KINEMATIC SHIFTS OF β-DELAYED PARTICLES AS A PROBE OF β-ν ANGULAR CORRELATIONS

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Abstract

Beta-delayed particles undergo a kinematic shift in energy due to recoil motion of the daughter nucleus following beta decay. A careful measurement of this energy shift can be used to establish the ratio of vector to axial vector components in beta transitions. Alpha-beta coincidence data for the beta-delayed alpha decay of ^{20}Na have been obtained. Component ratios for 6 transitions including the superallowed branch were found. Limits on charge dependent mixing with the analogue state were deduced for 5 states in ^{20}Ne*. For the superallowed branch the axial vector component was found; the polar vector component was deduced and establishes a value for the vector weak coupling constant of $G_V=(1.355\pm0.036)\cdot10^{-49}$ erg cm^3.

1. Introduction

Allowed β-decay between states with non-zero spin can involve both the polar- and axial-vector weak currents. With normal spectroscopic techniques, it is impossible to separate these two components, which lessens the usefulness of such transitions in studying small effects. For example, the most precise tests of the consistency of the vector coupling constant[1] have by necessity been restricted to $0^+\rightarrow0^+$ ($\Delta T=0$) transitions where the axial-vector component is forbidden by selection rules. Similarly, measurements of isospin mixing[2] that rely on observing a weak polar-vector component have also been restricted to specific types of transitions - in this case, those with $0^+\rightarrow0^+$ ($\Delta T=1$).

The two components of a mixed decay can be separated experimentally, but generally at the price of much added complexity. The angular correlation between the directions of emission of the electron (or positron) and anti-neutrino (neutrino) depends upon the ratio of the polar to axial-vector components, which when it is combined with the conventional ft-value can lead to a measurement of both individual components. However, the elusiveness of the neutrino makes this possibility - superficially, at least - seem unattractive. It is not really so. The recoil momentum of the daughter nucleus reflects the momentum of both the electron and neutrino, and consequently the angle between them. To illustrate, if the leptons travel in opposite directions their momenta tend to cancel, leaving the daughter nucleus nearly at rest; if they travel in the same direction, the daughter recoils strongly. The β-ν correlation can be deduced from the recoil momentum and indeed experiments relying on this trick form an important part of the experimental basis for the V-A interaction[3].

Typically the recoil energy of even a light nucleus is merely a few hundred eV - easier to measure than a neutrino but still hardly convenient. Even this inconvenience can be removed if the daughter nucleus emits a particle during its recoil; the energy and direction of the emitted particle then reflects the momentum of the nucleus from which it originated. Macfarlane[4] was the first to point out that this technique, based on an earlier ^{8}Li study by Barnes[5], could be generalized to any light delayed-particle emitter. He used it simply to analyze the α-particle peak-shapes in a singles spectrum from the decay of ^{20}Na, but it was soon recognized[6] that improved accuracy could result from coincidence measurements between the delayed particles and the preceding betas. We report here the first measurement - also on ^{20}Na decay - of such an experiment.

2. Theory

In allowed beta decay the angular correlation between the beta and the neutrino is given by the expression

$$W = 1 + a\left(\frac{v}{c}\right)\cos\theta \qquad (1)$$

where θ is the angle between the beta and neutrino momenta, v is the beta velocity and c is the velocity of light. The angular correlation coefficient is[3]

$$a = \frac{G_V^2 \langle 1\rangle^2 - 1/3\, G_A^2 \langle\sigma\tau\rangle^2}{G_V^2 \langle 1\rangle^2 + G_A^2 \langle\sigma\tau\rangle^2} \qquad (2)$$

where G_V and G_A are the vector and axial vector coupling constants, respectively, and $\langle 1\rangle$ and $\langle\sigma\tau\rangle$ the Fermi and Gamow-Teller matrix elements.

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From these expressions, $a=1$ for pure Fermi decays, in which case the leptons are preferentially emitted in the same direction; and $a = -1/3$ for pure Gamow-Teller decays where they are preferentially emitted in opposite directions. Consequently the recoil momentum imparted to the daughter nucleus in nuclear beta decay is related to the angular correlation coefficient a.

Beta-delayed particle decays provide a convenient method of obtaining information on the momentum of the beta-decay daughter, and hence also on the value of the angular correlation coefficient. Beta decay and subsequent particle emission are shown schematically in Fig. 1 where the

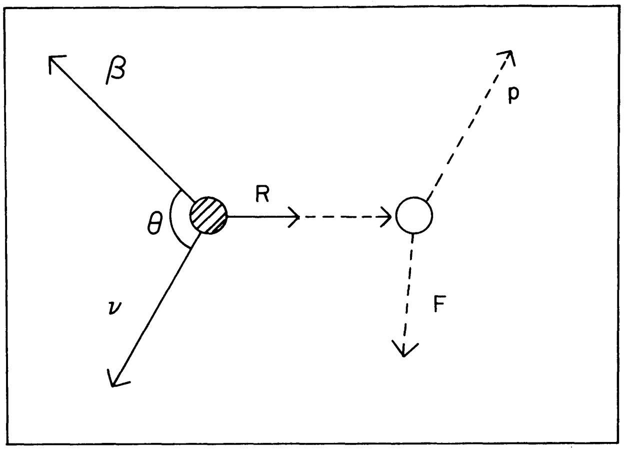

Fig. 1 A schematic representation of beta-delayed particle decay. The velocity of the daughter (R) following beta decay depends on the beta-neutrino angular correlation. In the subsequent particle decay the motion of the beta-decay daughter causes a shift in the energy of the delayed particle (p). The motion of the final nucleus is indicated by F.

beta decay is represented by solid lines and the subsequent particle emission from the daughter nucleus by the dashed lines. If we let $\bar{v}$ be the velocity of the delayed particle in the frame of the daughter nucleus, $\Delta\bar{v}$ the velocity of the daughter, μ the mass of the delayed particle, $\bar{\beta}$ the positron momentum, $\bar{\nu}$ the neutrino momentum and T the kinetic energy of the delayed particle in the laboratory frame, then:

$$T = \tfrac{1}{2}\mu(\bar{v} + \Delta\bar{v})^2 \qquad (3)$$
$$= \tfrac{1}{2}\mu v^2 + \mu\bar{v}\cdot\Delta\bar{v}$$

The first term is equal to the energy of a particle which is emitted from a nucleus at rest. The second term is the kinematic energy shift produced in the lab frame by the daughter's recoil motion. A small third term $1/2\mu(\Delta v)^2$ has been neglected. The kinematic shift is

$$\Delta T = \mu\bar{v}\cdot\Delta\bar{v} \qquad (4)$$

As a consequence of momentum conservation

$$\Delta\bar{v} = -\frac{\bar{\beta} + \bar{\nu}}{M} \qquad (5)$$

where M is the mass of the daughter nucleus. On substitution in (4) the kinematic shift becomes:

$$\Delta T = -kc(\beta\hat{\alpha}\cdot\hat{\beta} + \nu\hat{\alpha}\cdot\hat{\nu}) \qquad (6)$$
$$= -k(\sqrt{E^2 - m^2c^4}\,\hat{\alpha}\cdot\hat{\beta} + (Q + mc^2 - E)\,\hat{\alpha}\cdot\hat{\nu})$$

where $k = \sqrt{2q\frac{\mu(M-\mu)}{M^3c^2}}$ and m is the positron rest mass, Q the beta-decay endpoint energy, E the total beta energy and q the energy available for particle decay of the daughter nucleus. The unit vectors $\hat{\alpha}, \hat{\beta}$ and $\hat{\nu}$ are in the direction of the particle, beta and neutrino momenta, respectively.

Because of the large Q-value usually associated with beta-delayed particle precursors, both leptons can be regarded as relativistic particles in that they obey $E=pc$ to a good approximation. The contributions to the shift from each lepton are therefore approximately equal when they share the decay energy equally; the electron rest mass plays only a small role. The energy shifts expected are of the order of 20 keV for the beta-delayed alpha decay of ^{20}Na.

The energy shift of the delayed particle can be calculated from Eq. 6 for an experiment that has been designed to measure the energy of the delayed particle and the beta particle, and the angle between them. Furthermore, because of the correlation between the beta and the neutrino, the effect of the neutrino can also be observed in such an experiment despite the fact that neither the momentum of the neutrino nor its angle was measured. The probability distribution given in Eq. 1 is used to relate the unobserved factor $\hat{\alpha}\cdot\hat{\nu}$ in Eq. 6 to the observable $\hat{\alpha}\cdot\hat{\beta}$ resulting in the following expression for the energy shift of a delayed particle group averaged over all neutrino angles:

$$\langle\Delta T\rangle = -kc\,\hat{\alpha}\cdot\hat{\beta}\,(\beta + \nu\,\frac{a}{3}\,\frac{v}{c}). \qquad (7)$$

If the angle between the directions of the beta- and delayed-particles has been measured, the effect of the neutrino will manifest itself in two ways: as a broadening of the delayed-particle peak (since the neutrino can be emitted in any direction – although not isotropically); and as a shift of the centroid of the delayed-particle peak, equal in magnitude to the second term in Eq. 7. The second effect is the interesting one in our case since it is directly related to the beta-neutrino angular correlation coefficient a.

In Gamow-Teller decays the leptons carry away angular momentum and therefore align the daughter nucleus. The subsequent emission of delayed particles will then not be isotropic. In general their angular distribution has to be described in terms of a triple correlation[7] involving the positron, the neutrino and the delayed particle. Since the direction of the delayed particle is observed in the present experiment, this triple-correlation coefficient must be taken into account, introducing modifications in our derived expressions above. Only a minor modification is required for Eq. 7: a new coefficient A, the triple-correlation coefficient, replaces a. The new coefficient depends on the sequence of spins in the beta-delayed particle decay, and for the case of $^{20}Na(J^{\pi}=2^{+}) \xrightarrow{\beta} {}^{20}Ne^{*}(2^{+}) \xrightarrow{\alpha} {}^{16}O(0^{+})$ the result is:

$$A = \frac{G_V^2 \langle 1 \rangle^2 - G_A^2 \langle \sigma\tau \rangle^2}{G_V^2 \langle 1 \rangle^2 + G_A^2 \langle \sigma\tau \rangle^2}. \qquad (8)$$

The expected shift, according to the modified Eq. 7, for the 2.148 MeV delayed alpha group from ^{20}Na is shown in Fig. 2

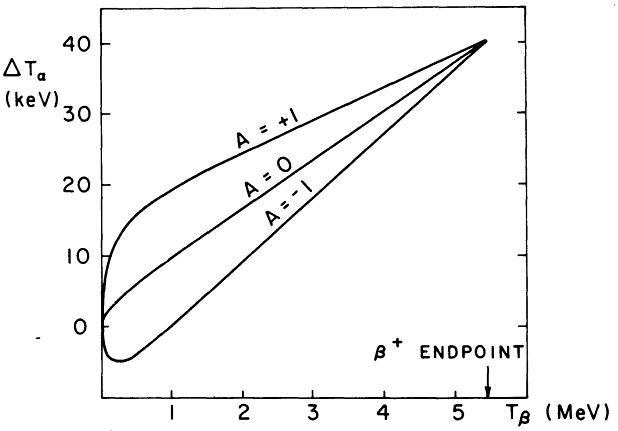

Fig. 2 The kinematic energy shift calculated for the 2.148 MeV delayed-alpha group from ^{20}Na as a function of the energy of the positron. The angle between the directions of the alpha- and the beta-particle is 180°.

for three values of A. The centre curve gives the result for A=0, an isotropic distribution of neutrinos, while the upper (A=1, pure Fermi decay) and lower (A=-1, pure Gamow-Teller decay) curves show the displacements that occur when the neutrino direction is correlated. The general upward trend of all three curves reflects the increasing momentum of the positron. At high beta energy, where the neutrino momentum approaches 0, the three curves merge together. The three curves also converge at low beta energy since the angular correlation is less pronounced as the v/c term in Eq. 1 approaches zero.

3. Experimental details

An accurate measurement of the kinematic shifts occurring in delayed particle decays requires a thin radioactive source in order to obtain good energy resolution The source must also be located precisely in order to determine accurately the angle between the detected particles. The on-line isotope separator [8] at Chalk River proved to be an excellent device for these purposes and, in addition, provided a source free from contaminant activities. The beta-delayed alpha decay of ^{20}Na was selected as a promising case for studies of kinematic shifts. The reaction $^{12}C(^{10}B,2n)^{20}Na$ at 50 MeV incident beam energy was used to produce this activity. The graphite target was situated inside the FEBIAD ion source of the isotope separator. The ion source was operated in the surface ionization mode ensuring a very high selectivity for alkali elements. The mass-20 beam from the isotope separator was directed through a 2 mm diameter collimator and implanted into a 30 μg/cm² carbon catcher foil situated at the centre of an array of detectors (Fig. 3).

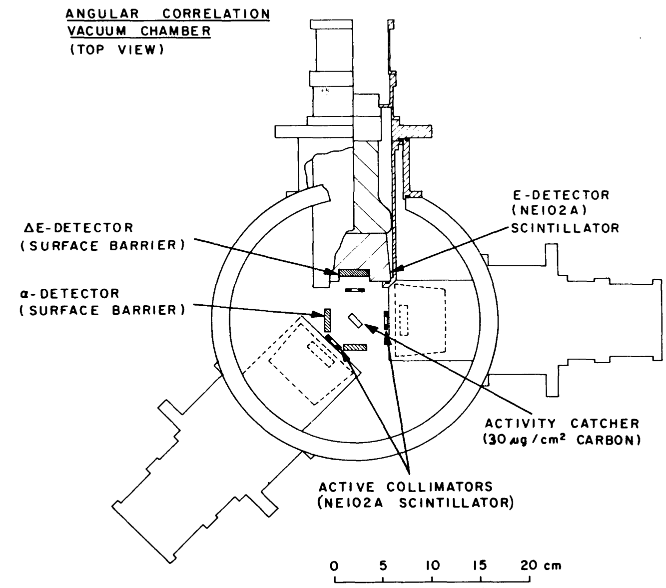

Fig. 3 The detector configuration used for the kinematic-shift measurements. Each of the two alpha detectors was operated in coincidence with any of the three beta detectors giving a total of six different detector combinations. The beam from the isotope separator enters the chamber normal to the plane of the drawing and is collected on the carbon foil, which is at an angle of 30° with respect to the same plane.

Subsequent beta-delayed alpha decays were observed with two alpha detectors and three beta detectors. The geometry allowed coincident alpha-beta events to be detected at three angles, 45°, 90° and 180°, from six different detector combinations.

The alpha-particles were observed with 100-μm-thick silicon surface-barrier detectors, each subtending a solid angle of 1.8% of 4π sr. Counter telescopes were used for all three beta detectors in order to discriminate against the detection of γ-rays. The rear detector in each telescope consisted of a cylindrical plastic scintillator (NE102A, diameter 7.6 cm, thickness 5.1 cm) coupled to an RCA-4900 photomultiplier. The scintillator had a cylindrical well (diameter 3.2 cm, depth 1.2 cm) located on the front face which contained the ΔE detector, a 700 μm totally-depleted surface-barrier detector. Each counter telescope subtended a solid angle of 0.4% of 4π sr.

One of the major problems associated

with experiments involving the detection of beta-particles is multiple scattering. Some of the precautions taken in this experiment in order to avoid problems of this type were:

i) low-Z material was used everywhere possible;

ii) a minimum amount of structural material was used in the experimental chamber, particularly in the vicinity of the radioactive source;

iii) active collimators were used in front of the beta detectors.

The active collimators consisted of thin (3 mm) plastic-scintillator discs, each with a circular opening of 8 mm diameter. They defined the entrance aperture of the beta detectors and were operated in anticoincidence with the beta telescopes.

The energy calibrations of the beta detectors were performed with the alpha-coincident beta spectra obtained during the experiment. The endpoint energies of the beta-transitions in question are known to good precision[9]. In order to obtain a calibration to the accuracy of 1%, the response functions of the beta telescopes have to be known in detail. The response function of each telescope was determined in a set of experiments utilizing mono-energetic beams of electrons and positrons from the Chalk River iron-free $\pi\sqrt{2}$ spectrometer[10]. Using various radioactive sources, the energy range of 0.5 - 3.5 MeV was covered at selected incident angles. The experimentally-determined response functions were parameterized as a function of beta-particle energy. The parameterized response functions were used for both the energy calibration and as a correction (see below) in the kinematic energy shift.

The α-detectors were calibrated using the 90° coincidence data and the known energies[11] of beta-delayed alpha particles from ^{20}Na decay.

4. Results

A decay scheme of ^{20}Na is shown in Fig. 4. The analogue state in ^{20}Ne (labelled T=1) has previously been identified by the superallowed character of the beta transition populating this state. One would therefore expect this transition to account for a major part, if not all, of the Fermi strength. Because of possible isospin impurities in states close to the analogue state some part of the Fermi strength might be found in the beta-transitions populating these neighbouring states. Indeed Macfarlane[12] has, in an experiment based on the analysis of the singles line shapes of delayed alpha groups from ^{20}Na, reported significant Fermi components in these beta-transitions.

A spectrum, observed in the present experiment, of beta-coincident alphas from ^{20}Na is shown in the lower part of Fig. 5. Six of

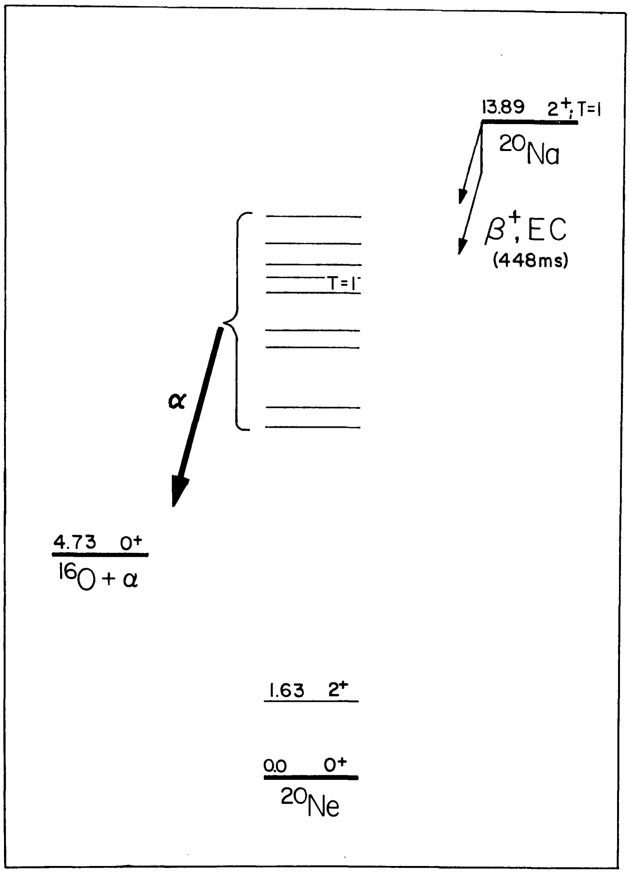

Fig. 4 A partial decay scheme of ^{20}Na. The delayed particle emitting states in ^{20}Ne are all 2^+. The analogue of the ^{20}Na ground state is indicated by T=1.

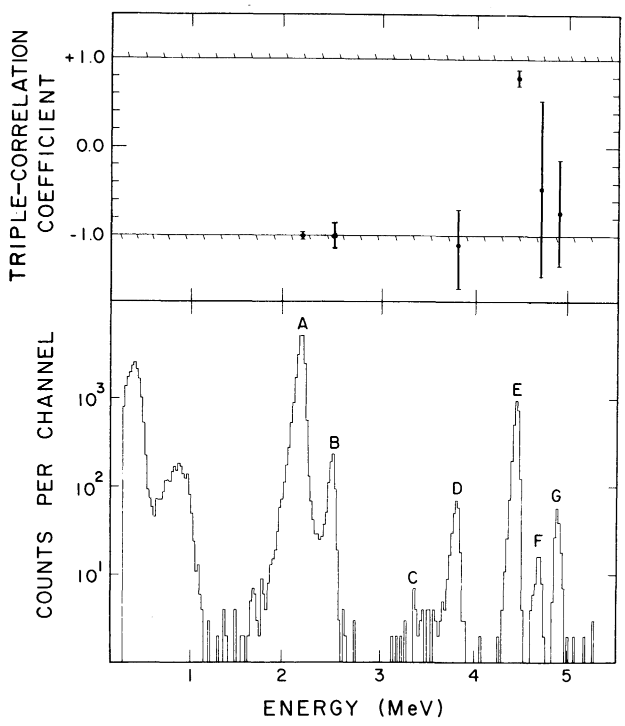

Fig. 5 A spectrum of delayed-alpha particles from ^{20}Na obtained in coincidence with betas is shown in the

lower part of this figure. The upper part of the figure shows the triple-correlation coefficients deduced for the alpha groups seen in the spectrum. For each transition the coefficient is plotted directly above the corresponding alpha peak. The hatched regions delineate the end of the allowed range of A.

the alpha groups seen in this spectrum were intense enough that their kinematic shifts could be determined. The energy shifts of these alpha groups were evaluated as a function of beta energy. As a sample of our data the results for one out of a total of seven runs are shown in Fig. 6,

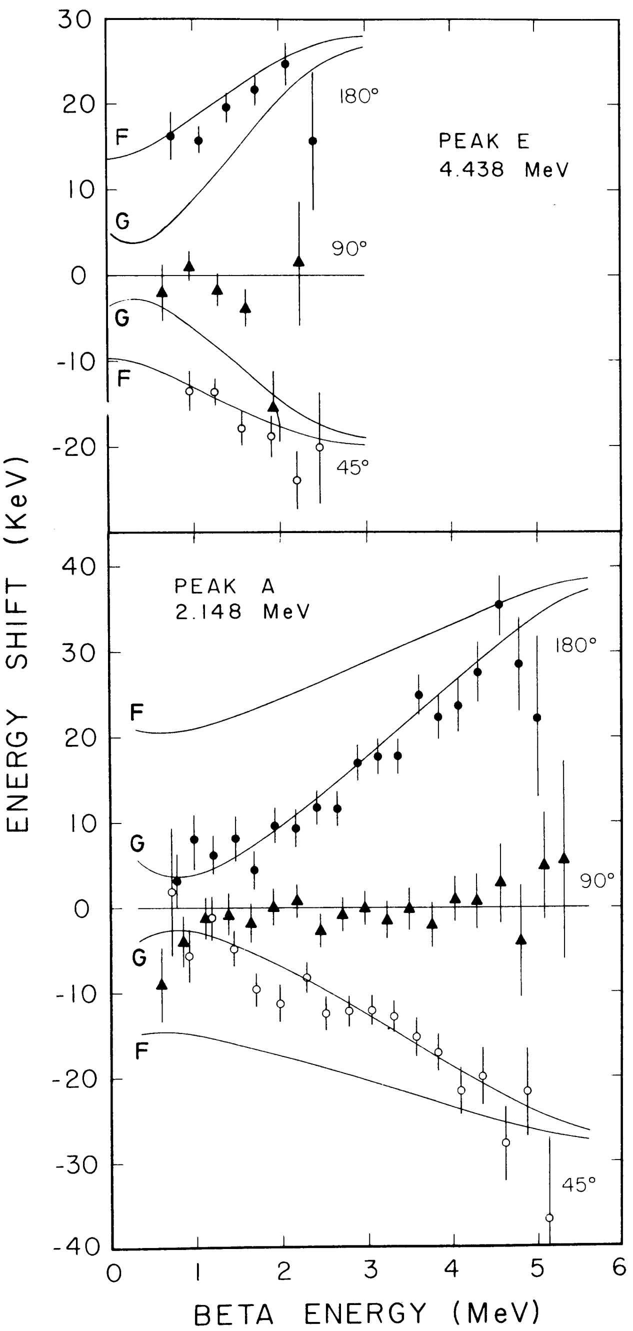

Fig. 6 The kinematic shifts of two alpha groups from ^{20}Na plotted against the energy of the beta particle.

The 90^{O} data were used to establish the zero on the vertical energy scale of the alpha group under investigation. The curves (corrected for the beta-detector response function) show the results of calculations using the extreme values allowed for the triple-correlation coefficient, A. F indicates A=1 (Fermi) and G indicates A=-1 (Gamow-Teller).

where the lower part of the figure represents the data obtained for the most intense transition, and the upper part represents the data for the transition to the analogue state. Data are presented for three angles - 45^{O}, 90^{O} and 180^{O}. The 90^{O} data show the unshifted α-particle energies. The solid curves are similar to those shown in Fig. 2 but corrections have been added to take into account the response function of the β-detectors. The functions describing the curves were fitted to the data points with A being the only free parameter. The values of A deduced from the fits for six beta transitions are listed in Table 1 and are also shown in the upper part of Fig. 5.

The values of A listed in Table 1 are consistent with five transitions being pure Gamow-Teller decays and the transition to the analogue state (Peak E) being mainly of the Fermi type.

The separation of the two components (Fermi and Gamow-Teller) of a mixed decay is achieved by combining Eq. 8 with the measured ft-value, the latter quantity being related to the matrix element by[2)]

$$ft = \frac{K}{G_V^2 \langle 1 \rangle^2 + G_A^2 \langle \sigma\tau \rangle^2}$$

where

$$K = \frac{2\pi^3 \ln 2\, \hbar^7 c^6}{(mc^2)^5}.$$

For those states that are predominantly T=0, the Fermi components have been used to deduce limits on isospin impurities. The mixing amplitudes and matrix elements for these states are given in Table 1. For the transition to the analogue state, the Gamow-Teller component was determined to be $G_A\langle\sigma\tau\rangle = (6.0^{+1.3}_{-2.0})\cdot 10^{-50}$ erg cm^3. The Fermi component can be used to deduce a value of G_V, the vector weak coupling constant, if the radiative (δ_R) and charge dependent (δ_C) corrections are taken from reference [2)]. With this assumption, $G_V = (1.355 \pm 0.036)\cdot 10^{-49}$ erg cm^3. This is the first measurement of this quantity from non $0^+ \to 0^+$ transitions between T=1 states. The result is not statistically in disagreement with the accepted value of $G_V = 1.413\cdot 10^{-49}$ erg cm^3. However, it is possible that there may be, in fact, additional isospin impurities in the analogue state beyond those described by δ_C[2)]. If we use the accepted value of G_V, we deduce that the T=1 intensity in this state is 0.91±0.05.

TABLE 1

Peak	$E_x(^{20}Ne)$ (keV)	ft†	A	mixing intensity α^2††	V_C(keV)†††
A	7416	$(1.596 \pm .026) \times 10^4$	$-.999 \pm .031$	$\leq 3.0 \times 10^{-3}$	≤ 156
B	7828	$(3.036 \pm .056) \times 10^5$	$-1.00 \pm .14$	$\leq 7.0 \times 10^{-4}$	≤ 65
D	9483	$(1.190 \pm .032) \times 10^5$	$-1.10 \pm .41$	$\leq 4.0 \times 10^{-3}$	≤ 50
E	10275	$(2.992 \pm .060) \times 10^3$	$+ .79 \pm .09$		
F	10586	$(5.62 \pm .22) \times 10^4$	$- .46 \pm 1.0$	$\leq 4.2 \times 10^{-2}$	≤ 64
G	10850	$(1.668 \pm .067) \times 10^4$	$- .74 \pm .60$	$\leq 7.8 \times 10^{-2}$	≤ 161

†Reference [13])

††Assuming two-state isospin mixing formalism

†††Coulomb matrix elements

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DISCUSSION

D.E. Murnick: Are your experiments at all sensitive to a finite mass for the neutrino?

E.T.H. Clifford: The most recent value measured for the neutrino mass is near 35 eV and this is orders of magnitude below the sensitivity of our experiment.

A. Gelberg: What is the influence of the measured ft on G_V and the Cabibbo angle?

E.T.H. Clifford: The errors on our measurement of the ft-value are too large for us to draw any conclusion about the Cabibbo angle.

K. Eskola: Decay of ^{20}Na is a good case to look at β-ν angular correlations because of large kinematic shifts. Have you found other as favourable cases in charded delayed-particle emitters for further studies?

E.T.H. Clifford: Yes. We wish to extend this work to the case of delayed-proton emitters. At present we are studying the decay of the delayed-proton emitter ^{25}Si.