^{34}Cl superallowed β decay

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The neutron separation energy of ^{34}S and the proton separation energy of ^{34}Cl have been measured accurately via the ^{33}S$(n,\gamma)^{34}$S and the ^{33}S$(p,\gamma)^{34}$Cl reactions. The measured values imply a Q value of 5492.48±0.20 keV for the total decay energy of ^{34}Cl if the calibration is based on the "mass doublet standard" and a Q value of 5492.42±0.23 keV if based on the 411.8044±0.0011 keV line in ^{198}Au. If the conserved vector current hypothesis is valid and the electromagnetic corrections are made properly, the ft values for superallowed $0^+ \rightarrow 0^+$ β decays should all be the same. The ft values for the superallowed ^{34}Cl and ^{14}O decays were found to be equal to better than (4±16) parts in 10^4, in agreement with the expectations.

NUCLEAR REACTIONS ^{32}S, ^{33}S, ^{34}S(n,γ), E=thermal; measured E_γ. ^{33}S, ^{34}S, ^{35}S deduced neutron separation energy. ^{33}S, ^{34}S(p,γ), E=0.9-1.4 MeV; measured E_γ. ^{34}Cl, ^{35}Cl deduced resonances, proton separation energy.
RADIOACTIVITY ^{34}Cl, ^{35}S, deduced Q. ^{34}Cl, deduced ft.

I. INTRODUCTION

Superallowed $0^+ \rightarrow 0^+$ β^+ transitions between members of an isospin multiplet have been studied for more than two decades. If isospin is a good quantum number, all the ft values are expected to be the same for these transitions. The ft values, in turn, lead to a value for the effective weak interaction vector coupling constant G_V'. The known superallowed ft values[1-3] are based on accurate measurements of decay energies, half lives, and branchings (where applicable). An uncertainty of less than 0.10% in a particular ft value has been the traditional goal of researchers in this field. This goal has been pursued, usually in a seesaw fashion, with significant improvements in the determination of decay energies followed by similar improvements in half-lives or vice versa. In 1976, when we began the present study, the ^{34}Cl $\rightarrow$ ^{34}S decay energy and the half-life were known[1] only to an accuracy of $\approx$ 0.3% each. We have now deduced an accurate value for this decay energy from proton (S_p) and neutron (S_n) separation energies measured in the ^{33}S$(p,\gamma)^{34}$Cl reaction and the ^{33}S$(n,\gamma)^{34}$S reaction, respectively. Our value, and other meticulous decay energy and half-life values for ^{34}Cl that have been reported since 1976, have made

the ^{34}Cl → ^{34}S decay one of the best known (smallest uncertainty in the *ft* value) of all superallowed β transitions.

II. CALIBRATION ENERGIES

In 1975, a set of precise mass differences for ^{1}H-^{2}H, ^{2}H-^{3}H, ^{12}C-^{13}C, and ^{14}N-^{15}N were reported by Smith and Wapstra[4] on the basis of measurements made with a unique radiofrequency mass spectrometer built by Smith[5] at Princeton. With these mass differences (referred to in the literature as the "mass-doublet standard") and a few other γ ray energies as primary calibration lines (see Table I), we developed a secondary list of calibration lines through (n,γ) measurements made at the Los Alamos Omega Reactor.[6] The quoted uncertainties (one standard deviation) in these lines do not include the uncertainties in the primary calibration lines. We employed these values in the analysis of (n,γ) data on all stable sulfur isotopes.

Meanwhile, a different set of calibration energies has been published by Greenwood *et al.*[7,8] Above 2 MeV, their values for the primary calibration lines differ from the Smith and Wapstra values by nearly −100 eV, a difference primarily arising from a lower value in the deuteron binding energy measured by Greenwood and Chrien[8] (see Table II). More recent measurements by van der Leun *et al.*[9] and Vylov *et al.*[10] reinforce the suggestion that the primary calibration lines above 2 MeV should be lowered by nearly 100 eV. The values reported in Refs. 8, 9 and 10 are ultimately tied to the 411.8044 ± 0.0011 keV line in ^{198}Au (known as the "gold standard"). The above systematic differences will, of course, propagate into the secondary lines of Table I. To first order, they will carry a possible systematic uncertainty of −50 eV. However, in arriving at the neutron separation energy of ^{34}S, we prefer to retain our independent analysis based on the "mass doublet standard" and make a systematic adjustment at the very end.

For the (p,γ) measurements, we employed the 6129-keV γ ray in ^{16}O as the calibration line because a portable source of this γ ray exists, and its energy is known with good precision. The portable source[11] utilizes the ^{13}C$(\alpha,n)^{16}$O reaction in a mixture of ^{244}Cm and ^{13}C. The energy of the 6129-keV γ ray has been measured by Shera[12] as 6129.170 ± 0.043 keV. In arriving at this value, Shera employed the same primary calibration lines given in Table I as those employed by us. He, however, used an approximate nuclear recoil correction. (The quantity *A* in footnote a of Table I in Ref. 12 should refer to the mass of the recoiling atom in atomic mass units instead of the mass number.) The correct value, based on the "mass doublet standard" and on a reanalysis of the original data,[13] is 6129.214 ± 0.043 keV. The uncertainty in this value includes all known sources of uncertainty except the changes intro-

TABLE I. Selected γ-ray calibration energies. In our notation, 411.794 *8*=411.794±0.008 keV, etc.

Source	Jurney and Raman[a] E_γ(keV)		Greenwood *et al.*[b] E_γ(keV)		Difference (eV)
Primary calibration lines					
^{198}Au decay	411.794[c]	*8*	411.804[d]	*2*	+10
^{60}Co decay	1173.208[e]	*25*	1173.237	*3*	+29
^{60}Co decay	1332.501[f]	*5*	1332.501	*4*	0
^{144}Ce decay			2185.662	*7*	
^{1}H$(n,\gamma)^{2}$H	2223.345[g]	*30*	2223.247	*17*	−98
^{12}C$(n,\gamma)^{13}$C	4945.416[g]	*30*	4945.319	*24*	−97
^{2}H$(n,\gamma)^{3}$H	6250.419[g]	*30*	6250.316	*24*	−103
^{14}N$(n,\gamma)^{15}$N	10829.199[g]	*30*	10829.101	*38*	−98
Secondary calibration lines					
^{12}C$(n,\gamma)^{13}$C	1261.765[h]	*27*			
^{14}N$(n,\gamma)^{15}$N	3532.067	*40*	3531.964	*87*	−103
^{12}C$(n,\gamma)^{13}$C	3684.035[h]	*40*			
^{14}N$(n,\gamma)^{15}$N	4508.744	*45*	4508.665	*53*	−79
^{14}N$(n,\gamma)^{15}$N	5269.177	*60*	5269.122	*35*	−55
^{14}N$(n,\gamma)^{15}$N	5297.862	*40*	5297.795	*35*	−67
^{14}N$(n,\gamma)^{15}$N	5533.433	*50*	5533.401	*35*	−32
^{14}N$(n,\gamma)^{15}$N	5562.118	*40*	5562.073	*35*	−45
^{14}N$(n,\gamma)^{15}$N	6322.493	*50*	6322.474	*60*	−19
^{14}N$(n,\gamma)^{15}$N	7298.975	*50*	7298.980	*90*	+5

[a]Unpublished values employed in analyzing thermal (n,γ) spectra from all stable sulfur isotopes.
[b]References 7 and 8.
[c]G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **45**, 177 (1963); Nucl. Phys. **63**, 353 (1965).
[d]E. G. Kessler, R. D. Deslattes, A. Henins, and W. C. Sauder, Phys. Rev. Lett. **40**, 171 (1978).
[e]R. G. Helmer, R. C. Greenwod, and R. J. Gehrke, Nucl. Instrum. Methods **96**, 173 (1971).
[f]R. G. Helmer, private communication (1975).
[g]Reference 4.
[h]Supersedes preliminary values reported by S. Raman, in *Neutron Capture Gamma Ray Spectroscopy and Related Topics 1981*, edited by T. von Egidy, F. Gönnenwein, and B. Maier (Institute of Physics, Bristol 1982) p. 357.

TABLE II. Changes in the deuteron binding energy (in keV). In our notation, 2224.662 *30*=2224.662±0.030 keV, etc. The recoil correction is nearly 1.319 keV.

$S_n(^2H)$=2224.662	*30*	(Smith and Wapstra[b] 1975)
2224.610	*40*	(Halverson and Johnson[c] 1978)
2224.628[a]	*16*	(Vylov *et al.*[d] 1978)
2224.564	*17*	(Greenwood and Chrien[e] 1980)
2224.575	*9*	(van der Leun *et al.*[f] 1981)
2224.563	*9*	(Vylov *et al.*[g] 1982)

[a]Original value of 2224.572±0.040 keV revised upwards by Greenwood and Chrien (Ref. 8) to reflect change in the 411-keV (^{198}Au) gold standard.
[b]Reference 4.
[c]J. E. Halverson and W. H. Johnson, Jr., Phys. Rev C **17**, 1414 (1978).
[d]Is Vylov, K. Ya Gromov, A. I. Ivanov, B. P. Osipenko, E. A. Frolov, V. G. Chumin, A. F. Shchus, and M. F. Yudin, Yad. Fiz. **28** 1137 (1978) [trasl.: Sov. J. Nucl. Phys. **28**, 585 (1978)].
[e]Reference 8.
[f]Reference 9.
[g]Reference 10.

duced by the change[8] in the deuteron binding energy. Including the latter in a complete reanalysis of the data results[13] in a value of 6129.142 ± 0.032 keV. Here again there is a problem because a slightly higher value, 6129.266 ± 0.054 keV, has been recently obtained by Alkemade *et al.*[14] on the basis of the "gold standard" and secondary calibration lines in ^{26}Al. The latter were developed via γ ray cascade-crossover relations generated by the use of resonances in the ^{25}Mg$(p,\gamma)^{26}$Al reaction. Just as in the (n,γ) case, we will proceed to use the corrected value of 6129.214 ± 0.043 keV based on the "mass doublet standard" and make a systematic adjustment at the very end to the proton separation energy of ^{34}Cl.

For determining the proton resonance energies, we chose the 991.91 ± 0.03 keV resonance in ^{27}Al, measured by Barker *et al.*,[15] and the 1317.17 ± 0.07 keV resonance, also in ^{27}Al, measured by Maas *et al.*[16] The value actually obtained by Maas *et al.* was increased by 30 eV to reflect the change in the ^{27}Al resonance calibration (991.91 keV instead of 991.88 keV) employed by these authors.

III. EXPERIMENTAL PROCEDURE AND RESULTS

A. (n,γ) measurements

The ^{33}S$(n,\gamma)^{34}$S reaction with thermal neutrons was studied at the Los Alamos Omega West reactor utilizing a 1.1-g target enriched to 88% in ^{33}S. The γ rays were detected with a 26-cm^3 Ge(Li) detector with a NaI(Tl) annulus, which was operated in either a Compton-suppressed or a pair-spectrometer mode. Despite the smallness of the thermal-neutron capture cross section ($\approx$ 300 mb), over 270 γ rays were identified in the 0.1- to 11.5-MeV region. Figure 1 shows a selected portion of the data. Over 250 γ rays were incorporated in a level scheme with 69 levels.

Table III shows eleven two-step cascades leading to $S_n(^{34}S)$. Based on the entire level scheme, a neutron separation energy of 11417.217 ± 0.016 keV was deduced for ^{34}S. The quoted uncertainty does not include either the uncertainties in the primary calibration lines or any systematic uncertainty. Including only the former, we obtain a value of 11417.217 ± 0.046 keV. There are no known previous measurements of the ^{33}S$(n,\gamma)^{34}$S reaction.

While the $S_n(^{34}S)$ measurement is the main focus of the present paper, we also present three other separation energies deduced along similar lines. They are $S_n(^{33}S)$ = 8641.912 ± 0.053 keV, $S_n(^{35}S)$ = 6986.089 ± 0.044 keV, and $S_n(^{37}S)$ = 4303.61 ± 0.07 keV. Brief descriptions of these (n,γ) measurements on all stable sulfur isotopes have been presented elsewhere.[17]

B. (p,γ) measurements

The (p,γ) measurements on selected resonances in ^{33}S and ^{34}S were made at the Triangle Universities Nuclear Laboratories (TUNL) at Durham. The high-resolution proton beam facility at the TUNL 3-MV Van de Graaff accelerator and the associated analyzer-homogenizer system have been described elsewhere.[18,19] A total incident proton energy resolution of 300-400 eV was maintained throughout the experiment. The $S_p(^{34}Cl)$ and $S_p(^{35}Cl)$ values were deduced from γ ray energies measured relative to the 6.1-MeV line and proton energies measured relative to the known resonances in ^{27}Al. Sulfur targets were prepared by evaporation of enriched isotopes (88.2% ^{33}S or 90.0% ^{34}S) in the form of CdS onto 10 μg/cm^2 carbon backings employing procedures developed earlier.[20] The targets were typically in the 0.1- to 0.5-μg/cm^2 range. Targets of ^{27}Al, matching in thickness to specific sulfur targets, were also made for concurrent use in the resonance energy measurements.

Proton excitation data were taken in steps of

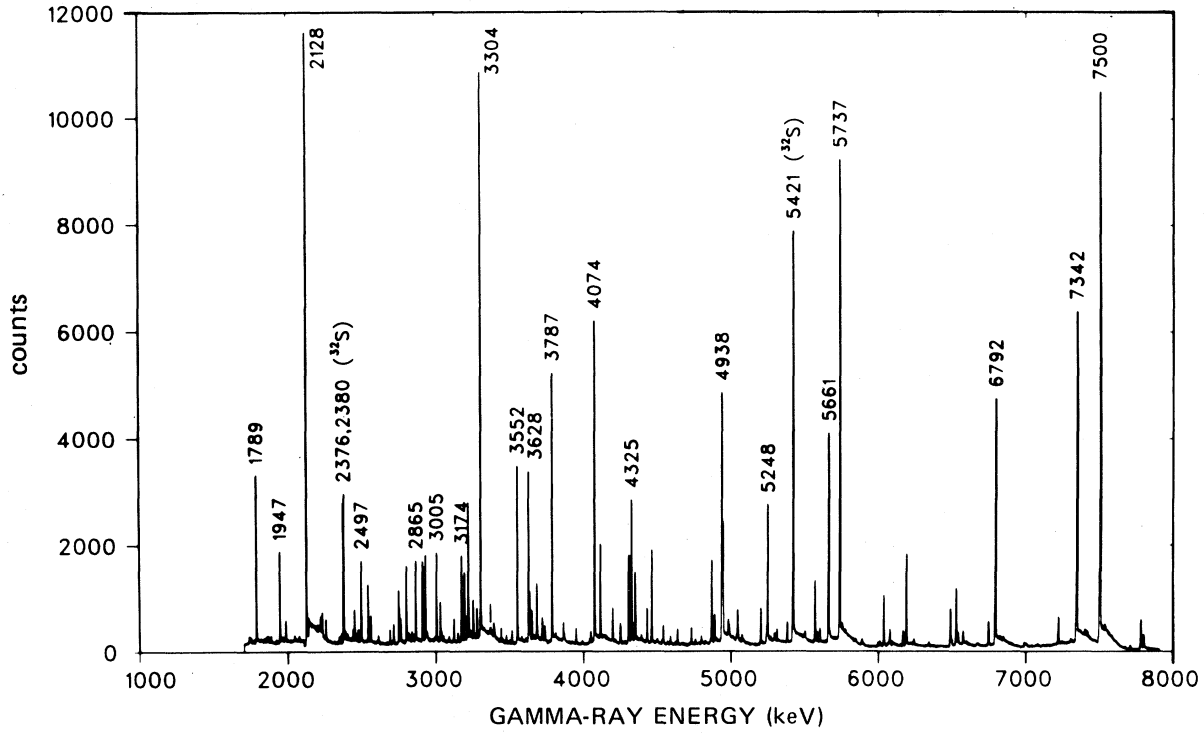

Fig. 1. Portion of the γ-ray spectrum from the ^{33}S (thermal n,γ)^{34}S reaction.

50 or 100 eV near resonances chosen for study. Proton beam intensities were typically 2-3 μA. Gamma rays and elastically scattered protons were detected with a 10-cm x 10-cm NaI(Tl) detector at 90° and a 50 mm^2 Si surface barrier detector at 135°, respectively. Portions of the data are shown in Fig. 2. Energy separations between the ^{33}S or ^{34}S resonances and the reference ^{27}Al resonances were obtained by repeated sequential measurements of their excitation functions. The ^{33}S resonance was found to occur 17.08 ± 0.15 keV lower than the 991.91 ± 0.03 keV

TABLE III. Selected two-step cascades leading to the neutron separation energy of ^{34}S. In our notation, 9288.280 *160*≡9288.280±0.160 keV, etc. E_r denotes the recoil correction.

$E(\gamma_1)$	+ $E_r(\gamma_1)$	+ $E(\gamma_2)$	+ $E_r(\gamma_2)$	= S_n
9288.280 *160*	+ 1.363	+ 2127.499 *20*	+ 0.072	= 11417.214 *162*
8111.990 *90*	+ 1.040	+ 3304.031 *20*	+ 0.173	= 11417.233 *93*
7341.670 *60*	+ 0.852	+ 4074.418 *20*	+ 0.262	= 11417.202 *64*
6526.840 *60*	+ 0.673	+ 4889.300 *80*	+ 0.378	= 11417.191 *100*
6035.680 *70*	+ 0.576	+ 5380.590 *90*	+ 0.458	= 11417.303 *115*
4197.690 *90*	+ 0.278	+ 7218.480 *130*	+ 0.823	= 11417.272 *159*
3635.830 *80*	+ 0.209	+ 7780.220 *100*	+ 0.957	= 11417.216 *129*
3278.790 *110*	+ 0.170	+ 8136.980 *170*	+ 1.046	= 11416.986 *203*
3031.690 *80*	+ 0.145	+ 8384.280 *90*	+ 1.111	= 11417.226 *121*
2910.280 *50*	+ 0.134	+ 8505.680 *100*	+ 1.143	= 11417.237 *112*
2390.820 *60*	+ 0.090	+ 9024.950 *170*	+ 1.287	= 11417.147 *181*
Separation energy based on these 11 cascades				= 11417.215 *34*
Separation energy based on all cascades				= 11417.217 *16*

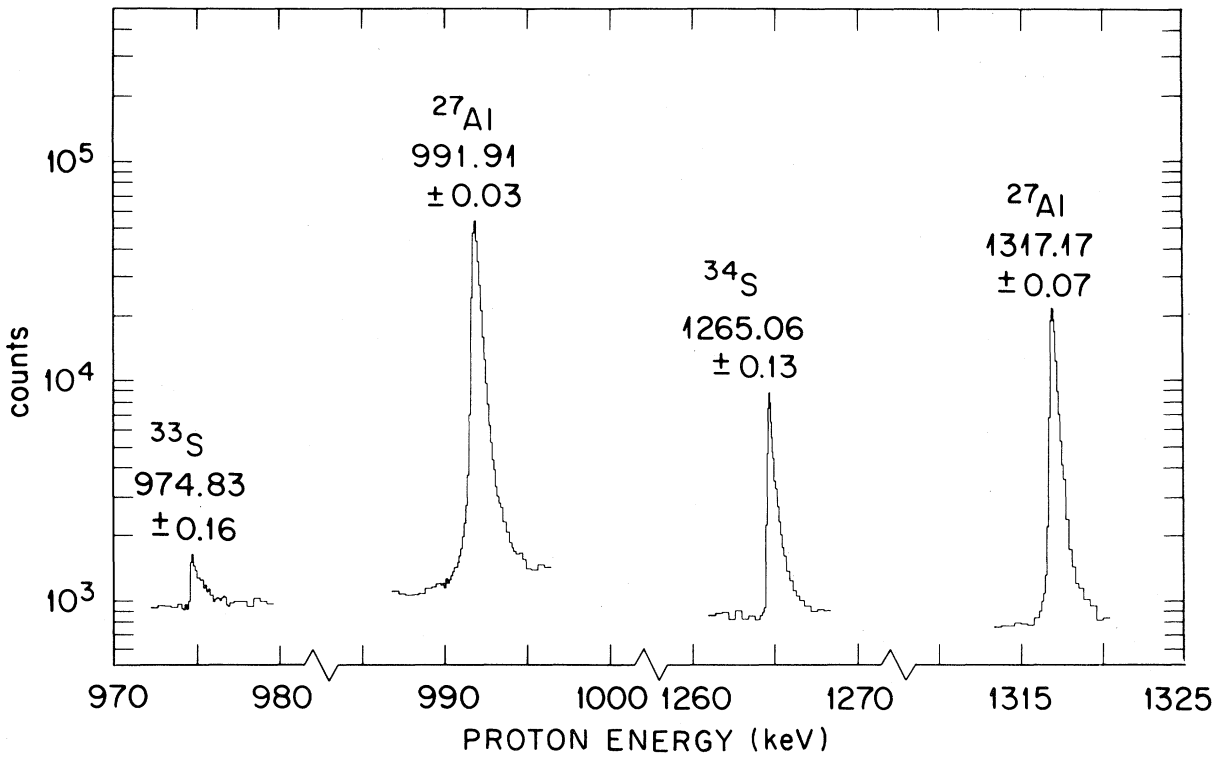

Fig. 2. Portions of γ-ray yield curves for the (p,γ) reactions on thin targets. Gamma rays were detected with a NaI(Tl) detector.

^{27}Al resonance or at 974.83 ± 0.16 keV. The ^{34}S resonance was located 52.11 ± 0.10 keV lower than the 1317.17 ± 0.07 keV ^{27}Al resonance, or at 1265.06 ± 0.13 keV.

Gamma-ray spectra were obtained from the 975-keV ^{33}S(p,γ) and the 1265-keV ^{34}S(p,γ) resonances with an 80-cm^3 Ge(Li) detector located at 90°. Portions of the γ-ray spectra are shown in Fig. 3. The 6088-keV γ ray, shown in the upper half, represents[21] a transition from the 975-keV resonance to the ground state of ^{34}Cl. This γ ray was found to occur 41.50 ± 0.10 keV below the 6129.214 ± 0.043 keV ^{16}O line, or at 6087.71 ± 0.11 keV. The 5835-keV γ ray, shown in the bottom half of Fig. 3, represents[21] a transition from the 1265-keV resonance to the first-excited state of ^{35}Cl. This γ ray was found to be 293.91 ± 0.15 keV below the 6.1-MeV line, or at 5835.30 ± 0.16 keV. The first excited state is known[22] to de-excite by the emission of a 1763.15 ± 0.10 keV γ ray.

After applying relativistic center-of-mass transformations and nuclear recoil corrections, the proton separation energy of ^{34}Cl was deduced as 5142.40 ± 0.19 keV and that of ^{35}Cl as 6370.44 ± 0.23 keV. The measured neutron and proton separation energies are also given in Table IV. Our measured $S_p(^{34}\text{Cl})$ and $S_n(^{34}\text{S})$ values, together with a value of 782.338 ± 0.010 keV for the neutron-proton mass difference, imply a Q value of 5492.48 ± 0.20 keV for the total (β^+ + electron capture) decay energy of ^{34}Cl. The uncertainty is dominated by the 0.15 keV uncertainty in the measurement of the resonance energy and the 0.10 keV uncertainty in the measurement of the γ-ray energy in the (p,γ) reaction.

C. Systematic Uncertainties

We are now in a position to consider systematic uncertainties and minor adjustments to the measured separation energies. These adjustments, though important, are small (< 100 eV) and comparable in magnitude to atomic and molecular effects which are not considered here.

For the present discussion, we switch our norm to the "gold standard." A comparison between the values 2224.662 ± 0.030 keV ("mass doublet standard") and 2224.568 ± 0.007 keV (weighted

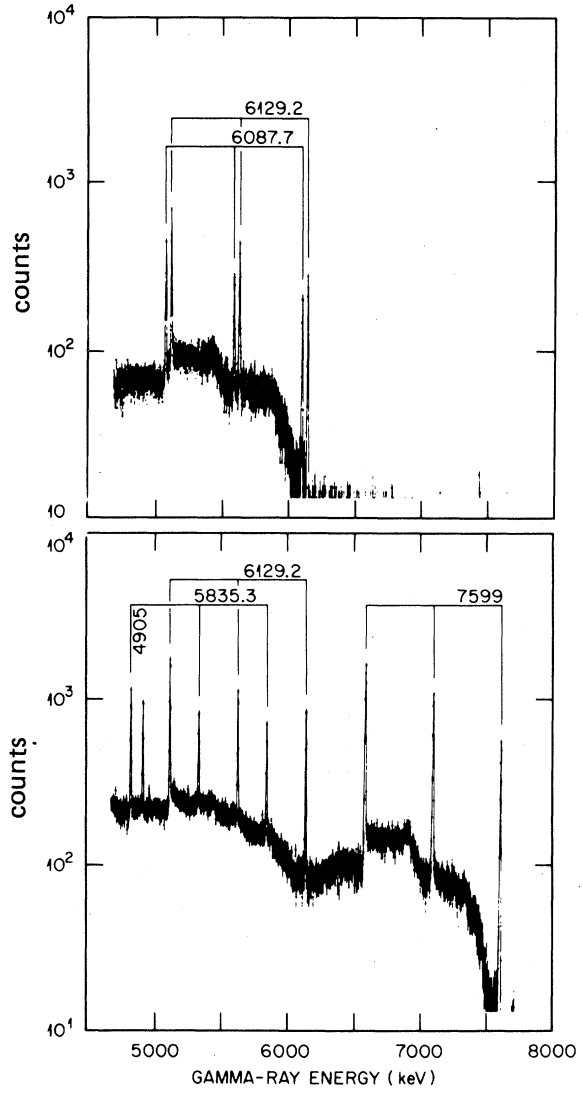

Fig. 3. Portions of γ-ray spectra obtained with a Ge(Li) detector. The top curve shows the spectrum measured at the 992 keV ^{33}S$(p,\gamma)^{34}$S resonance and the bottom curve the spectrum at the 1265 keV ^{34}S$(p,\gamma)^{35}$S resonance. The 6129.2 keV γ ray in ^{16}O is generated by a portable ^{244}Cm + ^{13}C source.

average of the "gold standard" measurements) for the deuteron binding energy (see Table II) implies that the measured separation energies should be lowered by 94 eV. We proceed to make this correction to our neutron separation energies which were based on the "mass doublet standard." Moveover, we have chosen to add half of this correction (47 eV) to the statistical uncertainties to provide a conservative estimate of the total uncertainties. The final adjusted S_n values are also given in Table IV.

We treat the S_p values differently because there exist two independent measurements of the energy of the 6.1-MeV ^{16}O γ ray. The measured values, 6129.142 ± 0.032 keV and 6129.266 ± 0.054 keV, both now on the same "gold standard," barely overlap. We adopt a weighted average of 6129.174 ± 0.055 keV and revise our γ ray energies measured in the (p,γ) reactions downward by 40 eV to reflect this change. The final adjusted S_p values are also shown in Table IV. A detailed comparison with previously published separation energies is unnecessary because the present values are more accurate. The adjusted $S_p(^{34}\text{Cl})$ and $S_n(^{34}\text{S})$ values imply a Q value of 5492.42 ± 0.23 keV for the total decay energy of ^{34}Cl. The adjusted S_n (^{35}S) and S_p (^{35}Cl) values imply a β^- decay energy of 166.74 ± 0.26 keV for ^{35}S, compared to the directly measured value[23] of 167.4 ± 0.2 keV. This discrepancy cannot be resolved further because the authors of Ref. 23 give few details concerning the estimation of uncertainties in their magnetic spectrometer measurements.

IV. BEST VALUES FOR ^{34}Cl AND ^{14}O

The ft value of a particular β transition depends upon the Q value and the partial half life. The relevant experimental data for ^{34}Cl and for the most accurately known superallowed datum at the present time, ^{14}O, are surveyed in Table V. For ^{34}Cl, the Q values are from Refs. 24-29, and the half-life values from Refs. 30-32; for ^{14}O, the Q values are from Ref. 28 and Refs. 33-38, and the half-life values from Refs. 39-44. All measurements formally published before August 1982 whose quoted uncertainties are within a factor of ten of the most precise measurement are listed, except where a datum has been superseded by a measurement from the same laboratory and the earlier one withdrawn. A number of published energies have been corrected for changes in the calibration standards reflecting the 1977 mass table,[45] the neutron-proton mass difference,[8] and the recent adjustment in the reference α particle energies.[46]

The first statistical procedure followed in analyzing the tabulated data for arriving at the "best" values is that recommended by the Particle Data Group.[47] Weighted averages are calculated according to:

$$\bar{x} \pm \delta\bar{x} = \left(\sum_i w_i x_i / \sum_i w_i\right) \pm \left(\sum_i w_i\right)^{-1/2} , \quad (1)$$

TABLE IV. Summary of results.

Reaction	Quantity	"Mass-Doublet Standard" Measured value (keV)	"Gold Standard" Adjusted value (keV)
$^{32}S(n,\gamma)^{33}S$	S_n	8641.912±0.053	8641.82±0.10
$^{33}S(n,\gamma)^{34}S$	S_n	11417.217±0.046	11417.12±0.10
$^{34}S(n,\gamma)^{35}S$	S_n	6986.089±0.044	6986.00±0.10
$^{36}S(n,\gamma)^{37}S$	S_n	4303.61 ±0.07	4303.52±0.12
$^{33}S(p,\gamma)^{34}Cl$	S_p	5142.40 ±0.19	5142.36±0.20
$^{34}S(p,\gamma)^{35}Cl$	S_p	6370.44 ±0.23	6370.40±0.24
$^{34}Cl(\beta^+ + \epsilon)^{34}S$	Q^+	5492.48[a] ±0.20	5492.42±0.23
$^{35}S(\beta^-)^{35}Cl$	Q^-	166.69[b] ±0.24	166.74±0.26

[a]Deduced from the measured $S_p(^{34}Cl)$ and $S_n(^{34}S)$ values.
[b]Deduced from the measured $S_n(^{35}S)$ and $S_p(^{35}Cl)$ values.

$$w_i = [1/(\delta x_i)^2] \ , \tag{2}$$

where the sums extend over all N relevant measurements. In each case, χ^2 was calculated and a scale factor S was determined:

$$S = [\chi^2/(N-1)]^{1/2} \ . \tag{3}$$

If $S>1$ and the δx_i are all about the same size, then the uncertainty $\delta\bar{x}$ in Eq. (1) was increased by the factor S, which is equivalent to assuming that all the experimental errors were underestimated by the same scale factor. If $S>1$, but the δx_i are of widely varying magnitudes, S was recalculated using only those results for which $\delta x_i \leq 3N^{1/2}\ \delta\bar{x}$; the scale factor was then applied in the same way. Uncertainties (one standard deviation) on the averages listed in Table V have been scaled according to the above prescription and the scale factors (S) have been noted. It should be emphasized that the scaling procedure for uncertainties does not affect the central average values.

The above method results in a set of values designated as SET A in Table V. The uncertainties quoted in this set are conservative and probably overstated because of the scaling procedure. For example, the large scale factor ($S=3.3$) occurs in the case of the ^{14}O Q values (see Table V) because four of the measured values (including the one with the smallest reported uncertainty) cluster around 5143.2 keV and the remaining three around 5145.2 keV. In arriving at the SET A values, all measurements were included because none of these have been explicitly withdrawn by the authors, and a rejection by us of any one value would have required lengthy explanations. The net result is that, even though an accurate Q value of 5143.13 ± 0.08 keV has been recently published by White *et al.*,[38] the statistical procedures followed above result in a value of 5143.26 keV, which is not too different, but carries a retrograde uncertainty of 0.25 keV.

In some cases (and especially in the above ^{14}O case), we could have chosen not to average the data at all, or to average only a subset of the data. This is not an uncommon practice amongst scientists and data evaluators. Therefore, we have also derived a set of values designated as SET B in Table V from a selective averaging of the data. In contrast to the SET A values, the uncertainties are now much smaller. Therefore, some readers might consider the SET B values as optimistic and the uncertainties understated.

V. THE $^{34}Cl \rightarrow {}^{34}S$ SUPERALLOWED *ft* VALUE

A careful treatment of uncertainties is important, because, ultimately, they will provide the limits by which the conserved vector current hypothesis (CVC) is verified by the superallowed $0^+ \rightarrow 0^+$ β transitions. According to CVC, the *ft* values for such transitions should all be identical after small radiative and Coulomb corrections have been applied.

Radiative corrections have been expressed as a sum of two terms:[48] the outer radiative correction δ_R, which varies from nucleus to nucleus, and the inner radiative correction Δ_R, which is nucleus-independent and which can be absorbed in the definition of the coupling constant. For a verification of CVC, only δ_R need be considered, and in Table VI the third-order values from Ref. 2 are listed.

TABLE V. Q values and half-life measurements in ^{34}Cl and ^{14}O superallowed β decays.

^{34}Cl			^{14}O	
		Q^a value (keV)		
Graber and Harris[24]	5494.10±1.64		Butler and Bondelid[33]	5143.60±0.70
Hyder and Harris [25]	5494.50±1.24		Bardin *et al.*[34]	5145.00±0.60
Freeman *et al.*[26]	5489.40±1.90		Roush *et al.*[35]	5145.40±0.50
Hardy *et al.*[27]	5490.20±2.30		White and Naylor[36]	5143.49±0.37
Vonach et al.[28]	5492.20±0.40		Vonach *et al.*[28]	5142.70±0.80
Barker *et al.*[29]	5491.79±0.55		Barker and Nolen[37]	5145.20±0.60
Present work	5492.42±0.23		White *et al.*[38]	5143.13±0.08
		Adopted		
Average (S=1.2)	5492.33±0.22	(SET A)	Average (S=3.3)	5143.26±0.25
Present work	5492.42±0.23	(SET B)	Reference 38	5143.13±0.08
		Half-life (msec)		
Hardy and Alburger[30]	1534.0±3.0		Alburger[39]	70480±150
Ryder *et al.*[31]	1526.0±2.0		Singh[40]	70320±120
Wilkinson and Alburger[32]	1525.2±1.1		Clark *et al.*[41]	70588±28
			Azuelos *et al.*[42]	70430±180
			Becker *et al.*[43]	70684±77
			Wilkinson *et al.*[44]	70613±25
		Adopted		
Average (S=1.9)	1526.2±1.8	(SET A)	Average (S=1.5)	70597±27
Average of values in Refs. 31 and 32	1525.4±1.0	(SET B)	Averages of values in Refs. 41, 43 and 44	70606±18

[a]Quoted is the ground state Q value. For ^{14}O, the Q value for the superallowed branch was obtained using 2312.798±0.011 keV as the excitation energy of the lowest 0^+ (T=1) state in ^{14}N. This energy measurement is by E. K. Warburton and D. E. Alburger, Nucl. Phys. **A385,** 189 (1982).

Likewise the Coulomb correction δ_c is considered to be made up of two components:[49] one, δ_{c1}, arising from charge-dependent configuration mixing with other 0^+ states, and the other, δ_{c2}, being due to small differences in the single-particle neutron and proton radial wave functions which cause the radial overlap integral of the parent and daughter nucleus to be less than unity. Strictly speaking, these two aspects of the calculation of δ_c cannot be separated, but in all calculations to date the division has been made. In Table VI the calculated values of Towner, Hardy and Harvey[50] for δ_c are listed.

The corrected ft values for superallowed decays are denoted by $\mathcal{F}t$, and the statement of CVC becomes $\mathcal{F}t$ = constant, where

$$ft(1+\delta_R)(1-\delta_c) \equiv f_R t\,(1-\delta_c) \equiv \mathcal{F}t \ . \qquad (4)$$

Thus, from the entries in Table VI, the ^{34}Cl and ^{14}O data are seen to be in excellent accord and to support the CVC hypothesis. The result, expressed as a ratio, is

$$\begin{aligned} R &= [\mathcal{F}t(^{34}\mathrm{Cl}) - \mathcal{F}t(^{14}\mathrm{O})]/\mathcal{F}t(^{14}\mathrm{O}) \\ &= (4\pm16)\times10^{-4}\ (\mathrm{SET\ A}) \\ &= (2\pm11)\times10^{-4}\ (\mathrm{SET\ B}) \end{aligned} \qquad (5)$$

where the bulk of experimental uncertainty comes from the ^{34}Cl lifetime. A similar analysis has recently been performed by Koslowsky *et al.*[51] They measured precisely the difference in Q value for the superallowed $0^+ \rightarrow 0^+$ β decays of ^{14}O and ^{26}Al^m, and their result, expressed as an equivalently defined ratio, is $R = (9\pm8)\times10^{-4}$.

It is clear that as experimental data improve in

Table VI. The ft values for ^{34}Cl and ^{14}O superallowed β decays

	^{34}Cl (SET A)	^{14}O (SET A)	^{34}Cl (SET B)	^{14}O (SET B)
$Q(\beta^+ + \epsilon)$ in keV (from Table V)	5492.33 ± 0.22	2830.46 ± 0.25	5492.42 ± 0.23	2830.33 ± 0.08
Statistical rate function,[a] f	1998.25 ± 0.45	42.715 ± 0.025	1998.44 ± 0.47	42.702 ± 0.008
Half-life in msec (from Table V)	1526.2 ± 1.8	70597 ± 27	1525.4 ± 1.0	70606 ± 18
Branching ratio[b] in %	100.00	99.336 ± 0.010	100.0	99.336 ± 0.010
Electron capture fraction[c] in %	0.081	0.091	0.081	0.091
Partial half-life in msec, t	1527.4 ± 1.8	71133 ± 28	1526.6 ± 1.0	71143 ± 19
ft in sec	3052.2 ± 3.6	3038.5 ± 2.1	3050.9 ± 2.1	3037.9 ± 1.0
Outer radiative correction,[d] δ_R in %	1.682	1.566	1.682	1.566
$ft(1+\delta_R)=f_R t$	3103.5 ± 3.7	3086.1 ± 2.2	3102.2 ± 2.2	3085.5 ± 1.0
Coulomb correction,[e] δ_c in %	0.85 ± 0.07	0.33 ± 0.03	0.85 ± 0.07	0.33 ± 0.03
$ft(1+\delta_R)(1-\delta_c)=$ $f_R t(1-\delta_c)=\mathcal{F}t$	3077.1 ± 4.3	3075.9 ± 2.4	3075.8 ± 3.1	3075.3 ± 1.4

[a]Using the computer code described in Ref. 49.
[b]From data in the following references: G. S. Sidhu and J. B. Gerhart, Phys. Rev. **148,** 1024 (1966); R. W. Kavanagh, Nucl. Phys. **A129,** 172 (1969); G. J. Clark, J. M. Freeman, D. C. Robinson, J. S. Ryder, W. E. Burcham and G. T. A. Squier, Phys. Lett. **35B,** 503 (1971); H. S. Wilson, R. W. Kavanagh, and F. M. Mann, Phys. Rev. C **22,** 1696 (1980); and A. M. Hernandez and W. W. Daehnick, Phys. Rev. C **24,** 2235 (1981).
[c]From the tables of N. B. Gove and M. J. Martin, Nucl. Data **A10,** 205 (1971).
[d]From Ref. 2.
[e]From Ref. 50.

Table VII. R values for different choices of δ_c (theoretically calculated Coulomb correction). See Eq. (5) for the definition of R.

	R(SET A)	R(SET B)
$\mathcal{F}t$: No δ_c, $\mathcal{F}t = f_R t$	$(57\pm14)\times10^{-4}$	$(54\pm 8)\times10^{-4}$
$\mathcal{F}t$: δ_c from Towner, Hardy and Harvey[50]	$(4\pm16)\times10^{-4}$	$(2\pm11)\times10^{-4}$
$\mathcal{F}t$: δ_c from Damgård[52]	$(21\pm14)\times10^{-4}$	$(19\pm 8)\times10^{-4}$
$\mathcal{F}t$: δ_c from Wilkinson[53]	$(24\pm14)\times10^{-4}$	$(20\pm 8)\times10^{-4}$

precision, the comparison can be used as a test of the δ_c calculations employed. For example, if no δ_c correction is used at all, then the ratio

$$[f_R t(^{34}\mathrm{Cl}) - f_R t(^{14}\mathrm{O})]/f_R t(^{14}\mathrm{O}) = (57 \pm 14) \times 10^{-4},$$

which is certainly not consistent with $R=0$. Here f_R is $f(1+\delta_R)$. Furthermore, if the calculation of Damgård[52] or the calculation of Wilkinson[53] is used for δ_{c2} rather than that of Towner, Hardy, and Harvey,[50] a poorer result ($R \neq 0$) is obtained in each case (see Table VII). Koslowsky *et al.*[51] observed a similar phenomenon. Of course, it is impossible to extricate separate conclusions about CVC and δ_c from a single comparison. Rather, it is the overall consistency[54] of all the superallowed β-decay data that tends to support the present method of analysis.

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