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Accurate Masses and β-Decay Schemes for ^{34}P and ^{33}Si†

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By using delayed β-γ coincidence techniques, the mass excesses of ^{34}P and ^{33}Si have been measured to be −24 546 ± 45 and −20 569 ± 50 keV, respectively, representing improvements in precision of a factor of 2 for ^{34}P and a factor of 4 for ^{33}Si over previous measurements. The first measurements of the high-energy γ rays from ^{34}P decay with a Ge(Li) detector are presented, revealing three new β branches. γ-ray energies (in keV) and relative intensities for the ^{34}S daughter transitions are 1787 ± 1 (0.30 ± 0.10), 1947.1 ± 1.5 (0.28 ± 0.10), 1987.2 ± 1.0 (1.0 ± 0.2), 2127.4 (100.0 ± 0.3), 4073.4 ± 1.5 (0.46 ± 0.06), and 4114.0 ± 1.5 (1.2 ± 0.2). The ^{34}S excitation energies and relative β branches are 2127.4 (100 ± 0.3), 3303.7 (<0.26), 3914.2 (0.30 ± 0.10), 4073.0 (0.76 ± 0.12), and 4114.5 (2.2 ± 0.3). For the decay of ^{33}Si, energies and relative intensities of γ rays were measured to be 415.8 ± 0.6 (6.7 ± 0.6), 1431.4 (13.1 ± 1.0), 1847.5 (100 ± 1), and 2537.5 (9.3 ± 0.8), representing excitation energies and relative β-ray intensities to the ^{33}P daughter states of 1431.4 ($5.1^{+1.0}_{-2.4}$), 1847.5 ($100^{+1.0}_{-2.8}$), and 2537.6 (10.5 ± 1.0). The half-lives of ^{34}P and ^{33}Si were determined by multiscaling γ-ray yields to be 12.45 ± 0.10 and 6.11 ± 0.21 sec, respectively. Combined with an earlier result, a half-life of 6.18 ± 0.18 sec is adopted for ^{33}Si. The transverse mass relationship of Garvey, using the present measurements for ^{34}P and ^{33}Si, predicts a mass excess of −20 251 ± 90 keV for the $T_z = 3$ nuclide ^{34}Si.

I. INTRODUCTION

A large amount of information has been reported[1,2] recently at various laboratories regarding the properties of exotic nuclei far from the valley of stability. Perhaps the most important reason for this is to test nuclidic mass relationships that have been proposed, although the structure information resulting from β-decay matrix elements connecting high-isospin states is certainly of interest in its own right. Mass measurements have now been reported for seven of the eight $T_z = \frac{5}{2}$ nuclides in the $2s$-$1d$ shell.[2] One of the most successful relationships connecting these masses with those of lower-isospin nuclei is the transverse relationship of Garvey *et al.*[3] The masses of the $T_z = 2$ nuclei required for the comparison of experiment with prediction are all known accurately with one exception, ^{34}P, which has been previously reported with a precision of 90 keV.[1] This previous measurement resulted as a by-product of the measurement of the mass of ^{31}Al, using a system tuned to the half-life of ^{31}Al (0.64 sec), which actually discriminates against ^{34}P ($T_{1/2} = 12$ sec).

A recent measurement[2] of the mass of ^{29}Mg revealed an interesting regular trend in the differences between measured and predicted $T_z = \frac{5}{2}$ masses. However, the ^{33}Si mass was known to a precision[4] of only about 250 keV, and with significant improvements in the experimental facility at this laboratory it was possible to remeasure both the ^{34}P and ^{33}Si masses to a precision of 50 keV.

The β decay of ^{34}P has been reported by Bleuler and Zünti,[5] Morinaga and Bleuler,[6] and Ward and Kuroda.[7] The only Ge(Li) measurements were made by Ref. 7, but their 4.00-MeV γ ray could not be measured with a Ge(Li) detector due to its weak counting rate. They quote an intensity of 0.7 ± 0.4% for the 4.00-MeV γ ray relative to the strong 2127-keV γ ray. We show in the present work that this 4-MeV line is a triplet, corresponding to three β-ray groups. Reference 7 also reports that 85 ± 2% of the ^{34}P β decay proceeds to the ^{34}S ground state with 15 ± 2% terminating at the 2127-keV level. Reference 5 reports values of 75 and 25% for these quantities, but unfortunately quotes no uncertainties. Reference 7 quotes a value for Q_β, the energy of the ground-state β ray, of 5.00 ± 0.20 MeV, in disagreement with the present value of 5383 ± 45 keV.

A rough β-decay scheme for ^{33}Si has been published by Goosman and Alburger,[4] but at the time of that work there was little information available regarding the energies and γ-ray branching ratios of the ^{33}P daughter levels. Since then, Poletti *et al.*[8] and Wagner *et al.*[9] have reported very detailed information regarding ^{33}P that has allowed us to set upper limits on low-energy β branches from the decay of ^{33}Si. This information on all possible β branches is essential to our method of determining masses, since in the present work the entire β-ray spectrum is fitted to a calculated shape, rather than employing the usual Kurie-plot analysis.

II. METHOD AND DECAY SCHEMES

^{34}P and ^{33}Si were produced by the ^{18}O(^{18}O, pn)^{34}P and ^{18}O(^{18}O, $2pn$)^{33}Si reactions, respectively, using a beam of 42-MeV ^{18}O ions bombarding a 3-mg/cm^2-thick Ta_2O_5 target, enriched to 99% in ^{18}O. After a few seconds of bombardment, the target was transferred pneumatically to a remotely located counting station with a 60-cm^3 Ge(Li) detector and a 7.6-cm-diam by 5.1-cm-deep NE 102 detector. The geometry used was identical to that shown in Fig. 1 of Ref. 1, except that for one of the runs 0.18 cm of Pb was inserted between the Ge(Li) detector and the rabbit tubing. The electronics and pileup-rejection systems are described in detail in Ref. 1.

A. ^{34}P β-Decay Scheme

For γ-ray intensity measurements, data were stored separately in two successive 14-sec time bins, in order to check the half-life of any new γ rays. Five previously unreported γ rays from the decay of ^{34}P were found and are shown in column 4 of Table I. The energies were determined by comparison with many calibration lines produced by reactions of ^{18}O with ^{18}O. The efficiency of the Ge(Li) detector was determined using standard sources, and summing corrections averaging about 5% were made to the observed intensities. The excitation energies listed in column 1 of Table I are those adopted from a comparison of our present γ-ray energy measurements and the results of previous publications as shown in Table II. The decay scheme is shown in Fig. 1. The γ-ray branching ratios shown for levels of ^{34}S are averages of those quoted by Mulhern *et al.*,[10] and these values were used to derive the relative β-ray intensities shown in column 2 of Table I. Because of many other β-ray activities, we were unable to measure the β branch to the ground state of ^{34}S, and therefore have adopted the measurements of Ref. 7 and combined them with ours to calculate absolute branches as shown in column 3 of Table I. A special run taken with seven consecutive 14-sec time bins yielded a half-life for ^{34}P of 12.45 ± 0.10 sec, determined from the decay

TABLE I. β decay of ^{34}P to levels of ^{34}S. All limits are at the 85% confidence level.

^{34}S level E_x [a] (keV)	I_β [b] (rel)	I_β [c] (%)	E_γ (keV)	I_γ [b] (rel.)	logft (expt.) [c]	logft (model) [d]
0		84.6 ± 2.0			5.16 ± 0.02	5.51
2127.4 ± 0.2	100 ± 0.3	14.9 ± 2.0	2127.3 [e]	100.0 ± 0.3	$4.93^{+0.06}_{-0.07}$	4.25
3303.7 ± 0.3	<0.26	<0.04	3303.5 [e]	<0.12	>6.62	5.33
3914.2 ± 0.6	0.30 ± 0.10	0.045 ± 0.016	1787 ± 1 [b]	0.3 ± 0.1	$5.98^{+0.14}_{-0.20}$	6.42
4073.0 ± 1.0	0.76 ± 0.12	0.11 ± 0.02	4073.4 ± 1.5 [b] 1947.1 ± 1.5 [b]	0.46 ± 0.06 0.28 ± 0.10	$5.38^{+0.10}_{-0.13}$	4.86
4114.5 ± 0.6	2.2 ± 0.3	0.33 ± 0.06	4114.0 ± 1.5 [b] 1987.2 ± 1.0 [b]	1.2 ± 0.2 1.0 ± 0.2	$4.86^{+0.09}_{-0.12}$	
4622.2 ± 0.6	<0.3	<0.045	1318.5 [e]	<0.21	>4.75	
4687.5 ± 0.6	<0.1	<0.015	2560.0 [e]	<0.11	>5.07	
4875.2 ± 0.6	<2.5	<0.37	1571.5 [e]	<1.0	>3.1	
4891 ± 3	<0.2	<0.03	4891 [e]	<0.08	>4.17	

[a] Values adopted in Table II.

[b] Present work.

[c] Calculated using our results in column 2 and the values 85 ± 2 and 15 ± 2% for the β-ray intensities to the ground and 2127-keV levels, respectively, as reported by Ref. 7.

[d] W. A. Lanford and B. H. Wildenthal, Phys. Rev. C 7, 668 (1973).

[e] Calculated from E_x values in column 1.

of the 2127-keV line. This value is in good agreement with the half-life of 12.40± 0.12 sec reported by Ref. 5. The weak γ rays reported in Table I decayed with a half-life consistent with this value.

B. ^{33}Si β-Decay Scheme

For this work data were taken in two 6.3-sec time bins, and the measured relative γ-ray intensities are shown in column 4 of Table III. The excitation energies in column 1 are taken from the summary shown in Table II of Ref. 8 of values presented by Refs. 4, 8, and 9. The relative β-ray intensities shown in Table III were calculated using the γ-ray branching ratios shown in Fig. 2, which are weighted averages of results presented by Poletti *et al.*,[11] Wagner *et al.*,[9] and Harris, Nagatani, and Olness,[12] except for the result for the branching of the 1847-keV level, which is from the present work. The uncertainties given for the β branches reflect consideration of uncertainties in possible higher feeding of the states in question. The half-life of ^{33}Si was determined to be 6.11 ± 0.21 sec, by multiscaling the γ-ray spectrum. Combined with an earlier result,[4] the adopted half-life for ^{33}Si is 6.18± 0.18 sec, as shown in Fig. 2.

TABLE II. Excitation energies in ^{34}S.

Level	E_x (keV)	Ref.	E_x adopted (keV)
2127	2127.52 ± 0.20	a	2127.4 ± 0.2
	2126.9 ± 0.4	b	
3304	3303.1 ± 0.4	b	3303.7 ± 0.3
	3303.0 ± 0.9	c	
	3303.8 ± 0.9	d	
	3304.0 ± 0.3	e	
3914	3913.0 ± 0.9	b	3914.2 ± 0.6
	3915.1 ± 0.9	c	
	3914.5 ± 1.0	f	
4073	4071.8 ± 1.0	b	4073.0 ± 1.0
	4075 ± 2	c	
	4074.1 ± 1.3	f	
4114	4114.2 ± 0.8	b	4114.5 ± 0.6
	4116 ± 2	c	
	4114.6 ± 1.0	f	
4622	4622.2 ± 0.6	b	
4687	4687.5 ± 0.6	b	
4875	4875.2 ± 0.6	b	
4891	4889.6 ± 4.0	b	
	4892 ± 3	c	4891 ± 3

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[e] Present work, using E_γ =1176.6 ± 0.12 keV from ^{34}Cl decay (D. E. Alburger *et al.*, to be published).
[f] Present work, using measured γ-ray energies.

III. MASSES OF ^{33}Si AND ^{34}P

The masses for ^{33}Si and ^{34}P were determined by measuring the spectrum of pulses in the NE 102 scintillator coincident with 1848- and 2127-keV γ rays, respectively. Our experience has shown that in this geometry the usual Kurie-plot analysis is less suitable than a shape-fitting procedure, because for scintillators with good resolution it is difficult to find a resolution function suitable for calculating the shape of the high-energy end of the observed spectra. We therefore compare the shape of the spectrum to be measured with those of several well-known calibration spectra.

The results shown in Sec. II provide the necessary groundwork for such a calculation, because with the shape-fitting method all inner β-ray branches cascading through the 1848-keV (or the 2127-keV) level must be removed from the spectrum before the comparison can be effected.

Figure 3 shows the 1848- and 2127-keV γ rays, with horizontal bars indicating peak and background regions. Pulses in the scintillator coincident with pulses in the Ge(Li) detector in the respective peak and background regions denoted

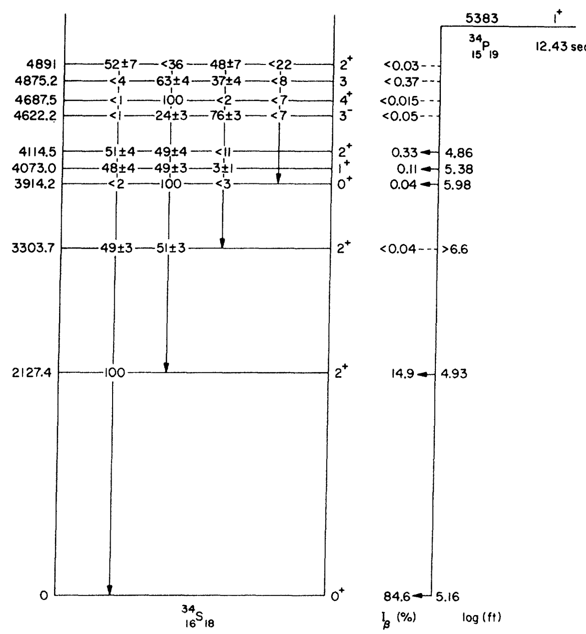

FIG. 1. The β decay of ^{34}P to levels of ^{34}S. The ratio of β-ray intensities to the ground and first excited levels of ^{34}S was taken from Ref. 7. The half-life is the average of the present work and that of Ref. 5. References for other information shown are given in Tables I and II.

TABLE III. β decay of ^{33}Si to levels of ^{33}P. All limits are at the 85% confidence level.

^{33}P level E_x [a] (keV)	I_β [b] (rel.)	E_γ [c] (keV)	I_γ [d] (rel.)	logft expt.	logft shell-model [e]
0	(38) [f]				5.4
1431.4 ± 0.3	$5.1^{+1.0}_{-2.4}$	1431.4	13.1 ± 1.0	>5.6	5.36
1847.5 ± 0.15	$100^{+1.0}_{-2.8}$	415.8 ± 0.6 [d] 1847.5	6.7 ± 0.6 100 ± 1	>4.16	3.91
2537.6 ± 0.5	10.5 ± 1.0	2537.5	9.3 ± 0.8	>4.76	4.50
3275.3 ± 1.0	<2.2	3275.1	<1.1	>4.9	4.71 [g]
3490.4 ± 1.0	<2.4	1642.9	<1.5	>4.7	
		2058.9	<1.3		
3627.3 ± 1.0	<0.7	2195.8	<0.50	>5.2	
4047.8 ± 1.0	<1.6	2616.3	<1.3	>4.4	
4193.7 ± 2.5	<0.8	4193.4	<0.77	>4.5	
4224.7 ± 1.0	<0.3	2377.1	<0.32	>4.9	
4856.1 ± 1.2	<1.6	3008.6	<1.4	>3.2	
5048 ± 3	<4.1	3200.3	<1.5	>2.4	
5190 ± 2	<1.3	3342	<1.2		
		3758	<0.9		

[a] Reference 11.
[b] Calculated from measured values of I_γ and γ-ray branching ratios shown in Fig. 2.
[c] Calculated from E_x values in column 1, unless otherwise indicated.
[d] Present work.
[e] Reference 15.
[f] Calculated from column 6.
[g] To either of the 3275- or 3490-keV levels.

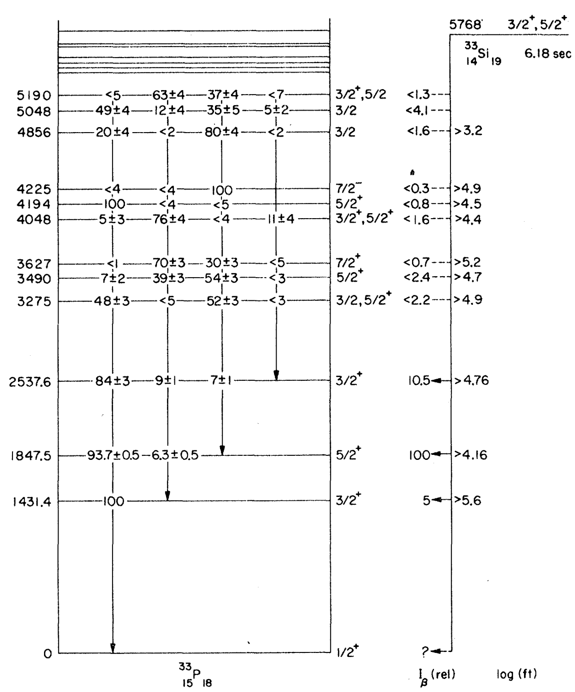

FIG. 2. The β decay of ^{33}Si to levels of ^{33}P. A ground-state β-ray branch of about 38% is expected from shell-model calculations. References for this information are given in Table II and Sec. II B.

"B1" and "B2" were recorded separately. Counting rates in the NE 102 detector ranged between 20 000 and 33 000 per second, and because of the large solid angle of the scintillator (40%) a reals-to-randoms ratio of 400 was maintained. The NE 102 pulses were shaped to a width of 700 nsec, and pileup-rejection circuitry vetoed events if two pulses occurred with a time difference between 25 and 1000 nsec.

A. Mass of ^{33}Si

After accumulating data for about 8000 cycles of irradiation and counting, the spectrum coincident with the 1848-keV peak region of Fig. 3 was corrected by removing from it the spectra coincident with the background regions B1 and B2. The shapes and magnitudes of the B1 and B2 spectra were statistically identical, and the sum of both was used to provide the best background.

Calibration spectra were accumulated by storing the spectra coincident with the 440-keV γ ray from the decay of ^{23}Ne, the 1779-keV γ ray from ^{28}Al, and the 1634-keV γ ray from ^{20}F. For each 440-keV γ ray detected in the Ge(Li) from the decay of ^{23}Ne, there is a 2.8% chance[13] that it corresponds to a β ray terminating on the 2076-keV level of ^{23}Na, emitting a 1636-keV γ ray in its cascade through the 440-keV level. Therefore, in addition to the 3939-keV β end-point spectrum, there are some events due to 2303-keV β rays, 1636-keV γ rays, and summing between the latter two events; all contributing to the observed spectrum for ^{23}Ne. As explained in more detail in previous papers,[1,2] these correction terms are easily computed and removed from the raw spectrum, leaving the desired result: the response of the scintillator to a 3939-keV end-point-energy β-ray spectrum. No corrections were needed for the ^{28}Al and ^{20}F spectra.

Figure 2 shows that for each observed 1848-keV γ ray from the ^{33}Si decay, there is a 0.74% chance that it is due to a β ray feeding the 2538-keV level in ^{33}P. Therefore the observed NE 102 spectrum was corrected for events due to this weak β branch and the corrected spectrum is shown in Fig. 4. The solid curve drawn through the points is the experimentally observed smoothed shape of the corrected ^{23}Ne spectrum, compressed to fit the ^{33}Si data. A least-squares-fitting program was used to fit the smoothed ^{23}Ne shape to both the unsmoothed ^{23}Ne data and the ^{33}Si data, resulting in stretching factors of 0.9996 ± 0.0023 and 0.9922 ± 0.0051, respectively. It is very fortunate that the ^{33}Si and ^{23}Ne end-point energies are so similar, since many systematic effects cancel out in the comparison. The fit shown in Fig. 4 would represent a β end point for ^{33}Si of 3911 ± 30 keV, except that a few corrections must be considered.

Figure 2 shows that weak branches to the 3275- and 3490-keV levels of the order of 2% could exist. Each level deexcites about 50% through the 1848-keV level, and thus unobserved higher feeding of the latter level could affect the calculated ^{33}Si β-ray energy. Calculations have been carried out, assuming branches to the 3275- and 3490-keV levels of 2.2 and 2.4%, respectively, resulting in an increase of about 10 keV in the calculated ^{33}Si β-ray energy for each assumed branch.

Count-rate-dependent gain shifts of the photomultiplier tube must be considered. Although the ^{23}Ne calibration spectrum was taken simultaneously with the ^{33}Si data, the latter activity decays a factor of 4 throughout the 12.6-sec counting period, while the ^{23}Ne decays only 20% during this period, so that rate-dependent gain effects do not cancel exactly. Tests with γ-ray sources at similar and higher counting rates revealed a possible slight increase in gain with count rate, but of such magnitude as to represent a correction of only about -10 keV or less to the ^{33}Si result. An internal check on this was provided by intercomparison of the ^{28}Al, ^{23}Ne, and ^{20}F spectra (see Sec. III B).

The shapes for the ^{23}Ne and ^{33}Si are not expected

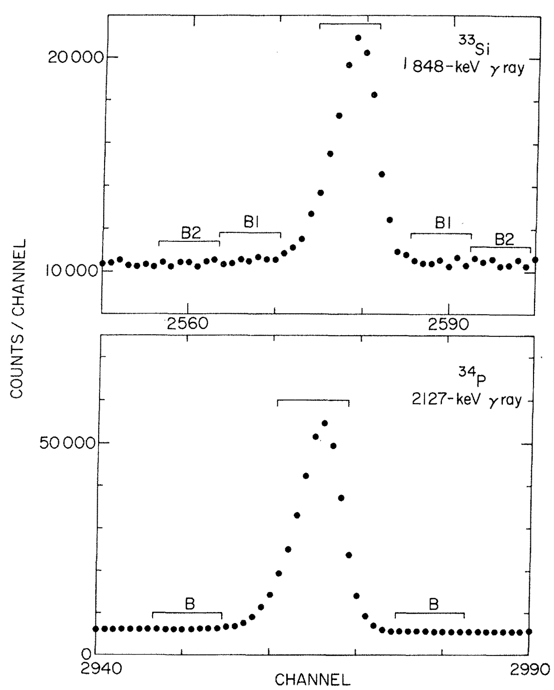

FIG. 3. Upper part: the 1848-keV γ-ray peak used for the ^{33}Si mass measurement. β spectra coincident with digital gates set on the peak and various backgrounds labeled "B1" and "B2" were recorded. Lower part: the 2127-keV γ-ray peak used for the ^{34}P mass measurement. Data were recorded for the peak region and for the sum of the two background regions.

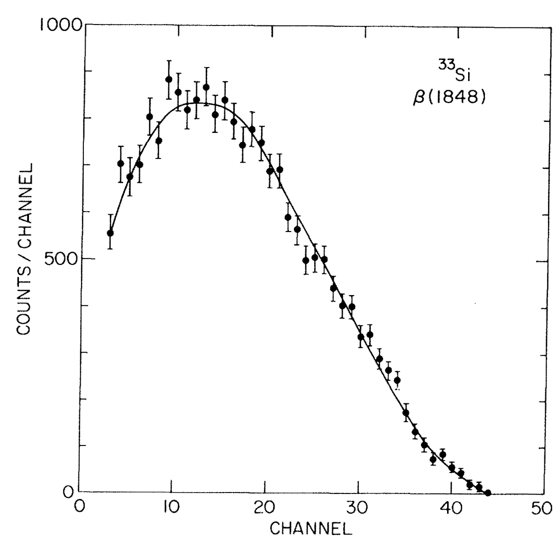

FIG. 4. The pulse-height spectrum in the scintillator coincident with the 1848-keV γ ray in ^{33}Si decay, corrected for events due to the β branch to the 2538-keV level. The solid curve is a corrected ^{23}Ne calibration shape stretched by a factor of 0.9922 to fit the ^{33}Si data. The dispersion is 90 keV/channel.

to be exactly the same, because they correspond to different values of Z. Examination of the Fermi functions for each decay reveals that one expects an excess of pulses in the observed ^{33}Si β spectrum shown in Fig. 4 of about 1% near channel 4 and about 0.3% near channel 9, the difference rapidly vanishing for higher channel numbers. The ^{33}Si data were refitted to the ^{23}Ne shape using only channels 10 and larger, resulting in a shift of about +14 keV from the previous result.

Also, the ^{23}Ne activity resides deeper in the target than the ^{33}Si, resulting in a correction of about −2 keV. Possible systematic effects in the background subtraction contribute an uncertainty of about 15 keV.

Because of the considerations listed above we adopt a β-ray end-point energy to the 1848-keV level of 3920 ± 50 keV, representing a value for Q_β (the ground-state β end-point energy) of 5768 ± 50 keV and a mass excess of −20 569 ± 50 keV, in agreement with, but much more precise than, the value of $-20\,509^{+250}_{-200}$ reported in Ref. 4.

B. Mass of ^{34}P

Figure 1 shows that the NE 102 spectrum coincident with 2127-keV γ rays has contributions due to β rays, γ rays, and summing between β and γ rays arising from β branches to the 3914-, 4073-, and 4114-keV levels of ^{34}S. In a manner similar to that described above, these nine small correction spectra were computed and removed from the observed ^{34}P data, resulting in the corrected spectrum shown in Fig. 5

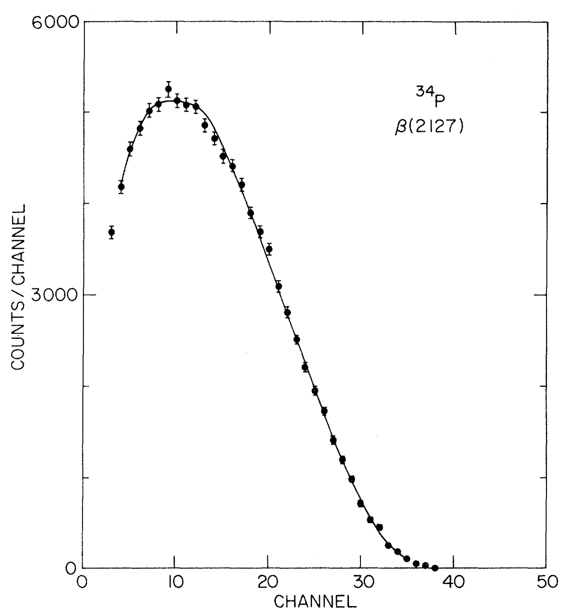

FIG. 5. The pulse-height spectrum in the scintillator coincident with the 2127-keV γ ray in ^{34}P decay, corrected for three inner β-ray branches. The solid curve is a shape-interpolation fit between ^{28}Al and ^{23}Ne calibration shapes.

Unfortunately, the closest calibrations for these data were the 2863-keV end-point β-ray spectrum from ^{28}Al and the 3939-keV ^{23}Ne spectrum derived in Sec. III A. A new technique for analyzing the ^{34}P data was used. Rather than stretching the ^{28}Al shape or compressing the ^{23}Ne shape, an interpolation procedure was developed. The ^{28}Al and corrected ^{23}Ne data were smoothed, normalized to the same height, and then the ^{34}P data were fitted by linearly interpolating between the shapes of the calibration spectra. This resulted in the solid curve shown in Fig. 5, representing the calculated shape for a β spectrum with an end-point energy of 3245 ± 20 keV, before corrections.

Corrections due to rate-dependent gain and Z-dependent shapes are smaller than for ^{33}Si, being about −5 and +8 keV, respectively. Unobserved feeding of the 2127-keV level and source-thickness effects are less than 10 and −3 keV, respectively. The linearity of the shape-interpolation technique is estimated to be correct within 20 keV, by comparison of the measured shapes for ^{28}Al [E_β(max) = 2863 keV], ^{23}Ne (3939 keV), and ^{20}F (5393 keV). Using the ^{28}Al and ^{20}F shapes, the calculated ^{23}Ne energy is correct to 15 keV. Uncertainties in the background subtraction (see Fig. 3) contribute about 10 keV to the over-all uncertainty.

With these sources of error considered, we adopt an end-point energy to the 2127-keV level of ^{34}S of 3256 ± 45 keV, corresponding to Q_β = 5383 ± 45 keV and a mass excess of −24 546 ± 45 keV. This value is in agreement with the value of −24 550 ± 90 keV that we reported previously,[1] but which was not corrected for the then unknown inner β-ray branches and other effects that are considered above.

IV. DISCUSSION

The masses presented here were incorporated into a previous publication[2] regarding ^{29}Mg and the systematics of masses of nuclei with $T_z = \frac{5}{2}$ in the 2s-1d shell, illustrating a regular trend among the differences between predicted and measured values. The present mass for ^{34}P was used in Ref. 2 to calculate the predicted masses for ^{33}Si and ^{35}P. The present mass for ^{33}Si is 421 ± 67 keV less tightly bound than the transverse relationship of Ref. 3 would predict, but falls nicely into place among the systematics presented in Ref. 2. Combining the present ^{33}Si mass with the measured ^{35}P mass[14] into the transverse relation:

$$M(^{34}\mathrm{Si}) = M(^{35}\mathrm{P}) + M(^{33}\mathrm{Si}) + M(^{34}\mathrm{S}) - M(^{35}\mathrm{S}) - M(^{33}\mathrm{P}),$$

one calculates the predicted mass excess for ^{34}Si to be $-20\,251 \pm 90$ keV. Attempts are under way to measure this mass.

Calculations of allowed β decay in the ***s-d*** shell by Lanford and Wildenthal[15] are compared with present results in Tables I and III and Figs. 1 and 2. For ^{34}P, one rather large discrepancy is evident, namely the lack of expected strength to the $J^{\pi} = 2^{+}$ state at 3304 keV. Our limit is more than 18 times weaker than the predicted strength. However, in Ref. 13 the state to which a logft of 5.33 is assigned is the "second $J^{\pi} = 2^{+}$ state." If the 4114-keV level were given this assignment, interchanging the character of the 3304- and 4114-keV levels, the observed β-decay strengths would fall more in line with predictions.

For ^{33}Si, we have no measure of the ground-state β branch, and therefore quote only limits on logft values. A logft of 4.71 strength to either of the 3275- or 3490-keV levels is expected, but is just at our limit of sensitivity. A ground-state branch of about 38% is predicted. In general the experimental strengths are weaker than the expected strengths.

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*Alfred P. Sloan Foundation Fellow.

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