Excitation energy of the 1.74 MeV state in ^{10}B

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The energy of the 1022 keV gamma ray which follows the positron decay of ^{10}C has been measured to be 1021.646±0.014 keV. This is a necessary step in an accurate determination of the ft value of the pure Fermi component of the decay.

In the positron decay of ^{10}C, the $0^+ \rightarrow 0^+$ component of the decay is one of those nuclear beta transitions between members of an isotopic triplet, whose ft values allow a test of the conserved vector current theory and the direct extraction of the vector weak interaction coupling constant G_v. Indeed, as has been emphasized by Marciano and Sirlin,[1] the case of ^{10}C has a particular interest, since one of the areas of theoretical uncertainty lies in the calculation of the Z-dependent radiative corrections to the ft values, and presumably these effects should be smallest for the nuclei of smallest atomic number.

Unfortunately there is a special difficulty associated with the determination of the ^{10}C superallowed ft value. The three parameters which need to be determined experimentally are the decay energy, the total half-life, and the branching ratio. This last is quite small, 1.465 ±0.014%,[2] and its 1% associated error has effectively precluded the use of the ft value for the determination of G_v and has meant that there has been little direct need for very accurate measurements of the other two quantities. Recently, however, progress has been made in establishing the branching ratio at the 0.2% level,[3] and so here we describe a step in the chain which will ultimately provide a sufficiently accurate value for the beta transition energy that its quoted error will not impinge on the final quoted error for the ft value.

In the evaluation of the ft value, f is an integral over the positron energy up to the maximum Q_β, and is approximately proportional to Q_β.[4] Hence to determine f to, for example 0.05%, Q_β must be determined to better than 0.01%, i.e., to 90 eV. In principle, the energy of the positrons could be measured directly, but in practice Q_β is most easily obtained from a knowledge of the excitation energy of the 1.74 MeV state of ^{10}B together with the Q_{pn} value of the associated reaction $^{10}\mathrm{B}+p \rightarrow {}^{10}\mathrm{C}+n$. In fact,

$$Q_\beta = -Q_{pn} - [n - {}^1\mathrm{H} + 2m_e]c^2 - E_{1.74}$$

where the symbols in brackets are the masses of the neutron, hydrogen atom, and electron, respectively, all three of which introduce negligible errors into Q_β. At present, the most precise value of Q_{pn} is given as -4430.17 ± 0.34 keV,[4] but a recently completed series of measurements has improved this and certainly reduces the error to the order of 100 eV.[5]

The 1.74 MeV state deexcites to the ground state with the emission of two successive gamma rays whose energies are currently quoted as 718.32 ± 0.04 keV and 1021.78 ± 0.14 keV,[6] giving a total excitation energy of 1740.18 ± 0.15 keV, where account as been taken of recoil energy losses. The aim of the present work is to reduce the uncertainty in the energy of the 1022 keV gamma ray, and hence of the 1.74 MeV state, as much as possible.

The 1.74 MeV state of ^{10}B was prepared by creating ^{10}C via the $^{10}\mathrm{B}(p,n)^{10}\mathrm{C}$ reaction. Of the ^{10}C decays, 1.5% proceed through this state, and although this small branching ratio means that far more gamma rays of 511 and 718 keV are produced than of 1022 keV, since these are at lower energy they do not unduly affect the measurements.

A very convenient method of determining the energy of the 1022 keV gamma ray is the mixed source technique, using in this case ^{56}Co as the calibration source. The ^{56}Co is easily made using the $^{56}\mathrm{Fe}(p,n)$ reaction on an iron foil; it has a half-life of 77 days, and it emits intense gamma rays in the range 850–3500 keV. The energies of many of these lines are quoted with uncertainties smaller than 10 eV.[7] In particular, there is a transition at 1038 keV which is a highly appropriate energy reference.

In a typical experiment a 100 nA beam of 6.8 MeV protons from the AURAII tandem accelerator struck a target of $\approx 100\ \mu\mathrm{g/cm}^2$, 99.5% pure ^{10}B which had been evaporated onto a 0.025 mm thick substrate of 99.999% pure gold. After a 20 s bombardment period, the beam was switched off 5 m upstream, the target lowered 40 cm using a magnetically coupled compressed air plunger, and, after a 2 s delay, the gamma rays emitted from the target were examined for 20 s using a 20% Ge(Li) detector, 70 mm away. The activated spot on the target, 3 mm in diameter, lay on the axis of the cylindrical detector. The target was then raised up to the beam axis again, and the whole cycle repeated about 100 times.

The ^{56}Co source, which had been made several days earlier in the same target chamber, had a similar diameter to the ^{10}C activated spot, and was also on the axis of the detector, 11 mm further away than the ^{10}C. The pulses from the detector were amplified and shaped in an ORTEC 572 main amplifier with 2 μs time constant, and were then digitized in 8192 channels in an NS643 ADC and stored in an HP1000 computer. Typical peak shapes for the 847 keV and 1238 keV lines from ^{56}Co, taken during a run, are shown in Figs. 1 and 2. These are the two lines whose positions essentially give the spectrum dispersion, in keV/channel in the region of the 1022–1038 keV doublet. The full widths at half maximum of the peaks are 1.63 and 1.83 keV, respectively. The 1022–1038 keV doublet from the same run is shown in Fig. 3. The small peak at 1229 keV in Fig. 2 is from the true coincidence summing of 511 and 718 keV gamma rays.

There were 14 runs made, giving spectra quite similar to the one whose extracts are shown in the figures. The total initial count rates to the ADC were from 1100/s to 3500/s, and the target-detector distance was varied from 45 to 70 mm. Eight of the runs had the cycling times given above and the other six substantially shorter times, for reasons to be discussed later.

The procedure used for establishing the position of a peak was as follows. Firstly the background was subtracted by fitting the contents of approximately 50 channels on either side of the peak to a polynomial function of channel number (normally a quadratic) and interpolating the resulting curve inwards under the peak. Then a Gaussian function was fitted to all those channel contents in the resulting peak which lay above the half maximum height. The center of this Gaussian was then taken to be the position of the peak.

Even an isolated full energy gamma ray peak displays a marked asymmetry in the background on either side of it, the lower energy part of which is due to multiple processes caused by the same gamma ray. Hence arguments might be advanced that the true background is better approximated by fitting channel contents only at higher energy than the peak, and extrapolating the curve back under the peak. This method was applied as an alternative approach to the analysis of the peaks in all the runs, and changed the final extracted energy of the 1022 keV peak by less than 1 eV.

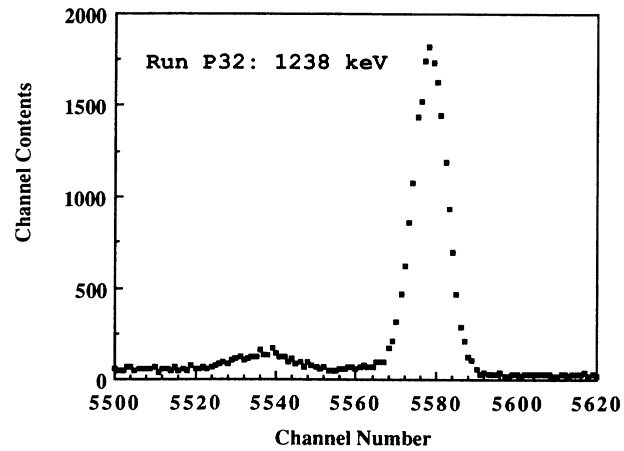

FIG. 2. The 1238 keV gamma ray from run P32.

The extremely small difference in the results obtained using the two background subtraction techniques may be due in part to the fact that the dispersion of the spectrum is obtained from the 847 and 1238 keV peaks, which are both large and sit on an asymmetric background, and for which the effects of the differing background analyses are liable to be very similar. The 1022 and 1038 keV peaks, on the other hand, are both quite small, sitting on a large background, and their treatments are largely unaffected by the difference in the analyses.

For a run, such as the one represented in the figures, using the energies of the ^{56}Co lines taken from Ref. 7, and in particular those of 846.764(6) keV, 1037.844(4) keV, and 1238.287(6) keV (where the figure in brackets represents a one standard deviation error in the last digit), the dispersion in the region of the 1022–1038 keV doublet was calculated as a straight line fit between the two outer points, giving in this case 0.222943(10) keV/channel. If a higher-order polynomial fit was made to the energy calibration curve, using the other intense lines of ^{56}Co, the dispersion in the 1 MeV region was unchanged. Then, with the positions of the 1022 and 1038 keV peaks at channels 4606.91(15) and 4679.52(9), respec-

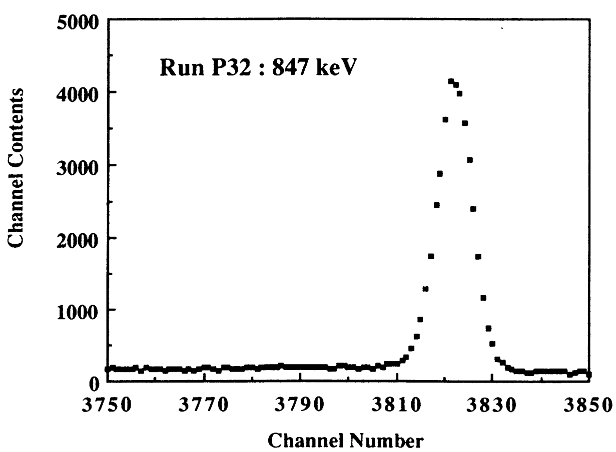

FIG. 1. The 847 keV gamma ray from run P32.

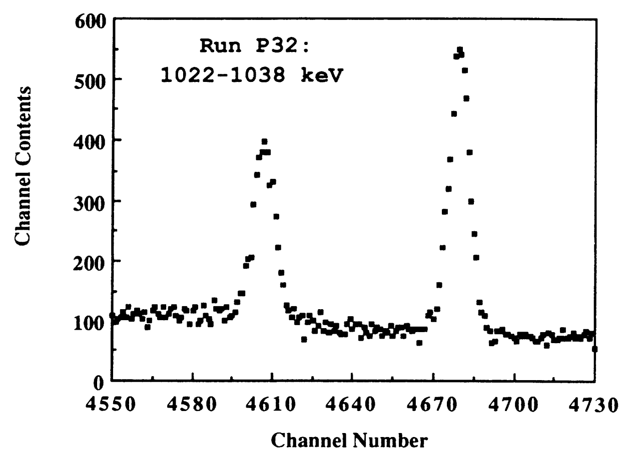

FIG. 3. The 1022 keV–1038 keV doublet from run P32.

tively, the energy difference between the two peaks becomes 16.187(39) keV, and the energy of the gamma ray itself 1021.656(39) keV.

Because each of the 14 runs was performed under slightly different conditions, the errors on the energy difference from each ranged from 37 to 48 eV, with one at 68 eV. The set overall gave a value of 16.195(12) keV with a normalized X^2 of 0.66.

Warburton and Alburger[8] have discussed problems which arise when studying gamma rays which follow short half-life beta decays. They are basically the possible count rate dependence of the system amplification, and Doppler effects brought about by the nucleus recoiling after the beta decay.

Normally in a mixed source energy measurement, such as the one described here, errors introduced by a count rate dependence of the gain of the detector and electronics are avoided by counting the calibration source and the source being studied simultaneously. However, when the latter decays appreciably over the time that the data are being accumulated, an error is introduced.

This effect was investigated in the following way. The first eight runs were performed as described above, essentially with irradiate and count times of 20 s each. The last six runs had these cycle times reduced to 5 s. Since the half-life of ^{10}C is 19 s, a difference in the gamma ray energies extracted from the two sets would point to the magnitude of the error. The means of the two sets were $E_8=16.197(14)$ keV and $E_6=16.191(19)$ keV, respectively. As the detection system gain increases with increasing count rate, the longer cycling runs would be expected to give a smaller energy difference than those for shorter cycling, i.e., E_8 would be less than E_6. There is no evidence for this in the results quoted above, and the corresponding correction has been set somewhat arbitrarily at 0 ± 5 eV.

In the example chosen in Ref. 8 to illustrate the effect of the Doppler shift induced by recoil following beta decay, that of ^{11}Be, the beta maximum energy was 9.4 MeV, the gamma energy 2.12 MeV, the lifetime of the gamma emitting state 5 fs, and the main beta-gamma spin sequence $\frac{1}{2}^+-\frac{1}{2}^--\frac{3}{2}^-$. In the present case these quantities are 0.9 MeV, 1.0 MeV, 4 fs, and $0^+-0^+-1^+$. In addition, since the ^{10}C was prepared using 6.8 MeV protons, the nuclei all recoil within $\pm35°$ and come to rest sufficiently far into the gold backing that when the gammas following the beta decay are emitted, the ^{10}B are all recoiling within the gold. As a consequence, the effect on the detected 1022 keV line shape is a slight broadening which is symmetric about the original position. With a maximum beta energy of 0.9 MeV, the extent of the broadening is within ±100 eV, which is negligible. In fact, in Fig. 3 the FWHM of the 1.022 MeV peak is 1.68 keV compared to 1.63 keV for the 1.038 MeV peak, but in the other runs it was not always greater.

When 1022 keV gamma rays are detected in the presence of positron decays, the resulting peak in the Ge(Li) spectrum must have a component from the pileup of accidentally coincident annihilation radiation. To estimate this in the present case, spectra from a strong source of ^{137}Cs, emitting gamma rays at a single energy, 662 keV, were accumulated in various conditions similar to those under which the ^{10}C has been studied. Each of these spectra contains a strong 662 keV peak and a weak 2×662 keV pileup peak. The relative contents of these peaks, together with the 662 keV full energy counting rate, were used to estimate the size of the 2×511 keV contribution to the 1022 keV peak in the ^{10}C runs. The largest contribution in any run was 2.0%. Then, artificial data were created which consisted of the sum of two Gaussian peaks, of FWHM 1.7 keV and 350 eV apart, whose relative amplitudes were varied from 1% to 20%, and these data sets were analyzed in terms of a single peak as outlined above for the real data. Pileup at the level of 2% gave an extracted energy which was too high by 5 eV. Accordingly, the final 1022 keV peak energy has been reduced by 3 ± 3 eV.

As a test of the experimental procedure, and of most parts of the data analysis, the energy of the 1.064 MeV gamma rays emitted from a source of ^{207}Bi was measured. Four runs were taken with variations in detector-source geometry and count rates which were similar to those of the ^{10}C runs, the main difference being that, since the ^{207}Bi source was rather strong, it was always 21 mm further away from the detector than was the ^{56}Co, in order to allow the interposing of 20 mm of lead between it and the detector.

The energy of the 1.064 MeV gamma ray is quoted in Ref. 9 as 1063.662(4) keV. The weighted mean of the four runs described above was evaluated as 1063.665(6) keV, and the good agreement supports our methods.

Taking the value for the 1022–1038 keV energy difference as 16.195(12) keV, and combining it with 1037.844(4) keV gives the energy of the gamma ray as 1021.649(13) keV, which becomes 1021.646(14) keV after correction for pileup and possible count rate dependent gain changes as described above. The energy difference between the first and second excited states of ^{10}B is then 1021.702(14) keV and the second excited state itself is $1021.702(14)+718.35(4)=1740.05(4)$ keV above the ground state.

The energy of the gamma ray deexciting the second excited state of ^{10}B has been measured to be 1021.646 ±0.014 keV, using as a reference the 1037.844 ± 0.004 keV line from ^{56}Co. The energy of the state itself is therefore 1740.05 ± 0.04 keV. This assigned error will contribute only marginally to the error on the Q value of the ^{10}C superallowed beta decay, when the latter is based on the Q_{pn} value for the ^{10}B$(p,n)^{10}$C reaction. If, however, Q_{pn} were to be determined more precisely than at present, then the energy of the 718 keV state of the ^{10}B would have to be remeasured.

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