Search for Neutral Currents in Nuclei

R.G.H. Robertson, R.A. Warner, T.J. Bowles,* and R.C. Melin

Unified gauge theories of the weak and electromagnetic interactions as formulated by Weinberg[1] and Salam[2], and Glashow, Iliopoulos and Maiani[3], have had a number of spectacular successes, notably the prediction of charm and of weak neutral currents. Both of these have been experimentally verified, giving very strong support to these elegant theories. However, recent experimental work designed to test other details of the of the theory have revealed some disturbing discrepancies. The probable observation of heavy leptons and the so-called high-y anomaly in inelastic neutrino scattering both indicate the need to extend the basic theory of Weinberg and Salam. The most clear-cut experimental evidence against the original form of the theory comes from the non-observation of parity mixing in atomic bismuth to a level some ten times below that expected[4,5]. Indeed, parity violation has not yet been explicitly demonstrated for the neutral currents, although the most plausible interpretation of ν and $\bar{\nu}$ scattering experiments is in terms of parity-violating neutral currents. Conversely, the atomic physics experiments are sensitive only to vector hadronic currents and therefore do not conclusively demonstrate that the neutral currents conserve parity.

In nuclei parity-mixing can be induced by both charged- and neutral-current hadronic interactions. A distinction between the two can be made through their isospin-dependence -- the charged currents cause principally $\Delta T=0$ and 2 mixing with a very small $\Delta T=1$ component, while the neutral currents produce mainly $\Delta T=1$ mixing. Thus nuclear physics experiments which are sensitive exclusively to parity-changing, $\Delta T=1$ forces are of special interest. Adelberger and collaborators[6] have pursued measurements on a particularly attractive case, the $J^\pi,T = 0^+, 1$ and $0^-, 0$ doublet in ^{18}F.

The α-decay of some T=1 states in self-conjugate nuclei is forbidden by both parity and isospin. Such states can α-decay if the weak neutral current induces a T=0 amplitude of the opposite parity. Many years before the development of unified gauge theories Wilkinson[7] examined such a case, the alpha decay of the 0^+, T=1 state at 3.562 MeV in ^6Li, and set an upper limit of 0.2 eV on the parity-violating alpha width (the state decays radiatively with a width of 8 eV). Renewed theoretical interest has prompted two new measurements of the alpha decay, that of Barrette et al.[8], who obtained $\Gamma_\alpha<1.7 \times 10^{-2}$ eV, and Bellotti et al.[9], who obtained $\Gamma_\alpha<8 \times 10^{-4}$ eV. Both of these upper limits are still well above the theoretical estimate made by Gari[10] in the framework of Weinberg-Salam theory, $\Gamma_\alpha \sim 10^{-8}$ eV.

All experiments on the ^6Li case have sought to detect resonant alpha capture by deuterium at an energy appropriate to the 3.562 MeV state of ^6Li, and have looked for γ-rays resulting from the capture. At MSU we have initiated a program to measure the radiative capture by detecting ^6Li recoil ions at 0^o in the Enge spectrograph. The technique offers considerable advantages: The recoil ions may be detected with the powerful methods developed for particle identification in the presence of extraneous background, and the detection efficiency is virtually 100% since all the recoil ions go forward into a cone of 1^o half-angle. The Enge spectrograph is ideally suited to these measurements. It has an entrance aperture just large enough to accommodate the recoil cone, and the focal plane is large enough to allow simultaneous measurement of the ^6Li recoils, the ^4He beam and the elastically scattered deuterons (for normalization).

Initial work has concentrated on development of the technique and reduction of background. The principal difficulty has been caused by degraded α particles of the same magnetic rigidity as the ^6Li ions. While their energy (2.8 MeV) is much lower than that of the ^6Li ions (4.1 MeV), pileup of two such alphas produces a peak which extends into the region of E-ΔE space occupied by ^6Li (the particles are detected in a thin-window proportional counter backed by a Si detector). A pileup rejection system based on pulse-shape discrimination has proven essential.

With the aid of this system radiative capture has been observed for the first time at E_α=6.15, 8.16, 10.14, and 12.15 MeV, corresponding to excitation energies of 3.52, 4.19, 4.85 and 5.52 MeV, respectively. While the analysis of the data is still very preliminary, the observed cross-sections are shown in Fig. 1, compared to a prediction made by Skopik et al.[11] based on their measurements of the $^6Li(e,e'd)^4He$ reaction. The lower cross-section observed near E_x=3.56 MeV than predicted is encouraging, because it increases the sensitivity of the parity-violation measurement (yet to be done). Another interesting feature is the rapid rise in cross-section above E_α=8 MeV, which we attribute to direct E1 radiative capture from continuum states into the 0^+, 1 state at 3.56 MeV. Unlike the direct ground state transition, no selection rules inhibit this cascade process.

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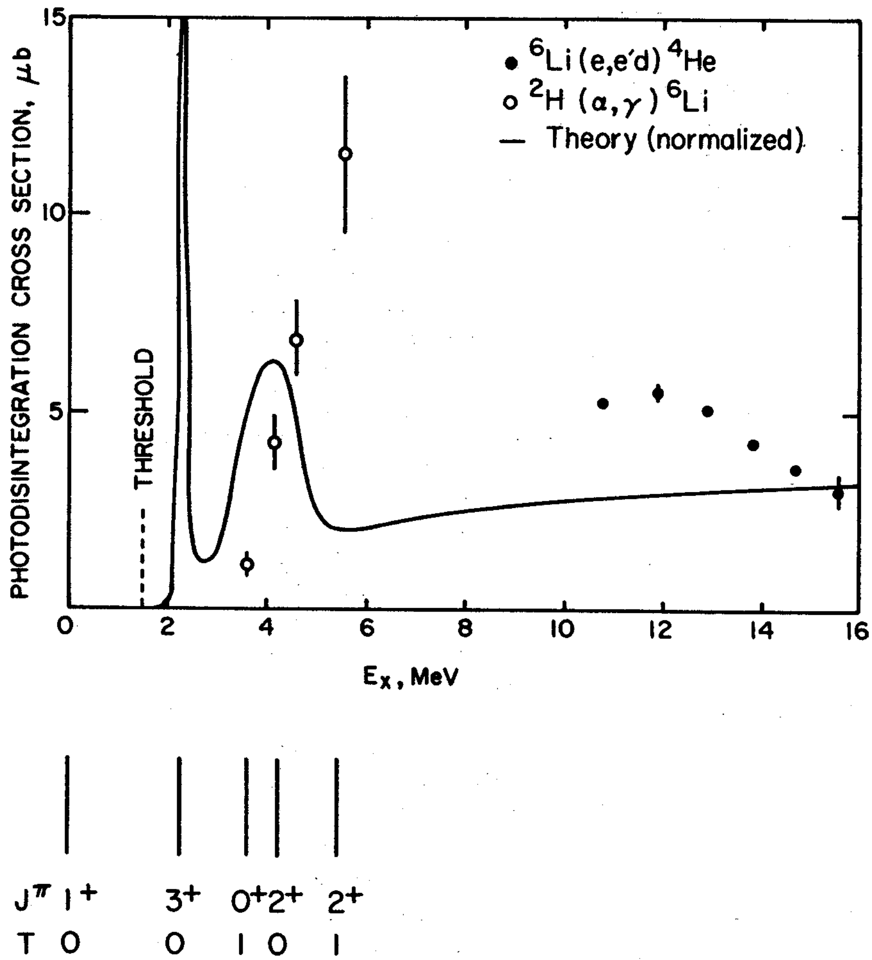

Upper Limit on Parity Mixing in the ^{93}Tc $17/2^-$ Isomer

B.A. Brown, O. Hausser,* T. Faestermann,* D. Ward,* H.R. Andrews* and D. Horn*

The isomeric decay of the $17/2^-$ level in ^{93}Tc has been shown to be very sensitive to parity mixing from a $17/2^+$ level separated by about 0.4 keV.[1] From the lifetime information alone upper limits of $|\alpha| \leq 7.4\times10^{-4}$ for the admixed amplitude and $|\langle 17/2^+ | H_{pv} | 17/2^- \rangle| \leq 0.34$ eV for the parity violating matrix element were obtained.[1] More recently the electron conversion of the isomeric decay has been studied.[2] Fom this experiment the matrix element limit was reduced to $|\langle 17/2^+ | H_{pv} | 17/2^- \rangle| \leq 0.13$ eV and it was found that it was necessary to know the E3/M2 mixing ratio in order to obtain a more precise value for the matrix element.

In the present work we have measured the angular distribution and linear polarization of the $17/2^- \rightarrow 13/2^+$ transition in order to determine the relative strengths of the E2, M2 and E3 components. In addition, a new measurement of the $17/2^- \rightarrow 17/2^+ \rightarrow 13/2^+$ isomeric branching ratio which is important for the interpretation of the present experiment has been obtained.

The ^{93}Tc $17/2^-$ isomer was populated by the ^{65}Cu(^{32}S, 2p2n)^{93}Tc reaction at E(^{32}S)=120 MeV on 1.8 mg/cm^2 thick targets of ^{65}Cu. Long-range evaporation residues were stopped in 64 mg/cm^2 thick Pb backings to maintain the nuclear alignment over several half-lives. The de-excitation of isomeric states was observed during 1.2 μs time intervals between 0.15 μs wide beam pulses spaced by 2 μs. The gamma-ray angular distributions were measured with a Ge(Li) detector placed 12.2 cm from the target, and the linear polarizations of delayed gamma rays with a three Ge(Li) detector Compton polarimeter placed at $\theta_\gamma = 90^\circ$. The angular distributions were normalized to gamma-ray intensities in the scattering crystal of the polarimeter or to the beam charge measured in a carefully suppressed Faraday cup. Both procedures yielded nearly identical results. Consistency checks of the angular distributions were performed with isotropic gamma rays following beta decay and nonisotropic, prompt gamma rays from Coulomb excitation of thick, natural Ge, whose angular distributions were compared to first order Coulex calculations. In all cases extremely good agreement with expectations was observed. The polarization sensitivity of the polarimeter was obtained with Coulex gamma rays.

The data from isomeric decays had to be corrected for the effects of a magnetic field of 140 μT which was measured at the target position. The resulting integral spin rotation effects ($|\omega\tau| = 7^\circ$ for the ^{93}Tc isomer!) were calcualted exactly for both angular distributions and linear polarizations.

Combining the results of the present experiment with the internal conversion measurement[2] the following properties of the delayed 750.78 keV γ ray have been obtained:

$\Gamma(E2)/\Gamma = 0.032 \pm 0.032$

$\Gamma(M2)/\Gamma = 0.35 \pm 0.10$

$\Gamma(E3)/\Gamma = 0.62 \pm 0.10$

and $\delta(E3/M2) = 1.33^{+0.36}_{-0.26}$

(δ has the sign convention of Rose and Brink)

As shown in Fig. 1 there is the possibility that part of the delayed 750.78 keV transition can arise from a $17/2^- \rightarrow 17/2^+ \rightarrow 13/2^+$ branch which of course would give a contribution to $\Gamma(E2)/\Gamma$ which is not due to parity mixing. We have measured this branching in this experiment by noting that the direct $17/2^- \rightarrow 13/2^+$ transition has a very different angular distribution ($a_2 \approx -0.19$) than the $17/2^+ \rightarrow 13/2^+$ transition ($a_2 \approx 0.18$). This difference gives rise to a small energy shift in the delayed transition as a function of angle. This energy shift relative to the 756-keV isomeric transition in ^{94}Ru which is produced with about equal intensity in the present reaction is shown in Fig. 2. The solid curve represents a 3±3% contribution from the $17/2^- \rightarrow 17/2^+ \rightarrow 13/2^+$ branch in the delayed transition assuming an energy difference of 0.32 keV between the $17/2^-$ and $17/2^+$ levels as determined in Ref. 2.

The present experimental results are summarized in Fig. 1. All of the measured E2 width of $\Gamma(E2)/\Gamma = 3 \pm 3\%$ can arise from the 3±3% $17/2^- \rightarrow 17/2^+ \rightarrow 13/2^+$ branch thus only an upper limit for a parity forbidden branch is obtained:

$\Gamma(E2\ 17/2^- \rightarrow 13/2^+)/\Gamma \leq 6\%$

This limit together with the $17/2^-$ - $17/2^+$ energy difference of 0.32±0.03 keV[2] gives

$|\langle 17/2^+ | H_{pv} | 17/2^- \rangle| \leq 0.06$ eV

The present value of $|\langle H_{pv} \rangle|$ is compared with the values obtained in ^{19}F and ^{180}Hf in Table I. Also in this table the γ ray electric-dipole transition rates between the two states involved in the parity mixing are given. The B(E1) value in ^{93}Tc is obtained using a calculated internal conversion coefficient[2,3] of 8.1×10^3. A scaling relation between the E1 and H_{pv} matrix elements is indicated. This scaling relation is probably related to the nuclear structure differences in the wave function and may indicate that the form of the effective H_{pv} operator in nuclei is similar to the E1 operator.

Further improvements in the parity mixing in ^{93}Tc should come from different experiments probing either the circular polarization of the $17/2^- \rightarrow 13/2^+$ gamma ray or its asymmetry, provided the $17/2^-$ isomer can be polarized. The present results on the partial widths of the $17/2^-$ state are essential for planning such future experiments.

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TABLE I. Comparison of experimental E1 strengths and matrix elements of the parity violating Hamiltonian $|\langle H_{pv}\rangle|$ deduced from various experiments.

Nucleus	J	Ref.	ΔE (keV)	B(E1) ($e^2fm^2x10^{-6}$)	$(B(E1))^{1/2}$ ($e\,fm x10^{-2}$)	$|\langle H_{pv}\rangle|$ (eV)
^{19}F	1/2	a	110	560±12	2.4	1.5±0.8
^{93}Tc	17/2	b	0.32	1.2±1.2	0.11±0.11	≤0.06
^{180}Hf	8	c	57	0.78x10^{-6}	0.88x10^{-6}	(1.2±0.2) x10^{-6}

[a] Ref. 4.
[b] Present experiment
[c] Ref. 5.

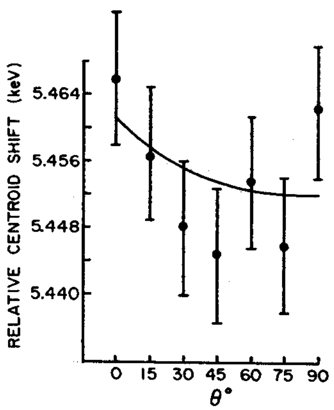

FIG. 2.--Centroid shift of the delayed ^{93}Tc 750-keV γ ray relative to the ^{94}Ru 756-keV γ ray as a function of angle. The solid curve is discussed in the text.

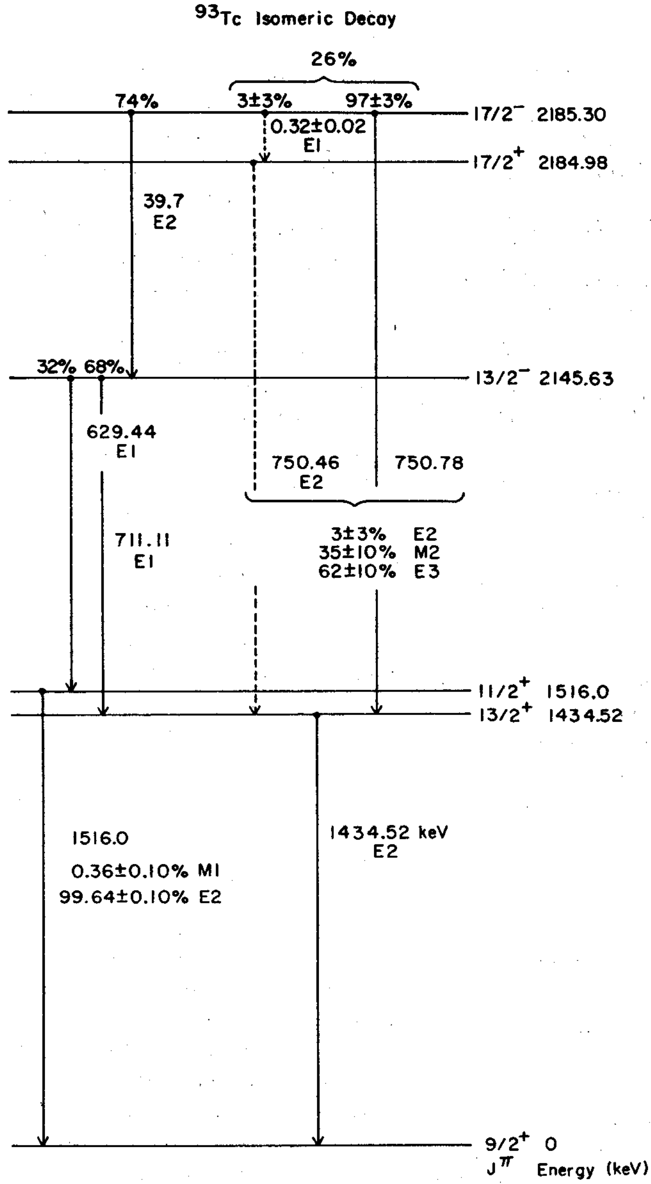

FIG. 1.--Summary of the ^{93}Tc isomeric decay scheme obtained in the present experiment. The energy levels are not drawn to scale.

Parity Mixing Calculations using $0p_{1/2}$-$0d_{5/2}$-$1s_{1/2}$ Shell-Model Wave Functions

B.A. Brown, Jan van Hienen, and D.O. Riska

Many experiments have shown evidence for parity violation in nuclear transitions.[1,2] These experiments serve as a unique test for the predictions of various models of the weak interaction concerning the interaction of hadrons with hadrons. Of particular interest is the presence of neutral currents predicted by the Weinberg-salam model. Neutral current events in both leptonic and semileptonic processes have been observed.[3] However, no experiments have demonstrated that neutral currents are parity violating. Thus it is very important to look for parity violating effects in nuclei which may be influenced by parity violating neutral currents in the nucleon-nucleon interaction.

In order to interpret quantitatively the measured effects in nuclei a reliable microscopic nuclear model must be used. In this work we report on initial results of calculations of nuclear parity mixing effects in the region of A=12-28 using the shell model wave functions of Reehal and Wildenthal[4] which are expanded in terms of a complete set of basis states within the $0p_{1/2}$-$0d_{5/2}$-$1s_{1/2}$ model space.

We have concentrated initially on the $\Delta T=1$ parity changing contribution from the $\pi^{\pm}$ meson exchange. This contribution is particularly sensitive to parity violating neutral currents.[3] The $\Delta T=0$ and 2 contributions are thought to arise predominantly from the short range ρ meson exchange and hence are more sensitive to the nuclear short-range correlations[1] which adds some uncertainty in their calculation.

The $\Delta T=1$ $\pi^{\pm}$ meson exchange interaction is given by:[1]

$$V^{\Delta T=1}_{(r)}=\frac{g_s g_w}{8\hbar m}(\vec{\tau}^1\times\vec{\tau}^2)_3(\vec{\sigma}^1+\vec{\sigma}^2)\cdot\vec{\nabla}\left(\frac{e^{-\mu r}}{r}\right) \qquad (1)$$

where $\vec{\nabla}\left(\frac{e^{-\mu r}}{r}\right)=-\hat{r}\mu^2\left(\frac{1}{\mu r}+1\right)\frac{e^{-\mu r}}{\mu r}$

$\vec{r}=|\vec{r}_1-\vec{r}_2|$

$g_s=13.5$ is the strong interaction coupling constant and $\mu=m_\pi=0.7\ \mathrm{fm}^{-1}$ ($c=\hbar=1$). g_w is the weak interaction coupling constant which is estimated in the standard Cabibbo model[1-3] as $g_w=3.2\times10^{-8}$ thus in total

$$\frac{g_s g_w \mu^2}{8\hbar m}=0.35\ \mathrm{eV}$$

The neutral current effects have the same form as Eq. 1 but the coupling constant g_w is enhanced on the order of a factor of ten using the Weinberg-Salam model.[3]

The matrix elements of Eq. 1 in the j-j coupling scheme were obtained by the usual LS-jj and Moshinsky transformations using harmonic oscillator wave functions. Using the shell model wave functions there are two types of contributions to the total matrix element, one (I) is a two-body interaction entirely within the model space (Fig. 1) which is obtained from the two-body model-space transition density and the other (II) is the interaction averaged over the inert core (Fig. 2) and is obtained from the one-body model-space transition density. The one-body reduced matrix elements from II are given by

$$\langle j_1|||V^{\Delta T=1}|||j_2\rangle$$

$$=\sum_{j_c}(-1)^{j_c+j_2+1}\sum_{JTT'}(-1)^{J+1}(2J+1)\sqrt{(2T+1)(2T'+1)}$$

$$\times\begin{Bmatrix}J & j_1 & j_c\\ j_2 & J^1 & 0\end{Bmatrix}\begin{Bmatrix}T & 1/2 & 1/2\\ 1/2 & T' & 1\end{Bmatrix}$$

$$\times\langle j_c j_1 JT|||V^{\Delta T=1}|||j_c j_2 JT'\rangle_a$$

where the sum is over all core orbitals j_c. II only contributes for $j_1=0p_{1/2}$ and $j_2=1s_{1/2}$.

The calculation has been carried out for several cases in which the parity mixing is expected to arise from mixing of two nearby levels. Wave functions were generated with the Oak Ridge shell model code in a 6 orbit proton-neutron formalism. The two-body off diagonal matrix elements (I) in perturbation theory are given by taking the overlap of the two sets of wave functions obtained with and without the $V^{\Delta T=1}$ perturbation. Corrections for short range correlations[1] and for center-of-mass motion in the shell model wave functions have not been included.

Preliminary results are given in Table I using the Cabibbo model for g_w. Contribution II is small mostly because of an almost complete cancellation between the terms with $j_c=0s_{1/2}$ and $j_c=0p_{3/2}$.

The only published experimental result in the mass region considered for which $\Delta T=1$ is allowed is for ^{19}F by Adelberger et al.[5] However, $\Delta T=0$ can also contribute in this case which makes the comparison with experiment difficult to interpret. $\Delta T=1$ is the only contribution in the other cases given in the table. Experiments for ^{18}F are currently being done by Adelberger et al.[6] and experiments for ^{20}Ne are being considered in this laboratory.[7]

Further theoretical calculations are planned to include the $\Delta T=0$ and 2 contributions in at least a phenomenological way and to extend the calculations to other doublets in this mass region.

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X Indicates a Weak Vertex

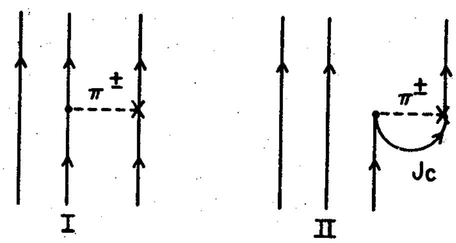

FIG I FIG 2

Table I

Nucleus	J	- parity T	- parity Ex exp (MeV)	- parity Ex th (MeV)	+ Parity T	+ Parity Ex exp (MeV)	+ Parity Ex th (MeV)	$\|<V^{\Delta T=1}>\|$th I (eV)	$\|<V^{\Delta T=1}>\|$th II (eV)	$\|<V_{pv}>\|$exp (eV)	Ref.
^{18}F	0	0	1.081	1.34	1	1.042	1.00	0.34	0.003		
^{19}F	1/2	1/2	0.110	0.23	1/2	0	0	0.06	0.005	1.5 ± 0.8[a]	5
^{20}Ne	1	0	11.23	6.10	1	11.26	9.95	0.09	0.003		
				10.07				0.10	0.003		
				12.77				0.13	0.0005		
				13.45				0.008	0.0013		

a) $\Delta T=0$ can also contribute in this case.

Reanalysis of the ^{22}Na Beta Spectrum

R.B. Firestone

An important measurement necessary to understand the second-order corrections to allowed beta decay is the precise measurement of the beta spectral shape. Unfortunately, as we will discuss below, these experiments require numerous, theoretical corrections which may detract substantially from their reliability. Two precise shape factor measurements for ^{22}Na decay were performed by Wenninger, Stiewe and Leutz,[1] one involving a ^{22}Na doped NaI detector and the second utilizing a magnetic spectrometer. The ^{22}Na doped NaI data is corrected here for experimental problems not directly addressed in the original analysis, however corrections to the magnetic spectrometer data are not so straightforward and can only be discussed more generally here.

To lowest order the β^+ spectra shape function for a positron of energy W is given by

$$C(W) = \frac{N(W)}{\text{const } pW(W_o-W)^2 F_o L_o} \qquad (1)$$

where W_o is the endpoint energy and $F_o L_o$ the familiar Fermi function. The previous analysis followed this format although only Fierz type terms

$$C(W) = 1 \pm b/W \qquad (2)$$

were investigated. In light of the preponderance of evidence against Fierz terms, it is now more useful to search for terms primarily linear in energy as are associated with second-order terms described elsewhere in this report.

Several important corrections are included here for the first time. The first correction to the shape factor is for photon emission which is described by Sirlin.[2] In the range of 100-400 keV betas, photon emission changes the slope of the shape factor by +2.0%/MeV. A second correction is necessary for positron annihilation in flight. In the ^{22}Na doped NaI experiment only events in coincidence with 2297 keV γ-radiation ($\gamma^{\pm}+\gamma_{1275}$) were accepted so that annihilation in flight events were generally excluded. These corrections have been worked out by Bethe[3] and give a further correction to the slope of +4.0%/MeV. Finally, an important correction is necessary for the escape of betas near the detector surface. The experiment was performed using different size NaI detectors so that this correction depends on how the statistics are weighted. The exact correction was calculated to vary from +6.3 - +12.3%/MeV depending on the detector. Additional corrections for screening and a newer beta endpoint energy of 546.7-keV were also included in this analysis.

The final corrected spectral shape is shown in Fig. 1 which is averaged for all three NaI crystals. The slope obtained by a least squares fit of the data between 100-400 keV yields

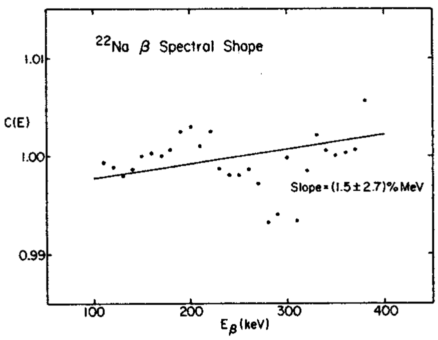

Fig. 1.--Reanalyzed ^{22}Na β spectral shape from E_β = 100 - 400 keV.

+1.7±2.5%/MeV. This differs widely from the slope -11.4±6.4%/MeV we obtained before these corrections. Detection of the photons associated with these correction terms will tend to diminish the positive slope to a small degree, however it appears that a significant positive slope still bests describes the data. The magnetic spectrometer data can only be corrected for photon emission and yields the slope -6.1±4.9%/MeV. Further corrections for slit scattering and annihilation in flight at the anthracene detector will contribute towards a positive slope, and it is not unlikely that this data would agree with the NaI data. It is clear, however, that no great weight can be placed on the slope data without careful experimental verification of the large corrections described here.

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Measurement of the 1952-keV M1 γ-ray Transition in ^{22}Na

R.B. Firestone and R.A. Warner

An important measurement necessary to explain the "anomolous" EC/β^+ decay branching ratio of ^{22}Na, described elsewhere in this report, is the transition probability for the analogous M1 γ-ray transition. This transition is described in Figure 1; the decay from the T=1, 2^+ state at 1952-keV in ^{22}Na to the T=0, 3^+ ground state. The mean-life of this T=1 state is known to be 9±5 fsec,[1] and, at the beginning of this experiment, the limit on the branching ratio was $\leq$2%.[1] This limit allows a weak magnetism contribution sufficiently large to explain the EC/β^+ ratio anomoly. In addition to the central issue of the EC/β^+ ratio, this measurement, in conjunction with other experiments, serves as a test of the validity of CVC theory.

The experimental technique chosen to measure the 1952-keV γ ray involves production of the T=1 state in ^{22}Na via the ^{25}Mg(p,α)^{22}Na reaction using the 12.7 p beam from the MSU sector-focused Cyclotron. The target is a 60 $\mu g/cm^2$ ^{25}Mg foil on a formvar backing, and α-γ coincidence data is collected to obtain the spectrum of ^{22}Na γ rays. The first alpha detector used consisted of an 80 mm^2, 50 $\mu g/cm^2$ Si surface barrier detector backed by a 150 mm^2, 150 $\mu g/cm^2$ Si surface barrier veto detector to eliminate betas and protons. A 10% efficient Ge(Li) detector (with respect to a 7.6 x 7.6 cm NaI(Tl) detector) with 2.3-keV resolution at 1331-keV was used for detecting the γ rays. Both detectors were placed at 90° with respect to the beam in order to minimize doppler broadening in the γ-ray spectra. The alpha detector was also placed at the appropriate angle such that the 1952-keV γ ray would fall kinematically in a low background part of the spectrum. The spectra obtained in this manner were quite free of contaminant activities with the exception that some low energy protons failed to reach the veto counter. Fortunately the observed (p,pγ) reaction impurity gave no significant background near 1952 keV making analysis of this data straightforward.

At this point 458,000 total coincidence pairs have been recorded representing approximately 14 hours of beam time. The resultant γ-ray coincidence spectrum, representing alpha events with $E_\alpha \geq 1.5$ MeV, is shown in Figure 2. By far the strongest observed level in ^{22}Na was the 1952-keV state with 11,300 events in the 1369-keV γ-ray transition peak. No significant counts were observed at 1952 keV, and a new upper limit has been set at $\leq$0.25% of all decays from the 1952-keV level. This limit is now a factor of three too small to explain the ^{22}Na EC/β^+ ratio assuming that CVC theory is correct. It should be emphasized that any E2 contribution wi will further lower this limit. We now hope to improve our statistics until the M1 transition can be seen. A recent shell model calculation by Chung and Wildenthal[2] indicates that this transition should be observed with only slightly lower intensity than our current limit.

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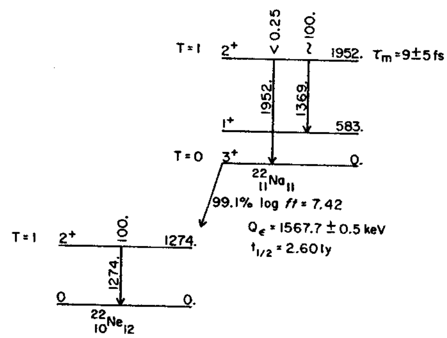

FIG. 1.--^{22}Na Analogue β and M1 γ-ray Decays.

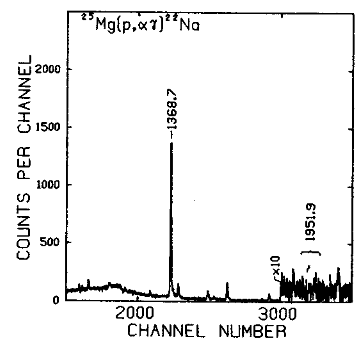

FIG. 2.--^{25}Mg(p,αγ)^{22}Na coincidence spectrum.

Second Order Corrections to ^{22}Na Beta Decay

R.B. Firestone, B.R. Holstein, and Wm. C. McHarris

With recent interest in second-class currents, CVC theory, EC/β^+ ratios and other aspects of beta decay relevant to general weak interaction theory it has been desirable to have a clear, usable theory good to second order for predicting experimental quantities. This is most difficult for large Z where Coulomb terms of order αZ become large, however for small Z these expressions can be derived in quite simple forms. For a Gamow-Teller case such as ^{22}Na five form factors are required. In elementary particle notation these are c, the usual Gamow-Teller term, which must be carried through order q^2, i.e.

$$c(q^2) = c_1 + c_2 q^2 \tag{1}$$

as well as b, the weak magnetic term; h, the induced pseudoscalar; and d, the induced tensor which may also contain the second class axial current.

In the ^{22}Na case we are most interested in the EC/β^+ ratio. We define a skew ratio $\mathcal{V}$ by

$$(EC/\beta^+)^{EXP} = (EC/\beta^+)_o \mathcal{V} \tag{2}$$

where $(EC/\beta^+)_o$ is the normal allowed ratio assuming $c_2=b=h=d=0$. Neglecting the electron binding energy we get, in general,

$$\begin{aligned}\mathcal{V} \approx\ & 1+\frac{1}{2M}\left(m_e-\frac{20}{3}\langle E\rangle+\frac{4}{3}m_e^2\frac{1}{\langle E\rangle}+\frac{7}{8}\Delta_o\right) \\ & -\frac{c_2}{c_1}\Big[\frac{40}{9}\Delta(m_e+\langle E\rangle)+\frac{40}{9}(m_e^2-\langle E\rangle^2)-\frac{4}{9}m_e^2\Delta\left(\frac{1}{m_e}+\frac{1}{\langle E\rangle}\right) \\ & -\frac{2}{3}\alpha E_o R-\frac{9}{2}\alpha^2(2Z'-1)+\frac{20}{3}\frac{\alpha Z'}{R}(m_e+\eta\langle E\rangle)\Big] \\ & -\frac{\alpha}{2MR}\frac{c_1^2-d-2b}{c_1}+\frac{4}{3M}\frac{b}{c_1}(m_e+\langle E\rangle) \\ & -\frac{m_e^2}{3M}\frac{(d+2b+h\frac{E_o}{2M})}{c_1}\left(\frac{1}{m_e}+\frac{1}{\langle E\rangle}+\frac{h}{c_1}\frac{1}{2MR}\left(\alpha\frac{E_o}{2M}-\frac{3}{2}\alpha^2\frac{2Z'-1}{2MR}\right)\right)\end{aligned} \tag{3}$$

where

$$\begin{aligned} & M=\frac{1}{2}(M_1+M_2) && Z' = \text{charge of parent} \\ & \Delta=M_1-M_2 && Z = \text{charge of daughter} \\ & \eta=Z'-1/Z && E_o=\Delta\left(1+\frac{m_e^2}{2M\Delta}\right)/(1+\Delta/2M)\end{aligned} \tag{4}$$

and substituting appropriately for ^{22}Na

$$\mathcal{V}=1-\left[18.0\frac{c_2}{c_1R^2}-1.72\frac{b}{Ac_1}+0.71\frac{d}{Ac_1}+0.0017\times\frac{h}{A^2c_1}\right]\times 10^{-3}. \tag{5}$$

Here and below quadratic terms are neglected which are very important for large d or h. The shape factor for β^+ decay is defined by

$$d\lambda_{\beta^+} = 2F_+(Z,E)\frac{G^2(\cos^2\theta c)}{(2\pi)^4}(E_o-E)^2pEf_1(E)dE \tag{6}$$

where

$$\begin{aligned}f_1(E)=\ & c_1^2-\frac{2}{3}\frac{E_o}{M}c_1(c_1-d-b)+\frac{2}{3}\frac{E}{M}c_1(5c_1-2b) \\ & -\frac{m_e^2}{3ME}c_1(2c_1-d-2b)+2c_1c_2\Big(\frac{11}{9}m_e^2+\frac{20}{9}EE_o-\frac{20}{9}E^2 \\ & -\frac{2}{9}m_e^2\frac{E_o}{E}-\frac{1}{3}\frac{\alpha ZE_o}{R}+\frac{10}{3}\frac{\alpha ZE}{R}-\frac{9}{4}\left(\frac{\alpha Z}{R}\right)^2\Big) \\ & -\frac{\alpha Z}{2MR}c_1(c_1-2b-d)+\frac{c_1h}{(2M)^2}\Big(\frac{\alpha Z}{R}E_o-\frac{3}{2}\left(\frac{\alpha Z}{R}\right)^2 \\ & -\frac{2}{3}m_e^2+\frac{2}{3}m_e^2\frac{E_o}{E}\Big).\end{aligned} \tag{7}$$

If the shape factor is defined between E_1=600 keV and E_2=900 keV ($E_i=E_\beta+m_e$) we get

$$\begin{aligned}S =\ & \frac{1}{E_2-E_1}\frac{f_1(E_2)-f_1(E_1)}{f_1(E_1)} \\ =\ & -\left[1.79\frac{b}{Ac_1}-7.78\frac{c_2}{c_1R^2}+0.178\frac{d}{Ac_1}+0.00010\times\frac{h}{A^2c_1}\right]\times 10.^{-3}.\end{aligned} \tag{8}$$

For a β-γ directional correlation we define

$$\begin{aligned}d\lambda_{\beta^+,\gamma} \approx\ & \frac{1}{2}F_+(Z,E)\frac{G^2(\cos^2\theta c)}{(2\pi)^5}(E_o-E)^2pEdEd\Omega_e d\Omega_{\hat{\gamma}} \\ & \times\left[f_1(E)+f_3(E)\left((\underset{\sim}{p}\cdot\hat{s}/E)^2-\frac{1}{3}\frac{p^2}{E^2}\right)\right]\end{aligned} \tag{9}$$

where potentially significant terms arising from tensors of rank 2 are ignored. We derive

$$A_{22} \equiv \frac{2}{3}\frac{f_3(E)}{f_1(E)} = \frac{-E}{21Mc_1}\left(c_1-b+d+\frac{8}{3}c_2M(E_o-E)-\frac{h}{2M}\frac{3}{2}\frac{\alpha Z}{R}\right) \tag{10}$$

$$\approx \text{(at E=850 keV)}\left[4.4\frac{b}{Ac_1}-4.4\frac{d}{Ac_1}+0.015\frac{h}{A^2c_1}-0.60\frac{c_2}{c_1R^2}\right]\times 10^{-5} \tag{11}$$

The longitudinal polarization may be found by the relationship

$$\begin{aligned}\frac{E}{P}P_L =\ & \Big[1-\frac{2m_e}{E}\Big(\frac{m_e}{6M}\frac{c_1-d-2b}{c_1}+\frac{2m_e(E_o-E)}{9}\frac{c_2}{c_1}+ \\ & \frac{m_e}{(2M)^2}\left(\frac{E_o+2E}{3}\right)\frac{h}{c_1}\Big)\Big]^{-1} \\ \approx\ & \text{(at E=750 keV)}\ 1+\Big[-2.5\frac{b}{Ac_1}-1.25\frac{d}{Ac_1} \\ & +0.00011\frac{h}{A^2c_1}-1.18\frac{c_2}{c_1R^2}\Big]\times 10^{-4}.\end{aligned}$$

More precise calculations including all quadratic terms have been performed for ^{22}Na decay and are displayed in figures 1-4.

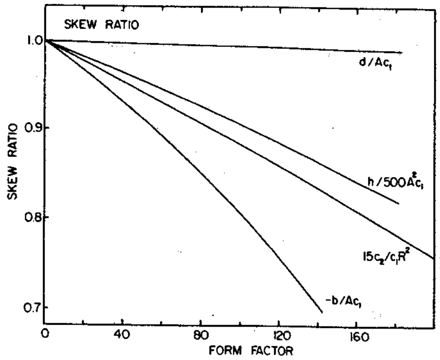

Fig. 1.-Theoretical Skew Ratios.

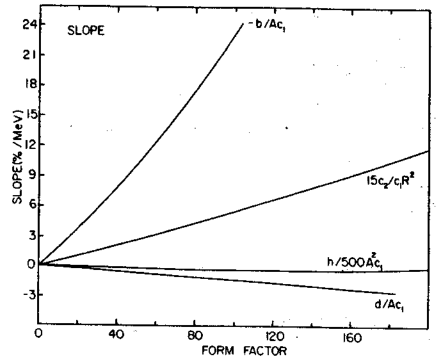

Fig. 2.-Theoretical Spectral Shapes (100-400 keV).

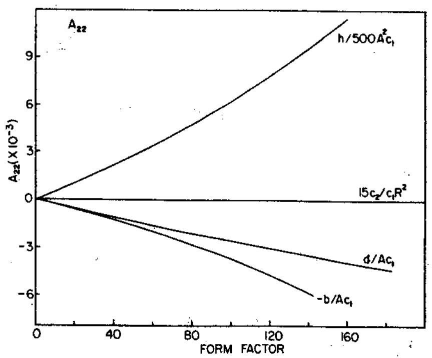

Fig. 3.-Theoretical β-γ Directional Correlation (350 keV)

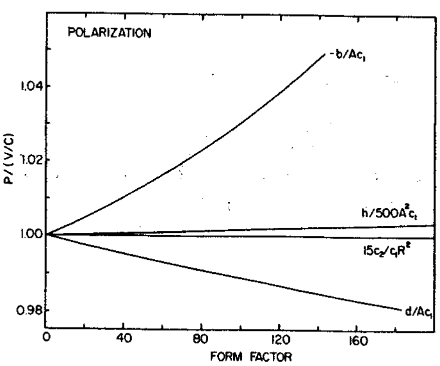

Fig. 4.-Theoretical β Polarization (350 keV).

The Anomalous β Decay of ^{22}Na

R.B. Firestone, B.R. Holstein, and Wm. C. McHarris

In the active period of weak interaction studies via beta decay, following the discovery of non-conservation of parity, the ^{22}Na ϵ/β^+ decay branching ratio was used as evidence of the absence of the S or T interaction, i.e. Fierz interference.[1] Early measurements were consistent with no Fierz interference at the 10% accuracy level,[1] and later more accurate correlative measurements have convinced most theorists that the weak interaction is pure V-A. Parallel to the accumulation of evidence against Fierz terms, the ^{22}Na ϵ/β^+ ratio has been measured to better than 1% accuracy. Four extremely precise values have been listed in Table 1. The three early values[2-4] agree quite closely and the later value of McMahon and Baerg[5] differs significantly for nonapparent reasons. Nevertheless, all values differ significantly from theory, and assuming no Fierz interference require some further explanation.

In addition to these accurate ϵ/β^+ ratios, measurements of the ^{22}Na spectral shape, discussed elsewhere in this report, yield a slope in the range $110 < E < 370$ keV of $+1.5\pm2.7$%/MeV. An upper limit for the analogue M1 γ-ray transition, also discussed elsewhere in this report, has been measured as $\Gamma_{M1}=0.0033$ eV. Finally, the ^{22}Na β-γ directional correlation has been measured[7] yielding an $A_{22}=(-1.8\pm0.3)\times10^{-3}$ which differs from the allowed prediction $A_{22}=0$.

The general theoretical explanation of these results is based on the so called second-order terms normally truncated in allowed theory. These include the second-order Gamow-Teller matrix element $c_2(q^2)$, the induced tensor d, the induced pseudoscalar h, and weak magnetism b. The formalism through second order is worked out elsewhere in this report and here we shall discuss the implications of the theory to the data. In order to explain the experimental ϵ/β^+ ratio, the moderate value of $b/Ac_1=-35$ or $c_2/c_1R^2=+3.5$ and/or a large value of $h/A^2c_1=3.5\times10^4$ were shown to be necessary although no value of d can be significant in this regard. To check the likelihood of these values we have calculated all of the relevant form factors in the impulse approximation using the extensive s-d shell model wavefunctions generated by Chung and Wildenthal.[8] The results give $c_1=0.00266$ which is much too small to explain the measured ft value which gives $c_1=0.016$. This regular Gamow-Teller term arises from the cancellation of three matrix elements of about equal magnitude. The calculations of b, c_2, d, and h do not suffer such problems so we choose to use the experimental value of c_1 and all other calculated values. Thus, we obtain

Table I. ^{22}Na Experimental ϵ/β^+ Branching Ratios

	ϵ/β^+	Skew Ratio	Experimenters
	0.1152±0.0003	--	Theory - Firestone
1.	0.1048±0.0007	0.910±0.008	Leutz, Wenninger (1967)
2.	0.1042±0.0010	0.905±0.011	Vatai, Varga, Uchrin (1968)
3.	0.1041±0.0010	0.904±0.011	Williams (1964)
4.	0.1077±0.0006	0.935±0.008	MacMahon, Baerg (1976)

$$\frac{b}{Ac_1} = -19,\quad \frac{d}{Ac_1} = +3.2,\quad \frac{c_2}{c_1R^2} = -0.37,\quad \frac{h}{A^2c_1} = 1.2\times10^3$$

These values give the skew ratio $\Psi= 0.97$, which is insufficient to explain the data. Assuming CVC theory, c_2 or h must be an order of magnitude larger to explain the data. This may be possible if the impulse approximation is not completely valid for hindered allowed transitions as suggested by Saperstein and Troitskii.[9]

The shape factor is almost certainly positive for ^{22}Na decay as only extraordinarily large values of d/Ac_1 can give significant negative slopes. Also values of b/Ac_1 sufficient to explain the skew ratio yield very large positive slopes suggesting CVC is indeed correct. Thus, either moderate values of c_2/c_1R^2 or h/A^2c_1 could explain both the experimental slope and ϵ/β^+ ratio. Calculations of the β-γ A_{22} show that values of h/A^2c_1 sufficient to explain the other data yield much too large an A_{22}. One should be cautious concerning the A_{22} however, because this calculation is sensitive to second rank tensors not included in the calculation. Also, c_2/c_1R^2 does not affect A_{22} requiring either a small positive b/Ac_1 or negative d/Ac_1. Assuming $b/Ac_1=h/A^2c_1=0$, we find that the data may be explained by $c_2/c_1R^2=+3$ and $d/Ac_1=-60$ which yield $\Psi=0.92$, S=+2%/MeV, and $A_{22}=-1.7\times10^{-3}$ all consistent with experiment although not with the impulse approximation. Additional correlative data should pin down this problem more exactly.

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Search for the Free "c" Quarks with the Cyclotron

M.L. Mallory and P.S. Miller

The announcement of the detection of fractional charges by LaRue, Fairbanks, and Hebard,[1] has motivated the search for quarks with the cyclotron. A previous search for quarks in hydrogen using a cyclotron had been performed by Muller, et al.[2] Fairbanks indicated that the fractional charges appeared when his samples underwent an annealing process on a substrate of tungsten. The estimated amount of tungsten contamination from this process taken with the observation of fractional charge (Ref. 1) implies 10^{11} quarks in every gram of tungsten[3], if the fractional charges represent quarks. In addition, these experiments indicated that the fractional charges are easily lost, implying that they may be loosely bound. A recent technique of sputtering solid materials into the cyclotron ion source has been developed[4] and this technique can sputter many atoms of tungsten, with the consequence of possibly freeing quarks if they are loosely bound in tungsten.

The advantage of using a cyclotron as a mass separator does not lie in its separation capabilities, but in its ability to add energy to the particles and hence making the detection of the particles a very positive signature with high sensitivity.[5] Because of the many parameters of a cyclotron that must be correctly tuned to extract a beam, a technique called the "analogue beam method" is used to set up the cyclotron.[6] A prediction of quark masses and charges is given by Glashow.[7] Only positive charge free quarks can be considered for cyclotron detection because of the voltage of the electrostatic deflector in the cyclotron extraction system and the present cyclotron frequency range. One predicted quark ("c") has the right mass to charge ratio for use of the analogue beam technique and was the object of this search using the MSU cyclotron.

The experiment performed was to scan the cyclotron frequency by ±5% about the predicted "c" quark mass to charge ratio (9/4). Initially $^7Li^{3+}$ and then $^9Be^{4+}$ beams were accelerated through the cyclotron, and the various cyclotron parameters, scan step width, and background were determined. Fig. 1 shows the intensity of the lithium beam vs. the rf. A scan step width of 10 kHz was picked, giving some frequency overlap. 200 rf steps were needed for the ±5% scan. The other parameters of the cyclotron which were adjusted in proportion to the frequency change are the electrostatic deflector voltage and the dee voltage sum. Figure 2 is the lithium beam intensity vs. the electrostatic voltage and shows no need for change in the ±5% frequency scan. However, the electrostatic voltage was adjusted by the theoretical amount.

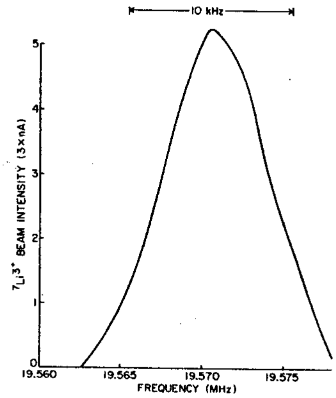

Fig. 1.--The measured beam intensity of $^7Li^{3+}$ as a function of cyclotron frequency. A scan step width of 10 kHz was used in the quark scans and this width is narrow enough to detect any cyclotron beam resonance with an ~25% intensity loss at most.

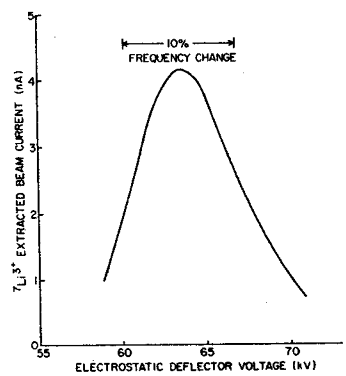

Fig. 2.--The measured beam intensity of $^7Li^{3+}$as a function of the electrostatic deflector voltage. A 10% frequency change should require a corresponding change in the deflector voltage. No change in the voltage would result in only a small decrease in the detection efficiency over the quark frequency scan range.

A $^9Be^{4+}$ beam was obtained in the cyclotron, using BeCu (2% Be) as the charge material. Final tuning of the cyclotron was done with this beam, as it is a close analog to the quark. The dee voltage sum is shown in Fig. 3 for beryllium beam and indicates no need to change over the desired range. However, it was also changed by the theoretical amount with the frequency dependence of the dee voltmeter circuit taken into account.

The detector was a coincidence ΔE,E telescope using silicon detectors with thicknesses 282μ and 3000μ, respectively. The expected range of the 17.2 MeV quark (m=1.5u, q=3/2e) is approximately 3100μ. The detector energy calibration was established with a pulse generator, calibrated by detecting α-particles from a ^{241}Am source.

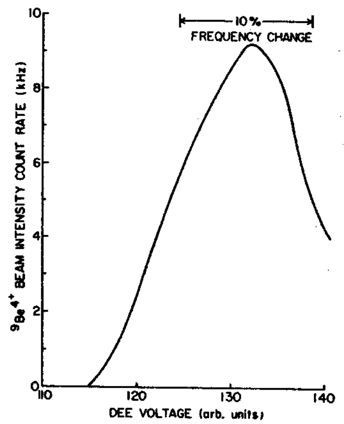

Fig. 3.--The measured beam intensity of a $^{9}Be^{4+}$ beam as a function of dee voltage. A 10% frequency charge should produce a corresponding change in the dee voltage. No change in the dee voltage would produce only a small decrease in the detection efficiency of the quark over the scanned frequency range.

In a background scan with the beryllium beam, no counts were seen except for the following. A beam with mass-to-charge ratio of 7/3 (near the end of our scan range) was detected and identified as $^{14}N^{6+}$ and $^{7}Li^{3+}$. This event verified the validity of our analogue scan technique over the desired frequency range. The scan was interrupted within 20 kHz of the Be frequency due to background from that ion. Second, some low energy pulses were detected, which we associated with rf sparking. In the scan for quarks the ion source with a piece of tungsten behind the source slit was operated using xenon support gas. Each 10 kHz step of the radio frequency was counted for one minute. The tungsten piece in the source was weighed before and after the experiment, and 6.0 x 10^{19} atoms of tungsten were sputtered. Estimating the efficiency of accelerating quarks once free of tungsten is very difficult, but in comparison with normal ions, we believe 1 in 10^4 is a good estimate. With these assumptions 3 x 10^{13} atoms of tungsten were sputtered per each scan step. From Fairbank's results, $\sim 10^3$ "c" quarks should have been detected. No pulses of the right signature were detected.

The following conclusions follow from the failure of the experiment to detect quarks. Any one of them is sufficient to explain the result. (1) The fractional charges seen by Fairbanks could be s, d, u quarks or others. (2) The mass to charge ratio of the c quark is not 9/4, or alternatively the effective mass of the c quark is not equal to the free quark mass. (3) The quark is not loosely bound, rather the tungsten atom containing the quark is loosely bound. The last conclusion can be experimentally checked with the completion of the superconducting cyclotron under construction at MSU, namely this cyclotron will allow acceleration of tungsten ions, possibly those containing quarks.

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