ton, Nucl. Phys. 79, 505 (1966).

[22] E. Kashy, A. M. Hoogenboom, and W. W. Buechner, Phys. Rev. 124, 1917 (1961).

[23] S. Sen, C. L. Hollas, and P. J. Riley, Phys. Rev. C 3, 2314 (1971).

[24] W. Fitz, R. Jahr, and R. Santo, Nucl. Phys. A114, 392 (1968).

[25] L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. 136, B405 (1964).

[26] G. Ripka, in *Proceedings of the Third International Conference on the Structure of Low-Medium Mass Nuclei, University of Kansas, 1968*, edited by R. L. Becker and J. P. Davidson (University Press of Kansas, Lawrence, Kansas, 1968).

[27] G. R. Satchler, Ann. Phys. (N.Y.) 3, 275 (1958).

[28] G. Ripka, in *Advances in Nuclear Physics,* edited by M. Baranger and E. Vogt (Plenum, New York, 1968), Vol. 1.

[29] J. Bar-Tuov and I. Kelson, Phys. Rev. 138, B1035 (1965).

[30] J. Bar-Tuov, A. Goswami, A. L. Goodman, and G. L. Struble, Phys. Rev. 178, 1670 (1969).

[31] R. Padjen and G. Ripka, Phys. Letters 29B, 548 (1969).

[32] R. Padjen and G. Ripka, Nucl. Phys. A149, 273 (1970).

[33] J. B. French, E. C. Halbert, J. B. McGrory, and S. S. Wong, in *Advances in Nuclear Physics,* edited by M. Baranger and E. Vogt (Plenum, New York, 1969), Vol. 3.

[34] P. W. M. Glaudemans, P. J. Brussaard, and B. H. Wildenthal, Nucl. Phys. A102, 593 (1967).

[35] B. H. Wildenthal, J. B. McGrory, and E. C. Halbert, Phys. Letters 27B, 611 (1968).

[36] P. W. M. Glaudemans, G. Wiechers, and P. J. Brussaard, Nucl. Phys. 56, 548 (1964).

PHYSICAL REVIEW C VOLUME 4, NUMBER 5 NOVEMBER 1971

Masses and Half-Lives of ^{20}Na, ^{24}Al, ^{28}P, ^{32}Cl, and ^{36}K from the (p, n) Reaction[*]

D. R. Goosman, K. W. Jones, E. K. Warburton, and D. E. Alburger
Brookhaven National Laboratory, Upton, New York 11973

(Received 17 June 1971; revised manuscript received 15 September 1971)

The (p,n) thresholds for the formation of ^{20}Na, ^{28}P, ^{32}Cl, and ^{36}K from targets of ^{20}Ne, ^{28}Si, ^{32}S, and ^{36}Ar, respectively, have been measured relative to the $^{24}\mathrm{Mg}(p,n)^{24}\mathrm{Al}$ threshold by detecting β rays from these short-lived activities. Half-lives were determined by multiscaling techniques. The resulting (p,n) thresholds (in keV), half-lives (in msec) are as follows: ^{20}Na (15 419 ± 6, 442 ± 5); ^{28}P (15 666 ± 6, 266 ± 4); ^{32}Cl (13 902 ± 9 and 13 978 ± 16, 281 ± 8); ^{36}K (13 976 ± 8, 336 ± 4). The half-life of ^{24}Al was measured as 2.054 ± 0.009 sec.

I. INTRODUCTION

In a recent series of reports[1-5] Wilkinson and Alburger have instituted a careful study of mirror symmetry in β decay. The point of view of this series was the possible existence of second-class terms[6] in the β-decay operator. From the most recent work in their series, a study of the mass-8 system,[5] it appears that the bulk of the deviation from mirror symmetry of β decay is not due to second-class terms but to nuclear-structure effects larger than heretofore expected, or to some so-far-unforeseen effect. This becomes a question of theoretical interest. Regardless of the outcome of this question, it has been reemphasized by this work that the comparison of mirror β decays is a fruitful way of testing our knowledge of the nucleus, and it is clear that our understanding should be good enough to demand as accurate a comparison as present experimental techniques allow.

The desire for more accuracy was, then, the main motive for initiating the studies of the $(p, n\beta^+)$ reactions reported herein. The targets used were the $4n$, $T_z = 0$ nuclei from ^{20}Ne to ^{36}Ar. Measurements consisted of (p, n) threshold determinations and therefore masses for ^{20}Na, ^{28}P, ^{32}Cl, ^{32}Cl*, and ^{36}K all relative to the mass of ^{24}Al, and half-life determinations for the positron emitters ^{20}Na, ^{24}Al, ^{28}P, ^{32}Cl, and ^{36}K. The results for ^{20}Na have been briefly reported previously[4]; they are included here for completeness.

II. EXPERIMENTAL METHODS AND RESULTS

The five (p, n) reactions under study have thresholds in the proton energy range from 13.9 to 15.7 MeV. Proton beams of the desired energy were provided by the second tandem of the Brookhaven National Laboratory three-stage MP tandem Van de Graaff facility. The thresholds for the various (p, n) reactions, and the half-lives of the activities produced were measured by detecting the emitted β rays in a 5-cm-diam × 2.5-cm-thick NE 102 plastic scintillator attached to an RCA 6342 photomulti-

TABLE I. Results of the half-life measurements.

Nucleus	Half-life (msec) Present	Half-life (msec) Previous	Reference
^{20}Na	442 ± 5	448 ± 4	9
		408 ± 6	10
^{24}Al	2054 ± 9	2080 ± 10	10
^{28}P	266 ± 4	270.3 ± 0.5	10
		285 ± 7	11–13
^{32}Cl	281 ± 8	298 ± 1	10
		294 ± 6	14
		306 ± 4	12
		320 ± 10	13
^{36}K	336 ± 4	345 ± 5	16
		265 ± 25	15

plier tube. The scintillator was located at 90° to the beam and 3 cm from the target by using a reentrant tube having a 0.063-cm-thick steel end wall.

Solid targets were clamped in a frame opposite the detector. For the gas targets a 7.5-cm-long bombardment cell was constructed from 1.8-cm-diam stainless-steel tubing with a wall thickness of 0.05 cm. The cell was fitted with removable entrance and exit windows and with two copper capillary tubes for gas circulation. In order to minimize background activities that might result from the scattering of protons into the walls of the cell, an internal liner of 0.32-cm-thick graphite was installed. The beam was collimated to a diameter of 3 mm and the cell was centered on the detector axis and accurately aligned so that the beam passed through the centers of the 6-mm-diam entrance and exit windows and thence to a beam dump 3 m downstream.

The ^{24}Mg measurement was made with a foil of 99.95% enriched ^{24}Mg having a thickness of 0.94 mg/cm^2. Since its threshold[7] of 15 286.3 ± 2.9 keV served as the primary calibration standard, it was run before or after each of the other targets. The Si target consisted of 1 mg/cm^2 of natural silicon evaporated onto a 5-mg/cm^2 Pt foil. For the threshold measurements made using gas targets, the entrance window was a Ni foil with a weight of 666 ± 20 μg/cm^2 which could support a gas pressure of ~20 cm of Hg. For the half-life measurements the entrance and exit windows were 5-μm-thick Pt which allowed pressures of ~1 atm to be used, thereby increasing the yield. The three gases included ordinary neon, argon enriched to 99.9% in ^{36}Ar, and natural H_2S. While static fillings were used for the ^{20}Ne and ^{36}Ar measurements it was found that the H_2S was dissociated by the beam, the sulfur being condensed out on the graphite liner. In order to avoid the resulting decrease in yield during the threshold measurements, a continuous flow system was devised utilizing a mercury bubbler that maintained the desired flow rate together with a constant pressure in the cell. The outlet gas was discarded. For the half-life measurement the H_2S target was used under static conditions but the gas was flushed out and replaced every 15 min during the run.

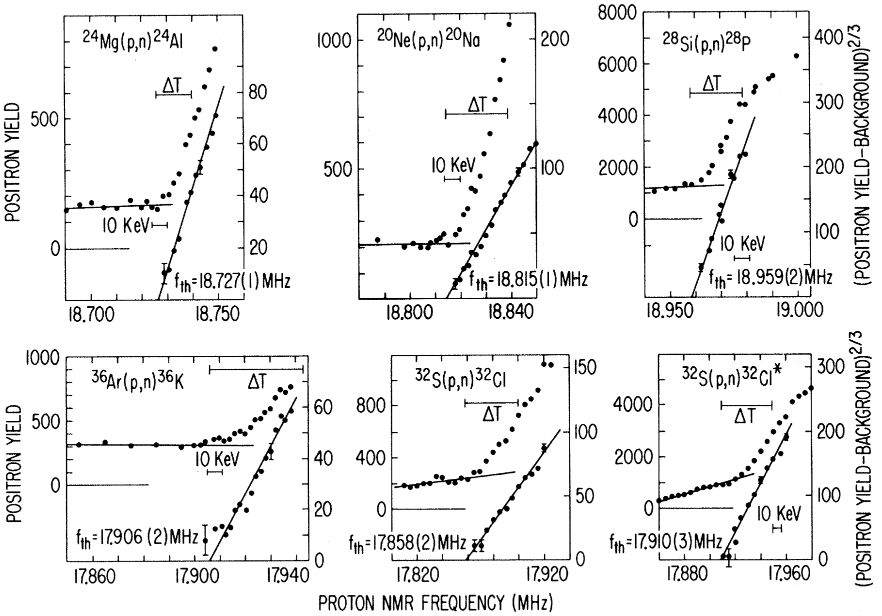

FIG. 1. Data from the threshold measurements for the indicated reactions as observed by detecting delayed positrons. The thicknesses of the targets for incident protons are indicated. For ^{32}Cl, threshold measurements for the first excited state and ground state are both shown.

TABLE II. The (p,n) threshold results.

Reaction	Threshold frequency (KHz)	Energy (keV)	Q value (keV)	Mass excess (keV)	Previous mass excess (keV)	Reference
^{20}Ne$(p,n)^{20}$Na	18 815 ± 2.4	15 419 ± 6	−14 674 ± 6	6850 ± 6	6863 ± 40	10
^{24}Mg$(p,n)^{24}$Al	18 725 ± 2.0	···	···	···	−50.7 ± 3	7
^{28}Si$(p,n)^{28}$P	18 958 ± 2.5	15 666 ± 6	−15 117 ± 6	−7155 ± 7	−7152.1 ± 4.2	7
^{32}S$(p,n)^{32}$Cl	17 860 ± 5	13 902 ± 9	−13 474 ± 9	−13 321 ± 9	−13 324 ± 14	7
^{32}S$(p,n)^{32}$Cl*	17 909 ± 10	13 978 ± 16	−13 548 ± 16	−13 247 ± 16	−13 238 ± 23	7
^{36}Ar$(p,n)^{36}$K	17 908 ± 4	13 976 ± 8	−13 593 ± 8	−17 421 ± 8	−17 396 ± 23	16
					−17 320 ± 40	17

Activation of the targets was carried out by using a pneumatic beam interceptor located in the accelerator room. A timing device operated the interceptor and started the counting of the activity a short time (~0.25 sec) after the beam was cut off. Electronic circuits were of commercial design including discriminators for setting biases on the β-ray energies to be counted and two Northern Scientific Company analyzers which could be used as precision multiscalers for half-life measurements. Pulse widths of 20 nsec were used in order to minimize pileup.

Half-life measurements were made under a variety of conditions of β-ray bias, beam intensity, and in some instances with the detector moved to various distances from the target. In all cases the beam energy was set ~1 MeV above the threshold and the activity was counted for at least 20 half-lives. In all of the half-life measurements the background was $<0.1\%$ of the initial counting rate. The general procedure and method of analyzing the decay curves has been previously described.[8] In brief, each decay curve was analyzed by a nonlinear iterative least-squares program assuming a single exponential plus a constant background. Tests gave no evidence in any case for deviations from this assumption. Corrections were made for analyzer dead time. These corrections were almost negligible since the initial counting rate was kept low in order to minimize this and other count-rate-dependent effects. As in previous work[8] it was found that the fitting uncertainty was usually considerably smaller than the variations in the half-life values from one run to another. An uncertainty was therefore assigned that reflected the magnitude of the run-to-run variations, rather than the fitting uncertainty. Table I summarizes the final averaged results of the many runs.

The half-life of ^{24}Al was measured from the decay of β's >4 MeV in a Pilot B scintillator and γ's near 7 MeV in a 5×5-in. NaI(Tl) detector. A pneumatic transport system moved the 0.005-in.-thick Mg target from the bombardment position ~20 ft through a concrete wall into the adjacent target room where the detectors were located. The ^{24}Al half-life derived from the various runs is included in Table I.

Threshold measurements were made after magnetically cycling the 90° energy-analyzing magnet. This was done to reduce the differential hysteresis at different locations along the beam path within the magnet. The standard procedure consisted of op-

TABLE III. Summary of superallowed β^+ decay.

Nucleus	$T_{1/2}$ [a] (msec)	Mass excess[b] (keV)	Analog excitation (keV)	Max. β^+ energy (keV)	Branching ratio (%)	Reference [c]	$\log f_0 t$
^{20}Na	445.7(3.1)	6850.0(6.0)	10 277.0(4.0)	2593(7)	1.4(0.15)	9, 10	3.79 ± 0.05
^{24}Al	2060.0(10.0)	−50.7(3.0)	9516.0(2.8)	3345(4)	48.0(4.0)	10	3.40 ± 0.04
^{28}P	268.0(4.0)	−7153.0(4.0)	9319.4(4.4)	3996(7)	13.0(5.0)	10	3.41 ± 0.17
^{32}Cl	285.0(8.0)	−13 321.0(9.0)	6998.0(2.8)	4672(9)	25.0(2.0)	10	3.44 ± 0.04
^{36}K	340.0(3.3)	−17 421.0(8.0)	6613.2(1.2)	5175(8)	43.0(3.0)	d	3.48 ± 0.03

[a] Our subjective average of the present and previous results of Table I.

[b] Our subjective average of the present and previous results of Table II.

[c] These are for the analog excitation energies and the branching ratios.

[d] D. W. Miller, D. A. Outlaw, F. Everling, T. G. Dzubay, G. A. Bissinger, and S. M. Shafroth, Bull. Am. Phys. Soc. 16, 554 (1971); private communication.

erating the magnet current at its maximum (saturation) for 5 min, reducing the current to zero for 5 min, and then bringing it up to the first point below the threshold. Thereafter the current was only increased.

In the course of this work the ^{20}Na, ^{28}P, ^{32}Cl, and ^{36}K thresholds were determined 3, 1, 2, and 2 times, respectively; while the ^{24}Al threshold, which served as the reference, was measured 5 times. Representative threshold measurements are illustrated in Fig. 1. The method of analysis was similar to that described by Overley, Parker, and Bromley.[7] First, a least-squares fit, assuming a linearly varying yield, was made to the region below threshold as illustrated in Fig. 1. This background was extrapolated beyond threshold and subtracted from the yield curve. The net yield so obtained was then raised to the $\frac{2}{3}$ power and a least-squares fit was made to these data as a function of NMR frequency as illustrated in Fig. 1. The zero intercept was taken as the threshold frequency. In all cases the result was based on a fit to the frequency region within one target thickness of threshold, but the results were not sensitive to the region included in the fit. This is not surprising since, as seen in Fig. 1, the $\frac{2}{3}$ power behavior is empirically observed to persist well beyond the target thickness (designated ΔT in Fig. 1).

As in the half-life measurements, the reproducibility of the results was considerably worse than the statistical errors would indicate. Thus the uncertainties placed on the final results reflect our estimate of the systematic errors, which have been amply discussed previously,[7] rather than the statistical errors. Our final averaged results are summarized in Table II. For the gas targets the conversion from observed threshold frequency to threshold energy includes a correction for the proton energy loss in the Ni foil; this was 13 ± 1 keV for the ^{20}Ne target and 14 ± 1 keV for the ^{32}S and ^{36}Ar targets.

III. DISCUSSION

As has been pointed out previously[8] the uncertainties assigned to the half-lives of radioactive nuclei have often been notoriously small. This is illustrated by comparison of the various measurements[9-16] collected in Table I. Our measurements cannot be said to be the last word. Unfortunately, in this type of study where systematic errors are very important and hard to estimate, there is probably no alternative to repetitive measurements at different laboratories under as widely varying conditions as possible.

Several possible systematic errors which may have influenced the present results are: (1) the presence of undetected components in the decay curves; (2) photomultiplier instabilities due to the high count rate during the irradiation period; and (3) in the case of gas targets, migration of the radioactivity outward from the beam path during the counting period. These possible sources of error and others were all checked for by varying the measuring conditions, such as the beam current, detector distance, gas-cell pressure, etc., and the analyzing conditions, such as the region of the least-squares fit and the number of assumed activities, but the possibility of relatively large systematic errors cannot be completely eliminated. In contrast to the half-life measurements, the threshold results are in fair agreement with previous work[7,10,16,17] as can be seen from the last two columns of Table II. Our values for the masses of ^{20}Na and ^{36}K are somewhat more precise than previous work. For ^{32}Cl we observe two thresholds 76 ± 16 keV apart, compared with the 86-keV separation found by Overley, Parker, and Bromley[7] and the reported[18] excitation energy of 67 ± 1 keV for the first excited state of ^{32}Cl.

As stated in Sec. I, the comparison of mirror decays provided the prime motivation for this work. However, both the $T_z = -1$ nuclei ^{32}Cl and ^{36}K decay overwhelmingly to excited states of the $T_z = 0$ nucleus while the energetics are such that the $T_z = +1$ member of their triads can only decay to the $T_z = 0$ ground state. In the case of mass 32, the ground-state decay of the $T_z = +1$ nucleus, ^{32}P, is allowed ($1^+ \rightarrow 0^+$) but highly retarded ($\log f_0 t = 7.9$), and so we expect higher-order contributions to its matrix element as well as magnification of the ordinary deviations from mirror symmetry. Equality to the mirror ^{32}Cl decay is not necessarily expected. In actual fact, the $\log f_0 t$ for the β^+ decay of ^{32}Cl to the ^{32}S ground state has recently been reported[10] as $6.7^{+0.3}_{-0.1}$ indicating a considerable deviation from mirror symmetry.

In the case of mass 36, the $T_z = \pm 1$ nuclei ^{36}Cl and ^{36}K, have $J^\pi = 2^+$ ground states,[10] and so the decay to the ^{36}Ar 0^+ ground state is first forbidden and equality of the matrix elements is not expected. As yet, a ground-state branch has not been observed in the decay of ^{36}K to ^{36}Ar.

For all the β^+ decays to the $4n$, $T_z = 0$ nuclei from ^{20}Ne to ^{36}Ar, the largest matrix element is for the superallowed decay to the analog of the $T_z = \pm 1$ ground states. For this decay, we have both Fermi and Gamow-Teller contributions to the decay, and so, in the absence of isospin mixing, we have $\log ft \leq 3.49$; this limit being the value expected for a negligible Gamow-Teller contribution. The data pertaining to these analog decays are collected in Table III. The half-lives and mass excesses are our adopted choices from the data of Tables I and

II. The $\log f_0 t$ values of the last column were calculated from the listed half-lives, β^+ end-point energies, and β^+ branching ratios. From these $\log f_0 t$ values it can be seen that all decays but that of ^{20}Na are consistent with the expected limit. The discrepancy in this case has been discussed.[4] If a fairly reliable theoretical estimate of the Gamow-Teller matrix element could be made, then the $\log f_0 t$ values collected in Table III could be used to investigate the isospin purity of the analog state in the $T_z = 0$ nuclei. For this purpose, more accurate determinations of the branching to these analog states would be valuable and, in the case of ^{28}P, necessary.

We would like to thank our colleagues, G. T. Garvey and D. H. Wilkinson, who collaborated in the inital phases of this work – specifically on the decay of ^{20}Na – and who have provided many useful suggestions.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] D. H. Wilkinson, Phys. Letters 31B, 447 (1970).

[2] D. E. Alburger and D. H. Wilkinson, Phys. Letters 32B, 190 (1970).

[3] D. H. Wilkinson and D. E. Alburger, Phys. Rev. Letters 24, 1134 (1970).

[4] D. H. Wilkinson, D. E. Alburger, D. R. Goosman, K. W. Jones, E. K. Warburton, G. T. Garvey, and R. L. Williams, Nucl. Phys. A166, 661 (1971).

[5] D. H. Wilkinson and D. E. Alburger, Phys. Rev. Letters 26, 1127 (1971).

[6] S. Weinberg, Phys. Rev. 112, 1375 (1958).

[7] J. C. Overley, P. D. Parker, and D. A. Bromley, Nucl. Instr. Methods 68, 61 (1969).

[8] D. E. Alburger and G. A. P. Engelbertink, Phys. Rev. C 2, 1594 (1970).

[9] N. S. Oakey and R. D. MacFarlane, private communication. This is a revision of the value quoted by N. S. Oakey and R. D. MacFarlane, Phys. Rev. Letters 25, 170 (1970).

[10] A. J. Armini, J. W. Sunier, and J. R. Richardson, Phys. Rev. 165, 1194 (1968); J. W. Sunier, A. J. Armini, R. M. Polichar, and J. R. Richardson, Phys. Rev. 163, 1091 (1967).

[11] P. M. Endt and C. Van der Leun, Nucl. Phys. A105, 1 (1967).

[12] N. W. Glass and J. R. Richardson, Phys. Rev. 98, 1251 (1955).

[13] S. W. Breckon, A. Henrikson, W. M. Martin, and J. S. Foster, Can. J. Phys. 32, 223 (1954).

[14] W. C. Anderson, L. T. Dillman, and J. J. Kraushaar, Nucl. Phys. 77, 401 (1966).

[15] R. E. Berg, J. L. Snelgrove, and E. Kashy, Phys. Rev. 153, 1165 (1967).

[16] A. A. Jaffe, G. A. Bissinger, S. M. Shafroth, T. A. White, T. G. Dzubay, F. Everling, D. W. Miller, and D. A. Outlaw, Phys. Rev. C 3, 2489 (1971).

[17] T. G. Dzubay, A. A. Jaffe, E. J. Ludwig, T. A. White, F. Everling, D. W. Miller, and D. A. Outlaw, Bull. Am. Phys. Soc. 15, 1690 (1970).

[18] E. H. Berkowitz and C. P. Browne, Bull. Am. Phys. Soc. 16, 59 (1971).