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The weak positron transition in the decay of ^{30}P

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Abstract. The weak positron branch in the decay of ^{30}P has been detected by using both gas flow and pneumatic transfer techniques in conjunction with a Ge(Li) detector. The log ft value for the transition to the first excited state of ^{30}Si has been found to be $(5{\cdot}66 \pm 0{\cdot}04)$, at variance with the previous experimental value and considerably different from the value calculated by Engelbertink and Brussaard. It has been shown that an increase in the $d_{3/2}$ mixing in the ^{30}P and ^{30}Si nuclear states is required to explain this result.

1. Introduction

Figure 1 shows the first few excited states of ^{30}Si in relation to the ground state of ^{30}P (Endt and Van Der Leun 1967). It can be seen from energy considerations that it is possible for ^{30}P to decay by β^+ emission to the ground and first excited states only of ^{30}Si. These decays are both allowed Gamow–Teller (GT) decays. The intensity of the transition to the excited state was expected to be about 0·6 % of that to the ground state.

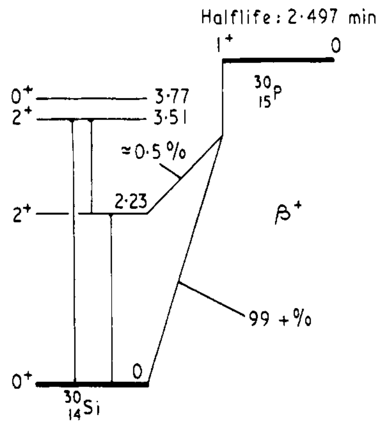

Figure 1. The decay scheme of ^{30}P to ^{30}Si.

In the calculation of this ratio the nuclear matrix elements for the two relevant states in ^{30}Si were assumed to be equal, the positron end-point energy was taken to be $3205{\cdot}4 \pm 2{\cdot}6$ keV (Wapstra and Gove 1971) and the halflife of ^{30}P as $2{\cdot}497 \pm 0{\cdot}005$ min (McDonald *et al* 1963); the Fermi functions used were calculated from tables due to

Behrens and Jänecke (1969). The corresponding log *ft* value for each transition was found to be 4·84. In support of this result a weak positron transition to the first excited state of ^{30}Si has been reported by Morinaga and Bleuler (1956). These authors estimated the ratio of this transition to be 0·5% using a NaI scintillation spectrometer. However, examination of the decay scheme of ^{30}P by the present authors during a previous experiment (Ledingham *et al* 1971) showed that the gamma ray following the weak β^+ transition was much less intense than the above discussion would indicate. Theoretical calculations of the log *ft* values of a number of beta transitions, including those of ^{30}P, have been made by Engelbertink and Brussaard (1966) using nuclear wavefunctions derived from shell-model calculations of Glaudemans *et al* (1964) and are given as 4·05 and 3·86 for the ground and excited states respectively. Thus the comparative halflife to the excited state appears to be smaller than that to the ground state, contrary to the above discussion. In order to compare the theory and experiment more accurately a measurement of the relative intensity of the excited state transition was performed using a Ge(Li) spectrometer to detect the decay gamma rays.

2. Experimental technique

The ^{30}P used in this experiment was prepared by irradiating 99·5% pure phosphine, PH_3, with the bremsstrahlung radiation from the 100 MeV electron beam of the Glasgow linear accelerator. The gas-flow technique used has been described in detail elsewhere (Ledingham *et al* 1971). The phosphine, after irradiation, flowed through polythene tubing wound in concentric layers around the aluminium can of a 30 cc Ge(Li) detector. This source–detector arrangement enabled the maximum count rate to be obtained for a given beam current. The electronic arrangement consisted simply of an amplifier followed by a baseline restorer and a 1024 channel pulse-height analyser. A scaler was used to monitor the total count rate since the amplifier gain was sensitive to this. Ten irradiations, each of one hour's duration, were made with an analyser counting rate of about 25 000 counts per minute. The sum of the ten spectra is shown in figure 2 and the relevant data appear in table 1 under the heading run A. Subsequent phosphine irradiations provided the data listed in table 1 as run B.

The gain of the system was checked after each irradiation by using calibration sources of ^{22}Na, ^{60}Co and ^{88}Y and was found to be constant to within half a channel for each of the calibration peaks over the total experimental time. The gamma rays of ^{40}K and ^{208}Tl appearing in figure 2 are due to the natural occurrence of ^{40}K in concrete and ^{232}Th in lead. A peak at 1022 keV is due to the simultaneous absorption of two 511 keV β^+ annihilation gamma rays. The energies of the two remaining peaks were found to be (680 ± 3) keV and (2230 ± 3) keV. A background run of the same duration as the total source run was made under the same experimental conditions, and is also shown in figure 2. It can be seen that there is no evidence for a gamma ray at either 680 keV or 2230 keV in this spectrum. From a previous halflife measurement (Ledingham *et al* 1971) competing activities produced in these irradiations were found to be less than 1%.

The intensity of the 2230 keV gamma ray was too small for a halflife measurement to be made, but it was felt that its identification with the first excited state of ^{30}Si could be made with reasonable confidence, since the production of any other isotope in this region of the periodic table would require the presence of other gamma rays of comparable intensity. The gamma ray at 680 keV has not as yet been identified.

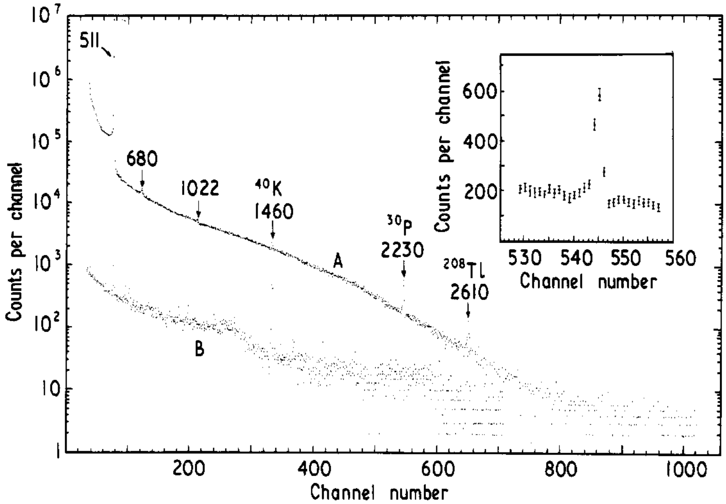

Figure 2. The spectrum obtained from the positron decay of ^{30}P using a 30 cc Ge(Li) detector. The inset shows the region around channel 545 (2·23 MeV) using a linear scale. A is the source run while B shows the background in the same time. Peak energies are marked in units of keV.

3. Efficiency calibration of Ge(Li) detector

Since the photopeak efficiency of a Ge(Li) detector is a rapidly varying function of energy, it was essential to calibrate the detector in the region of interest (ie between 511 and 2230 keV). Unfortunately the possibility that the relative efficiency depends on the source–detector geometry could not be ruled out. Thus it was decided to flow a calibration source in the same manner as the phosphine was flowed. ^{34m}Cl was found to be one of the most suitable positron emitting nuclei with a de-excitation gamma ray of an energy close to 2230 keV. This source can easily be made using methyl chloride CH_3Cl.

The decay scheme of this isotope is given by Endt and Van Der Leun (1967). The isotope ^{34m}Cl was prepared by the (γ, n) reaction on ^{35}Cl, under the same experimental conditions as the phosphine irradiations. The irradiated gas was expected to contain ^{11}C from the (γ, n) reaction on the natural carbon in CH_3Cl. Hence a halflife measurement of the irradiated gas was made in order to determine the fraction of positrons due to ^{34m}Cl. The window of a single channel analyser was set to encompass the positron annihilation peak and the output recorded on a 100 channel multiscaler. A least-square fit to the resultant data using both the minimization computer programs Minuit (CERN Program Library D504, see also Rosenbrock 1960) and VA04A (Powell 1964) showed that within statistical errors the positrons arose entirely from ^{34m}Cl and ^{11}C. The ratio of ^{34m}Cl to ^{11}C was found to be ($0{\cdot}223 \pm 0{\cdot}011$). From this result, the ^{34m}Cl spectrum, and the quoted decay scheme of ^{34m}Cl, five points were obtained on the energy against relative efficiency graph shown in figure 3. The remaining ten points on the graph were obtained using point calibration sources of ^{22}Na and ^{56}Co which were placed on the axis of the detector about 1 cm from the detector can. The latter measurement was made in order to detect the effect, if any, of the difference in geometries on the relative efficiency. A least-squares fit of the analytic expression

$$\lg \epsilon = a + b \lg E + c(\lg E)^2$$

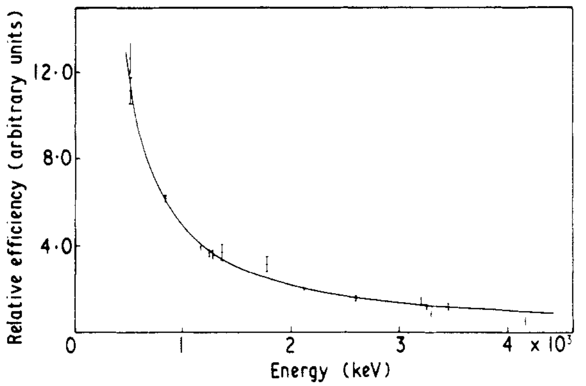

Figure 3. The relative efficiency of the 30 cc Ge(Li) detector as a function of energy. ⧫ refer to gamma rays from the ^{22}Na and ^{56}Co sources; ⧫ refer to gamma rays from ^{34m}Cl.

was made to the point source calibration using the program VA04A (Powell 1964) where ϵ and E are the relative efficiency and gamma ray energy respectively. The parameters a, b and c were varied to obtain the best fit to the points. This analytic expression is given by Barker and Connor (1967) who also give the relative intensities of the gamma rays following the decay of ^{56}Co. The points due to ^{34m}Cl were normalized so that the relative efficiencies given by both graphs were equal to 2·13 MeV. The error bars on the graph are representative of the errors incurred in measuring the areas under the photopeaks and the uncertainties in the decay-scheme intensities. It can be seen that below about 2·5 MeV the two sets of measurements agree rather closely, showing in fact that geometry differences are small in this region. The ratio of the relative efficiencies was thus taken as the ratio of the experimental point, due to ^{34m}Cl, at 511 keV and the value of the analytic expression at 2230 keV. This ratio was found to be $(6{\cdot}74 \pm 0{\cdot}47)$. The analysis of the data described in this section was carried out on the PDP-10 computer of the Kelvin Laboratory.

In order to check that no large systematic errors were being introduced in the gas-flow technique it was decided to irradiate solid phosphorus using a fast pneumatic-transfer system. A number of samples, each weighing about 1 g, of 99·999 % pure red phosphorus were irradiated and subsequently analysed using the Ge(Li) detector. The radioactive phosphorus was completely surrounded by about 1 cm of aluminium in order to cause the positrons to annihilate near the source, and thus approximate point-source geometry. From the resulting pulse-height spectrum (run C) the ratio of the relevant gamma rays was found to agree, within experimental errors, with those from the gas-flow runs.

Table 1

Run	Number of 2·23 MeV γ rays	Number of 0·511 MeV γ rays	Ratio of $\gamma_{2\cdot 23}/\beta^+$
A phosphine	870 ± 63	$1{\cdot}24 \times 10^7$	$(1{\cdot}40 \pm 0{\cdot}11) \times 10^{-4}$
B phosphine	1320 ± 100	$2{\cdot}13 \times 10^7$	$(1{\cdot}24 \pm 0{\cdot}09) \times 10^{-4}$
C solid phosphorus	510 ± 60	$0{\cdot}82 \times 10^7$	$(1{\cdot}24 \pm 0{\cdot}15) \times 10^{-4}$
weighted mean of A, B, C			$(1{\cdot}29 \pm 0{\cdot}6) \times 10^{-4}$

The errors quoted in table 1 are purely statistical. The systematic errors incurred in the measurements are given as follows: (i) separation of the continuum from the peaks (3% for each peak); (ii) uncertainties in the differential absorption of the gamma rays in the material surrounding the detector (3%).

The weighted mean given in table 1 together with the previously quoted efficiency thus gives a value of $(8{\cdot}7 \pm 0{\cdot}9) \times 10^{-4}$ for the ratio of the two positron branches, assuming that the number of 2·23 MeV gamma rays arising from possible electron capture decays from ^{30}P to the second and third excited states of ^{30}Si is negligible.

4. Discussion of results

The work of the present authors yields a result for the intensity of the weak positron transition in ^{30}P which is a factor of about six less than that estimated by Morinaga and Bleuler.

The log *ft* value for the transition, from the present result, was found to be $(5{\cdot}66 \pm 0{\cdot}04)$ using the data given in the introduction. It is stated by Engelbertink and Brussaard (1966) that the log *ft* value of 4·05 for the ground state transition is reasonably close to the experimental value of 4·84 for the particular wavefunctions used. However, there is a large discrepancy between the value of 3·86 and the value of 5·66 derived from the experimental results given in this communication.

The wavefunctions obtained for ^{30}P and ^{30}Si by Glaudemans *et al* (1964) were calculated assuming an inert core of fourteen protons and fourteen neutrons with the remaining two particles existing in combinations of the $2s_{1/2}$ and $1d_{3/2}$ shells. If we assume that this description is valid, we can use the present result to obtain a qualitative estimate of the relative s and d shell amplitudes in the ^{30}P and ^{30}Si states involved. We can express the theoretical value of *ft* (Engelbertink and Brussaard 1966) as

$$(ft)_{\text{theor}} = \frac{4381}{M_{\text{GT}}^2}$$

where C_A/C_V has been taken as $(-1{\cdot}18 \pm 0{\cdot}05)$ and the Fermi matrix element has been set equal to zero. The matrix element M_{GT}^2 can be written as

$$M_{\text{GT}}^2 = \langle\sigma\rangle^2$$

where σ is the Pauli spin operator.

The three relevant nuclear states, that is, the ground state of ^{30}P and the ground and first excited states of ^{30}Si can be written in terms of seven parameters representing the combinations of $2s_{1/2}$ and $1d_{3/2}$ wavefunctions; for instance, for the ^{30}P ground state we have

$$A(s_{1/2}^2) + B(s_{1/2}d_{3/2}) + C(d_{3/2}^2)$$

where the particles are coupled to give $J = 1^+$. A, for example, represents the probability that both extra-core nucleons will be found in the $2s_{1/2}$ shell.

For each of the two β decay transitions we can thus establish a relationship between the coefficients A, B, C, D, E, F, and G. These two relations, along with the normalization conditions $A^2 + B^2 + C^2 = 1$, etc, give five constraints among the seven parameters.

A further relationship was derived by Dr A Watt of the University of Glasgow by using the known electromagnetic transition rate from the 2^+ to the 0^+ state in ^{30}Si.

This gives us six relations among the seven parameters and is thus not enough to determine them uniquely. However, the expression for the transition rate can only be satisfied within experimental errors at its maximum value. In this case we have effectively the same number of constraints as parameters. A further complication arises in that the quantity $\langle\sigma\rangle$ is used in two of the relations, whereas it is the square of this value which is determined experimentally, that is, $\langle\sigma\rangle$ is ambiguous to within a sign. Although the solution of the relationships is not unique, the number of solutions is small. All of the solutions point to the amount of $d_{3/2}$ mixing in each of the states being increased over that given by Glaudemans *et al* (1964)—a factor of about six in the case of the ground state of ^{30}P.

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Note added in proof. The 680 keV peak (see the last sentence in § 2 of this paper) is thought to be due to the detector simultaneously absorbing an annihilation quantum and the 170 keV radiation due to the backscattering of a similar quantum. A similar effect has been noted in NaI(Tl) detectors (Van Lieshout R *et al* 1965 *Alpha, Beta and Gamma Ray Spectroscopy* vol 1 ed K Siegbahn p 501).

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