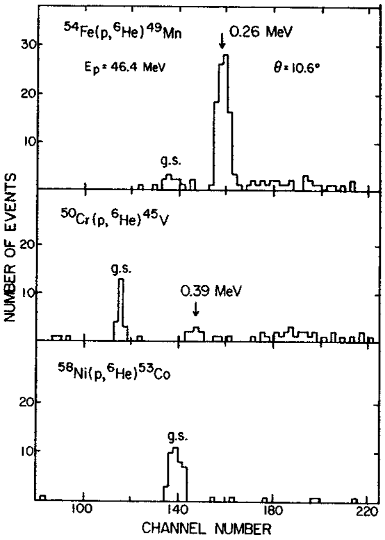

Fig. 1.--Spectra of ^{6}He particles at θ=10.6°.

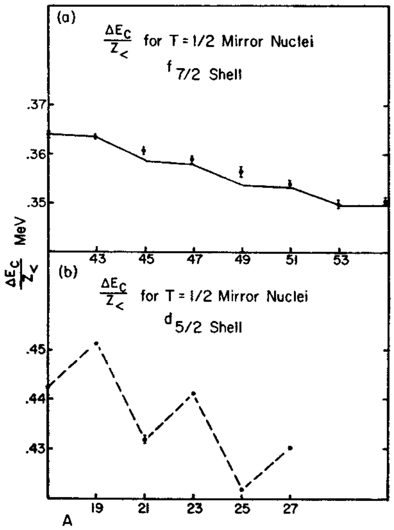

Fig. 2.--Graph of $\Delta E_c/Z_<$ versus A for T=1/2 mirror nuclei in the $f_{7/2}$ and $d_{5/2}$ shells. In the $f_{7/2}$ graph the points with error bars indicate experimental data from Table 3. The solid line is a prediction by W. Chung and B. H. Wildenthal. The dashed line in the $d_{5/2}$ graph connects experimental points.

Second Mass Quartet in A=9 Nuclei

W. Benenson and E. Kashy

We have recently located and measured the mass excess of the first excited state of ^{9}C and its analog in ^{9}B, which lies at 17.076 MeV. The $^{12}C(^{3}He,^{6}He)^{9}C$ and $^{11}B(p,t)^{9}B$ reaction were employed. (Spectra from these two reactions are given in Figures 1 and 2.) The resulting mass excesses complete a quartet which also includes known levels in ^{9}Li and ^{9}Be.

Fitting the isobaric multiplet mass equation to the mass excesses of Table I results in the parameters given in Table II. The ground state A=9 quartet is also given for comparison. The change in the b- and c-coefficient is due to the larger spatial extent of the excited state wave functions. The d-coefficient of the new quartet is both consistent with a very small deviation from the predictions and with the d-coefficient of the ground state quartet. Hence the new data do not help much in explaining the large d-coefficient for the ground state A=9 quartet.

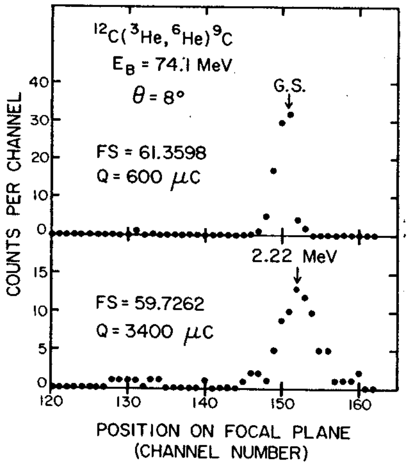

Fig. 1.

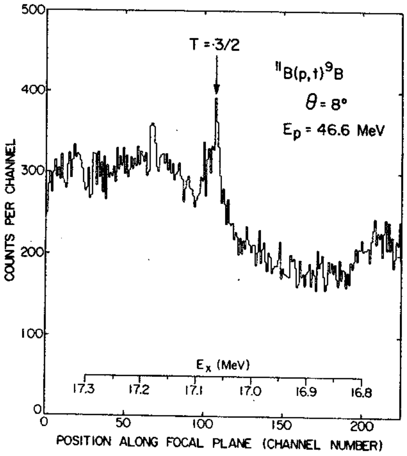

Fig. 2.

TABLE I.--Second T=3/2 levels in A=9 nuclei.

T_z	Nucleus	Mass Excess	E_x(keV)	Γ(keV)	Ref.
3/2	^{9}Li	27657±7	2691±5	bound	a)
1/2	^{9}Be	28325.7±1.4	16977.3±1.5	≤0.5	b)
-1/2	^{9}B	29492±4	17076±4	22±5	present
-3/2	^{9}C	31131±11	2219±10	100±20	present

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TABLE II.--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	

Mass of ^{9}Li

E. Kashy

The continuing interest in the IMME and in the ground state A=9 T=3/2 quartet where a cubic term (d=7.6±1.7 keV) has been observed,[1] has led to an additional evaluation of the mass of ^{9}Li. Plate data from the (t,p) reaction at 23 MeV have been scanned and analyzed. The plates were sent to MSU by F. Ajzenberg-Selove who did the exposure at the Los Alamos Tandem in cooperation with E. R. Flynn, T. D. Barnett and O. Hansen. By analyzing the positions of protons group from triton bombardment of ^{16}O, ^{12}C, ^{7}Li, and ^{1}H, a new value of the mass excess of ^{9}Li is determined, based upon the excitation energy of certain levels in ^{14}C and ^{18}O and their ground state masses.

Table I shows the results of the analysis of three angles. The symbol* indicates that levels[2] were used in the fitting procedure.

The value of 24.9555 MeV which has an error of 3.0 keV is 10 keV lower than the previous work. Using that value in the IMME for the A=9 quartet reduces the d-coefficient slightly from 7.6 to 5.9 keV which is still very significant, and brings it within striking distance of theoretical estimate of its value.[4] We intend to further check this result by looking at the ^{10}Be(d,He^{3})^{9}Li reaction, in collaboration with Benenson, Robertson and Goosman.

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4. G. Bertsch and S. Kahana, Phys. Lett. 33B, 193(1970).

TABLE 1.

θ_{LAB}	Mass Excess of ^{9}Li (MeV)	Ex^{14}C(6) (MeV)	Ex^{14}C(7) (MeV)	Ex^{18}O(15) (MeV)
15°	24.9569	7.3411*	8.3186*	7.1133
10°	24.9552	7.3414	8.3181*	7.1145*
5.5°	24.9543	---	8.3180*	7.1139*
Ave.	24.9555	7.3412	8.3182	7.1139
Prev. result	24.966±.005[3]	7.3414±0034[2]	8.318±.005[2]	7.114±.002[2]

Observation of T=2 State in ^{8}B

R.G.H. Robertson and W. S. Chien

Until recently no more than three members of any isobaric quintet (T=2 multiplet) were known. Those states were invariably in the $T_z=0$, +1, and +2 nuclei. However, our recent experiments on the (α, ^{8}He) reaction performed in a collaboration with the Kernforschungsanlage, Jülich, have resulted in the identification of the $T_z=-2$ nuclides ^{8}C and ^{20}Mg and a measurement of their masses.[1] There is now a good possibility that we will be able to complete at least one quintet (A=8) and obtain thereby a rather sensitive test of the Isobaric Multiplet Mass Equation (IMME). We report here observation of the T=2 state in the $T_z=-1$ nucleus ^{8}B by means of the ^{11}B (^{3}He, ^{6}He) reaction. Only the T=2 state in ^{8}Li is still unknown in the mass 8 quintet.

Although it was realized many years ago that the (^{3}He, ^{6}He) reaction could be employed to reach T=2 states in $T_z=-1$ nuclei by an isospin allowed process, in practice the reaction also unselectively populates the T=1 states in the same region of excitation. Thus efforts at Berkeley, MSU, and Princeton to observe the T=2 states in ^{12}N and ^{24}Al have not been fruitful. It might be expected, however, that the most favorable case would be a very light nucleus where the T=1 states (which can decay by isospin allowed nucleon emission) would be so broad that a sharp $T_>$ state would stand out clearly on a continuum of $T_<$ states. Our experiments on ^{11}B(^{3}He, ^{6}He)^{8}B show that this is indeed the case.

The experimental arrangement is very similar to that described previously.[2] Spectra taken at 9°, 10°, 11°, and 13° (lab) reveal a sharp state at 10.619(10) MeV, close to the excitation energy, 10.72(7) MeV, predicted by the IMME, for the T=2 state in ^{8}B. The kinematic signature is consistent only with a state in A=8 to within a small fraction of a mass unit. There are no other sharp states in evidence within ±2 MeV of the observed one, and we conclude that the mass excess of the lowest T=2 state in ^{8}B is 33.542(10) MeV. The observed cross section at 9° is 190nb sr^{-1} (lab).

The mass excesses of three other T=2 states in A=8 are known, ^{8}C: 35.38(17) MeV,[1] ^{8}Be(T=2): 32.425(10) MeV,[3] and ^{8}He: 31.57(3) MeV.[4] The four states fit the three-parameter IMME with a χ^2 of 2.2. Alternatively the coefficient d of a $T_z{}^3$ term would have a value of $-33(22)$ keV.

There are now two quintets with four known members (A=8, 20) and experiments are in progress to locate the T=2 state in ^{8}Li by ^{10}Be (p, ^{3}He), in collaboration with D. R. Goosman.

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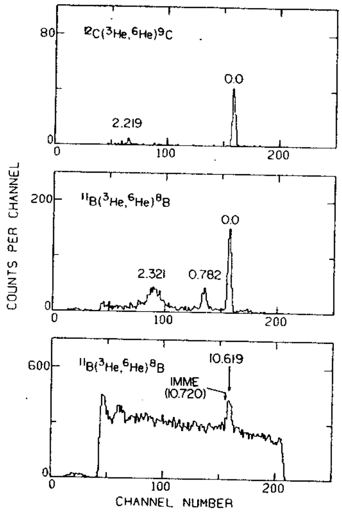

Figure 1.--Spectra taken with a position-sensitive wire proportional counter in a magnetic spectrograph, showing the calibration reaction ^{12}C(^{3}He,^{6}He) (top), the low-lying states in ^{8}B from ^{11}B (^{3}He,^{6}He)^{8}B, (center) and the T=2 state in ^{8}B at 10.619 MeV excitation (bottom).

Observation of T=2 States in ^{8}Li and ^{8}Be

R.G.H. Robertson, W. S. Chien,
and D. R. Goosman*

Elsewhere in this report, we describe experiments on the $^{11}B(^3He,^6He)^8B$ reaction whereby the T=2 state in ^{8}B has been located. Since the ground states of ^{8}He and ^{8}C, and the T=2 state in ^{8}Be are already known, it is necessary only to locate the T=2 state in ^{8}Li in order to complete the first full isobaric quintet. This goal has been accomplished with the observation of the T=2 state in ^{8}Li by means of the $^{10}Be(p,^3He)$ reaction, in a collaboration with D. R. Goosman.

Targets of 1.6 My ^{10}Be (from $^{13}C(n,\alpha)^{10}Be$, in the Oak Ridge H.F.I.R. Reactor) were prepared in the form of ^{10}BeO on Pt backings by Goosman.[1] The target used in these experiments consisted of 126 μg cm^{-2} ^{10}BeO on a 1 mg cm^{-2} Pt-backing.

A beam of 45 MeV protons was used to induce the $(p,^3He)$ and (p,t) reactions on ^{10}Be. Reaction products were analyzed in an Enge split-pole spectrograph and observed with a 1mm thick x 5 cm long Si position-sensitive detector. The lowest T=2 state in ^{8}Li is calculated from the Isobaric Multiplet Mass Equation to lie at 10.816(15) MeV excitation, while the T=2 state in ^{8}Be has been observed by Black _et al._[1] as an isospin-forbidden resonance in the reaction $^6Li(d,p)^7Li$ at 27.483(10) MeV excitation. The figure shows $^{10}Be(p,^3He)^8Li$ and $^{10}Be(p,t)^8Be$ spectra to the appropriate regions of excitation and in both cases sharp states are clearly seen. Detailed analysis has not yet been carried out, but there seems every reason to believe that these sharp states are the T=2 states.

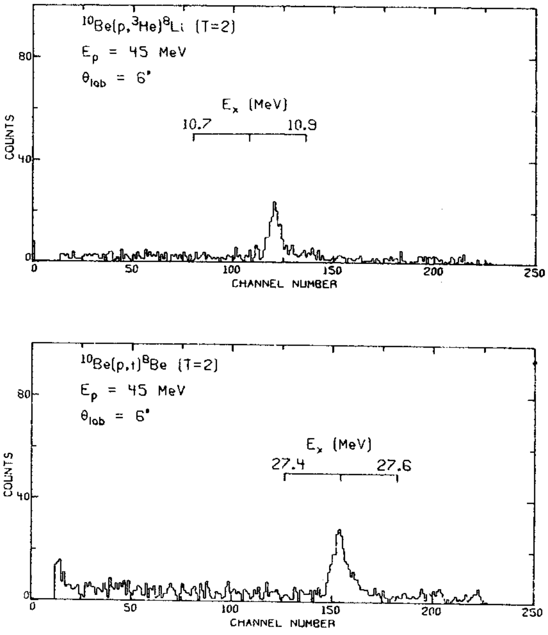

FIGURE 1.--Spectra resulting from proton bombardment of a ^{10}Be target, showing T=2 states in ^{8}Li (top) and ^{8}Be (bottom).

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The Mass of ^{12}N

J. Nolen, M. Cantino,[*] and F. Calaprice[+]

An accurate knowledge of the mass of ^{12}N is important because of its role in one of the main tests of the conserved vector current theory of beta-decay. Gell-Mann suggested in 1958 that a term in weak interactions which is analogous to the magnetic part of electromagnetic interactions should be evident in a comparison of the beta-spectra of the forbidden mirror decays ^{12}N(β^+)^{12}C and ^{12}B(β^-)^{12}C. A summary of the experimental and theoretical situation as of 1964 is given by C. S. Wu.[1] The CVC theory of weak magnetism predicts the amount by which the shape of the beta-spectra should differ from that of a standard allowed spectrum. The ratio of the actual spectrum to the theoretical allowed spectrum is predicted to vary approximately linearly with beta energy:

$$C_+(E) = 1 + (8/3)a^+E \qquad (^{12}\text{N decay})$$

and

$$C_-(E) = 1 - (8/3)a^-E \qquad (^{12}\text{B decay})$$

where C_+ and C_- are the energy dependent correction factors and $a^- - a^+ = 1\%$ per MeV. The prediction based on the old Fermi theory is an order of magnitude smaller.

The end-point energies of the ^{12}N and ^{12}B spectra affect the experimental extraction of these ratios because they are input to the calculation of the allowed Fermi shapes. At the time of the beta-decay measurements of Lee, Mo, and Wu[2] the mass of ^{12}B was known to 1.5 keV and, therefore, contributed a negligible amount to the experimental uncertainty. However, the mass of ^{12}N indicated in reference (a) of the table below was used in that analysis with the 60 keV quoted uncertainty contributing about 0.2% per MeV uncertainty to the experimental result of 1.19±0.24% per MeV. In a reanalysis of Wu[1] the mass from reference (d) below was used and an experimental result of 1.07±0.24% per MeV was given. However, because of the effects on the spectra of branches to the ^{12}C 4.4 and 7.6 MeV levels there has been a preference indicated by other workers to use only the high energy ends of the spectra in the analysis.[3] In this region the ratios are more sensitive to the end point energy. Hence it seems appropriate to remeasure the ^{12}N mass with a precision comparable to that of ^{12}B so as to completely remove this uncertainty from this experimental test of the CVC theory of weak interactions.

The measurement currently in progress is a determination of the ^{14}N(p,t)^{12}N Q-value relative to that of ^{16}O(p,t)^{14}O which is known to ±0.3 keV. Data were recorded on nuclear emulsions in the Enge Split-Pole Spectrograph at a beam energy of 31.2 MeV. At this beam energy the tritons corresponding to the ground state of ^{14}O are near the elastic protons while those corresponding to the ground state of ^{12}N are between the ^{12}C 4.439 and ^{14}N 5.106 MeV states from the (p,p') reaction. Using the simultaneous calibration procedure described in reference 4 a final precision of about 1 keV on the mass of ^{12}N is expected. The preliminary result indicated in the figure is in excellent agreement with the last four measurements but the smallest error previously quoted was ±7 keV. The error associated with the previous weighted average indicated by the dashed line is ±5 keV.

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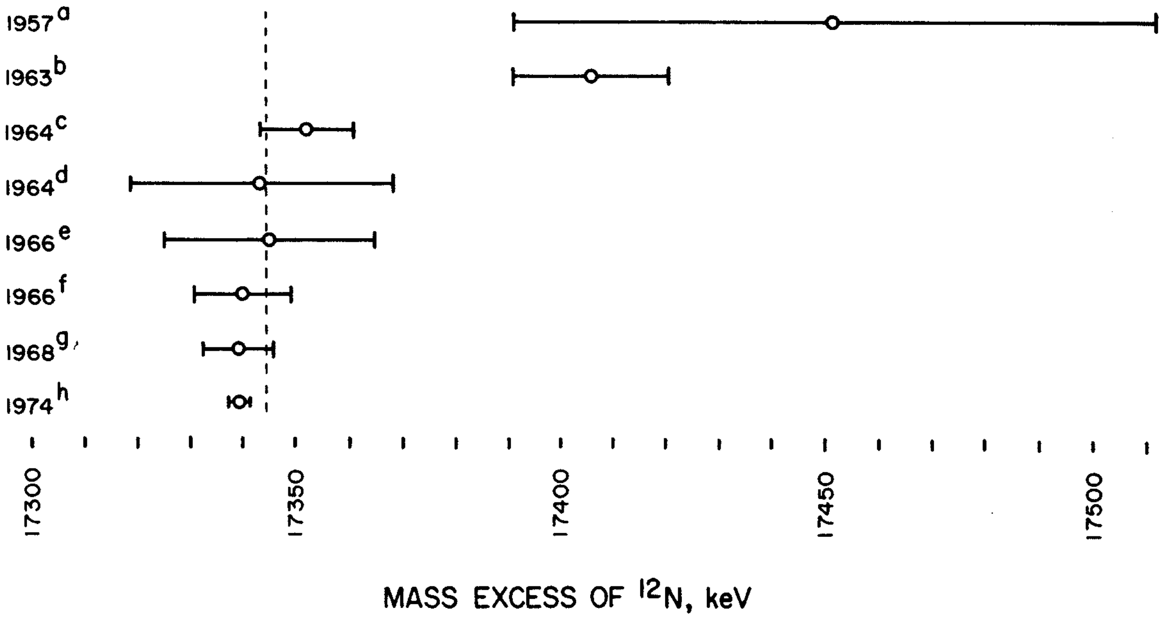

FIGURE 1.

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