The half-width of the He^5 ground state was determined by fitting a Gaussian curve to the high-energy side of the proton peak after background was subtracted out. The c.m. half-width was 0.55 ± 0.030 Mev after correction for instrumental contributions.[35]

The cross section for the $He^4(d,p)He^5$ ground state was obtained from the area under the Gaussian curve (Fig. 15) which gave 25 ± 5 mb/sterad and 15 ± 4 mb/sterad at 18° and 24°, respectively. He^4 has the configuration $s^4(J^\pi=0^+)$, while the He^5 ground state has the configuration $s^4p(J^\pi=\frac{3}{2}^-)$; therefore, the stripping reaction $He^4(d,p)He^5$ ground state is expected to be an $l=1$ transition with a single-particle reduced width. By fitting an $l=1$, $r_0=4.5\times10^{-13}$ cm Butler curve to the observed cross sections, a reduced width of 0.05 was determined for this reaction. This value is within the range observed empirically[16] for $l=1$ single-particle stripping reduced widths of bound states, but is approximately a factor of ten smaller than the reduced width obtained from the resonant reaction[36] $He^4(n,n)He^4$.

[35] Other experimental values for the He^5 ground-state half-width are tabulated by Craig, Cross, and Jarvis, Phys. Rev. **103**, 1427 (1956).

ACKNOWLEDGMENTS

We wish to thank Dr. J. B. French for many invaluable discussions and Dr. R. S. Bender and Dr. A. J. Allen for their help during the course of this project.

[36] R. K. Adair, Phys. Rev. **86**, 155 (1952).

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Radioactive Decay of Ne^{23}†

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The beta and gamma radiations of 38-sec Ne^{23} have been studied by means of scintillation spectrometer techniques. Beta transitions were found to the ground, first, and second excited states of Na^{23} with end-point energies equal to 4.39 ± 0.05, 3.95 ± 0.05, and 2.4 ± 0.1 Mev, respectively. Their percent intensities and $\log ft$ values are: 67 ± 3, 5.25; 32 ± 3, 5.38; and 1.00 ± 0.15, 5.88, respectively. Gamma rays are coincident with the latter two beta transitions and with one another; their energies and percent relative intensities are: 436 ± 4 kev; 100; 1647 ± 16 kev, 3.0 ± 0.3, respectively. Higher energy gamma radiation was present in less than 0.2% of all decays. No beta transitions with $\log ft$ values in the superallowed group were found. A decay scheme based on the above data is proposed.

The half-life of Ne^{23} was remeasured together with the half-lives of O^{15} and Ne^{19}. The results are: Ne^{23}, 37.6 ± 0.1 sec; O^{15}, 123.95 ± 0.50 sec; Ne^{19}, 17.7 ± 0.1 sec.

INTRODUCTION

INTEREST in the decay characteristics of the $N-Z=3$ nuclides was stimulated recently by speculations of King,[1] and of Feenberg,[2] into the origin of the reported[3] superallowed transition in Ne^{23}. In this work of Brown and Perez-Mendez[3] the beta spectrum of Ne^{23} was found to consist of two groups with end-point energies of 4.21 ± 0.15 and 1.18 ± 0.04 Mev, and with relative intensities of 93 and 7%, respectively. The log ft value for the lower energy group was given as 3.8, which places the transition in the superallowed class.

In their review of the energy levels of light nuclei Endt and Kluyver[4] pointed out that the end-point energy of the high-energy beta group in the decay of Ne^{23}, as determined by Brown and Perez-Mendez,[3] was in disagreement with the value of 4.388 ± 0.007 Mev which was calculated from Li's[5] compilation of the masses of light nuclei.

For the above reasons we undertook a reexamination of the Ne^{23} decay. A preliminary account of our work has been published in abstract form.[6] Concurrently, Gerber, Muñoz, and Maeder[7] also reinvestigated this radioisotope. Our results are in substantial agreement for the more intense radiations. However, in the work of Gerber *et al.*, contamination from other activities obscured gamma radiation of low intensity above about 500 kev. Nevertheless, they were able to quote a lower limit of 5.0 on the log ft value associated with the beta decay of Ne^{23} to the 3.0-Mev state of Na^{23}.

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[1] R. W. King, Phys. Rev. **99**, 67 (1955).

[2] E. Feenberg, Phys. Rev. **99**, 71 (1955).

[3] H. Brown and V. Perez-Mendez, Phys. Rev. **78**, 812 (1950); V. Perez-Mendez and H. Brown, Phys. Rev. **78**, 812 (1950).

[4] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).

[5] C. W. Li, Phys. Rev. **88**, 1038 (1952).

[6] J. R. Penning and F. H. Schmidt, Phys. Rev. **100**, 954(A) (1955).

[7] Gerber, Muñoz, and Maeder, Helv. Phys. Acta **28**, 478 (1955); and Phys. Rev. **101**, 774 (1956).

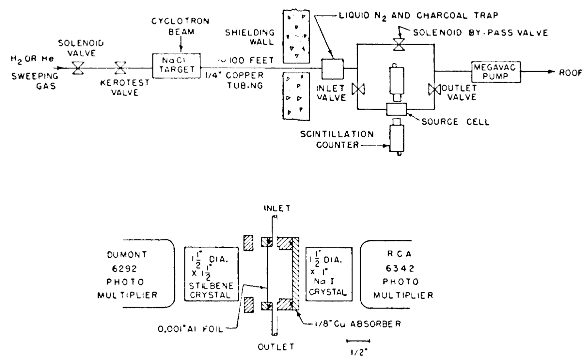

FIG. 1. Experimental arrangement of the gas flow system (top) and the source and counter geometry (bottom).

EXPERIMENTAL METHODS

We produced Ne^{23} by the $(d,2p)$ reaction on Na. A NaCl powdered target was bombarded with 22-Mev deuterons in the University of Washington 60-in. cyclotron.[8] The active gases were swept by means of a continuous flow of helium to a source chamber of small volume located outside the cyclotron shielding wall about 100 ft away from the target. Contaminating activities were removed by an activated cocoanut charcoal trap cooled with liquid nitrogen. Figure 1 is a schematic diagram of the gas plumbing system.

For observation of beta rays the source chamber, shown also in Fig. 1, was covered on one face by a 0.001-in. aluminum foil. Space was provided between the source chamber and counters for the insertion of absorbers.

Beta particles were detected in a stilbene crystal $1\frac{1}{2}$ in. in diameter and $1\frac{1}{2}$ in. high. Gamma radiation was detected in two cylindrical NaI(Tl) crystals, 1 by $1\frac{1}{2}$ in. and 2 by $1\frac{3}{4}$ in., respectively. Both RCA type 6342 and DuMont type 6292 photomultiplier tubes were used. All tubes were checked for variation in gain[9] over the range of counting rates used.

The pulses from the photomultipliers were amplified in conventional non-overloading linear amplifiers and

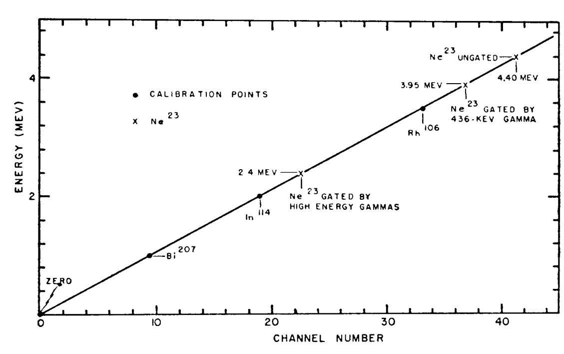

FIG. 2. Energy calibration curve of the beta counter from which the indicated Ne^{23} end-point energies were derived.

[8] Schmidt, Farwell, Henderson, Morgan, and Streib, Rev. Sci. Instr. **25**, 499 (1954).

[9] Bell, Davis, and Bernstein, Rev. Sci. Instr. **26**, 726 (1955).

shaped by means of shorted delay lines. The pulse heights were determined with a single-channel analyzer, or a 20-channel analyzer as required. For coincidence measurements two preamplifier outputs, one differentiating and the other integrating, were provided at each photomultiplier. The differentiated pulses were used to trigger a fast coincidence circuit. One of the integrated pulses could be selected by a single-channel analyzer and, together with the fast-coincidence pulse, used to "gate" the pulses into the 20-channel analyzer from the other detector. The resolving time 2τ of the system was 1.5×10^{-7} sec.

CALIBRATION OF THE DETECTORS

The beta detector was calibrated by using known radiations[10] from several standard radioactive sources; *viz.*, the internal conversion electrons from Cs^{137} (626 kev) and Bi^{207}, and the end points of the beta spectra of In^{114} (1.984 Mev) and Rh^{106} (3.53 Mev). The Bi^{207} internal conversion line was corrected for the finite resolution of the spectrometer (25% at 626 kev) and the K/L internal conversion ratio. The apparent peak of the combination of the K and L lines was 993 kev for our spectrometer.

Calibration with the standard beta spectra was done in the following manner: a Kurie plot of each spectrum was made by using the calibration indicated from Cs^{137} and Bi^{207} electrons. The resulting end point then would differ from the known value by a small amount. This provided a correction to the assumed calibration which was then used to reconstruct the Kurie plot. Usually one such corrective procedure was sufficient to bring the measured end point in agreement with the known end point. All beta spectra were corrected for the finite resolution of the spectrometer in the manner described by Palmer and Laslett.[11] The beta detector was linear to less than one percent. A typical calibration curve is shown in Fig. 2.

The gamma-ray detectors were calibrated in energy and efficiency by using sources of Y^{88} (908 and 1853 kev), Na^{22} (511 and 1277 kev), In^{114} (190, 552, and 722 kev), Cs^{137} (662 kev), Hg^{203} (279 kev), Bi^{207} (569 and 1063 kev), Na^{24} (1368 and 2750 kev), and ThB (2614 kev). Relative efficiencies of the crystals for the photopeaks were determined by measuring the area under two such peaks for pairs of gamma rays of known relative intensity, for example Y^{88}, where the gamma rays are in cascade. Other energy gamma-ray groups were then fitted by interpolation. The points for Na^{22} were corrected for 11% electron capture.[12] For measurement of the higher energy gamma rays a one-half inch lead absorber was interposed between the source and NaI(Tl) detector in order to reduce the more intense

[10] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).

[11] J. P. Palmer and L. J. Laslett, Iowa State College Report ISC-174, 1950 (unpublished).

[12] R. Sherr and R. H. Miller, Phys. Rev. **93**, 1076 (1954).

radiations of lower energy. The efficiencies were also determined for this arrangement in the manner described above.

The relative efficiency calibration curves of the gamma-ray detectors were normalized to total absolute photopeak efficiencies (including the solid angle factor) by coincidence methods. Sources of Na^{22}, Y^{88}, and Bi^{207} were used. The total absolute efficiencies were required in order to measure the beta-decay branching ratios.

It should be noted that most of the calibrating sources were approximately point sources, whereas the Ne^{23} occupied the entire source chamber volume. The effect of this geometrical difference on the relative efficiency calibration was shown to be negligible by comparison of the relative crystal efficiencies obtained for the point sources with that obtained for a volume source[13] of O^{14}. The effect of the volume source on the total absolute efficiency was not negligible, and $\beta-\gamma$ coincidences of O^{14} were used to renormalize the total absolute efficiency curves.

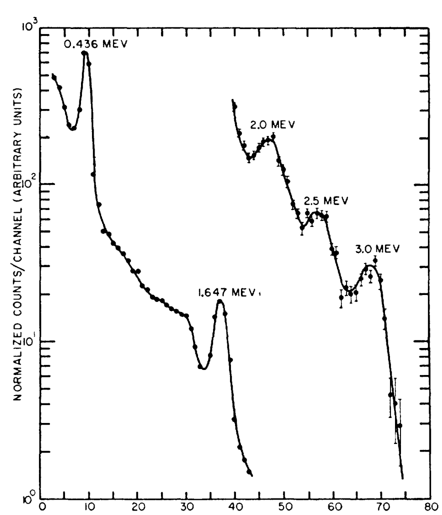

FIG. 3. Pulse-height spectrum of Ne^{23} taken with a $1\frac{3}{4}$-inch diameter 2-inch thick NaI(Tl) scintillation spectrometer through $\frac{1}{2}$ in. of lead.

All data were appropriately corrected for background which was for the most part negligible.

BETA- AND GAMMA-RAY SPECTRA

Figure 3 shows the gamma-ray spectrum of Ne^{23} taken through $\frac{1}{2}$ inch of lead. Two gamma rays are observed: one at 436 ± 4 and the other at 1647 ± 16 kev. The photopeak of the 436-kev gamma ray was then used as the coincidence gate for the 1647-kev gamma ray. The results of this measurement are displayed in Fig. 4 which demonstrates that the two transitions are in cascade. Proof that there are no competing transitions is demonstrated by the fact that the relative intensities of the two gamma rays as measured by coincidence methods is the same as that measured by comparison of their relative photopeak areas after correction for crystal efficiency. The 1647-kev gamma ray is $(3.0\pm0.3)\%$ as intense as the 436-kev gamma ray.

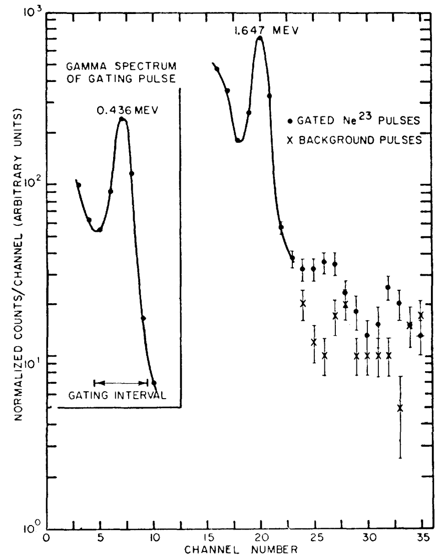

FIG. 4. Pulse-height spectrum of higher energy gammas in coincidence with the photopeak of the 436-kev gamma ray of Ne^{23}. The insert shows the spectrum of the gating pulses together with the gating interval.

The very weak higher energy spectrum, shown in Fig. 3, which extends out to 3.0 Mev was analyzed by successive subtraction into six gamma rays of energies 2.06, 2.20, 2.42, 2.54, 2.87, and 2.99 Mev and with intensities relative to the 1647-kev gamma ray of 0.083, 0.046, 0.010, 0.0215, 0.019, and 0.037, respectively. Although all but one of these six gamma rays can be associated fairly well with transitions between known energy levels[4] of Na^{23}, we believe it unwise to assign them definitely to the decay of Ne^{23}. A check run with improved shielding would have been desirable, but was not feasible because of the limited time available on the cyclotron. The intensities of the higher energy gamma rays were used to set upper limits on possible lower energy beta transitions in the decay of Ne^{23}.

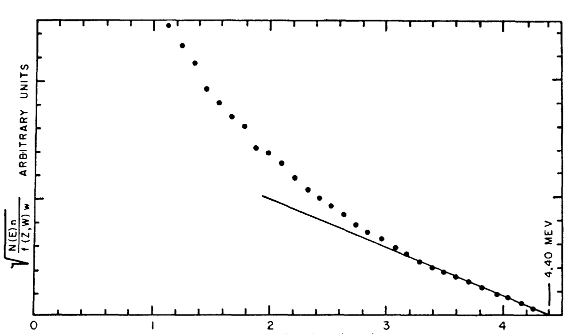

FIG. 5. Kurie plot of the Ne^{23} beta-ray spectrum.

[13] R. Sherr and J. B. Gerhart, Phys. Rev. **91**, 909 (1953); J. R. Penning and F. H. Schmidt, Phys. Rev. **94**, 779(A) (1954).

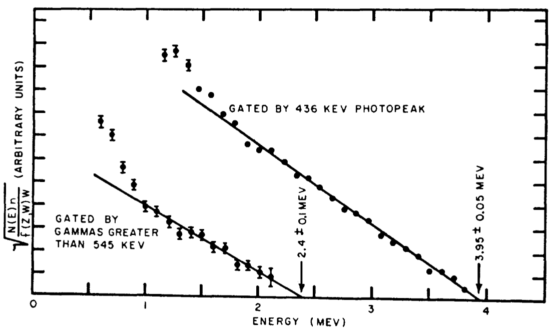

FIG. 6. Kurie plots of the beta-ray spectra of Ne^{23} which are in coincidence with the photopeaks of the indicated gamma rays.

The results of the beta-spectrum studies with the stilbene scintillation spectrometer are displayed as Kurie plots in Figs. 5 and 6. The spectrum in Fig. 5 is the one obtained wihtout demanding a coincident gamma ray. Figure 6 shows the spectra which are in coincidence with the indicated gamma rays. Two gamma-ray gates were used: the photopeak of the 436-kev gamma ray, and all gamma-ray pulses greater than 545 kev which therefore includes the photopeak plus many Compton events due to the 1647-kev gamma ray. The measured end points are 4.40, 3.95±0.05, and 2.4±0.1 for the three transitions. The end point of the intermediate energy transition could be determined with the best precision. Since it is in cascade with the 436-kev gamma ray, we assign a value of 4.39±0.05 Mev to the ground-state beta transition. The intermediate-energy transition thus takes place to the well-known[4] 439-kev level in Na^{23}. The weak 2.4-Mev transition is in cascade with the 1647-kev gamma ray, and is therefore to the 2.08-Mev level[4] in Na^{23}.

The relative intensity of the two higher energy beta transitions was determined by comparing the beta counting rate in a known energy band of the ungated spectrum with the beta counting rate when gated by the 436-kev gamma ray. Each of these counting rates then was normalized to total transitions by assuming each beta decay to be allowed. Finally, the gated spectrum was corrected for total absolute photopeak efficiency of the gamma detector. Ground-state transitions account for (67±3)% of all decays; (32±3)% go to the first excited state of Na^{23}, and (1±0.15)% to the second excited state.

HALF-LIFE MEASUREMENTS

We remeasured the half-life[3] of Ne^{23} and two other short-lived radioisotopes, O^{15} and Ne^{19}, with a new instrument designed for precision measurements of short half-lives. This device converts any amplified pulses (for example, from a single channel pulse analyzer) into pulses the amplitudes of which increase with time in a uniform "stairstep" manner. The length of each step is adjustable by factors of 2, 5, or 10 from 5 msec up to 1000 sec and is obtained by scaling down the output of a crystal-controlled 100 kc oscillator. The output of the unit is analyzed by means of a 20-channel pulse-height selector. The height of each step is made equal to one channel of the analyzer, so that each channel provides one point on a radioactive decay curve.

A decay curve was obtained for the 436-kev photopeak of Ne^{23}. The decay was followed well into the background and no trace of any longer period activity was detected. In order to insure that no active gas leaked out of the source chamber during the decay measurements, manually operated valves were closed at both inlet and outlet. In addition, the system was carefully pretested for possible leaks.

A least-squares analysis of the decay curve (after subtraction of background) gave the value 37.6±0.1 sec. The error quoted is the internal probable error

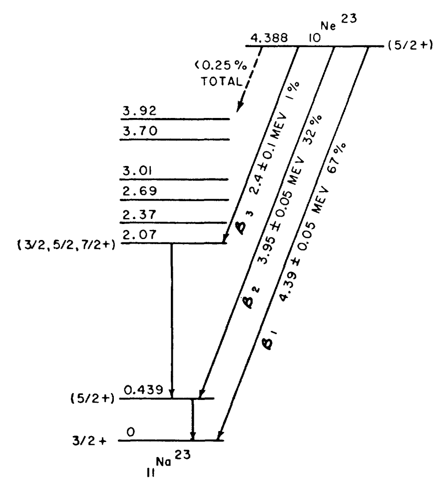

FIG. 7. Decay scheme proposed for Ne^{23}. Indicated energy levels to which no beta transitions were measured are those reported by other groups.

obtained from the analysis. The half-life of scintillation pulses corresponding to energies greater than 800 kev was also measured and found to agree with the lower energy results.

The half-lives of O^{15} and Ne^{19} were also remeasured because of their general interest in beta-decay theory. The O^{15} was made by the $(\alpha,\alpha n)$ reaction on oxygen gas, the Ne^{19} by a (p,n) reaction on fluorine using a gaseous freon target. The results are: O^{15}, 123.95±0.50 sec; Ne^{19}, 17.7±0.1 sec.

DISCUSSION OF RESULTS

The experimental data are summarized in the decay scheme displayed in Fig. 7. Included in the figure are the levels of Na^{23} which have been reported by other groups[4] but to which no beta transitions were observed to occur.

We note that the end-point energy of 4.39±0.05 Mev for the ground-state transition is in excellent agreement with the Ne^{23} disintegration energy (4.388±0.007 Mev) given by Li^5 based on the nuclear reaction studies of Van Patter *et al.*[14]

From our beta-ray end-point measurements and half-life determinations we obtain the log *ft* values 5.25 and 5.38 for the transitions to the ground and first excited states, respectively. These decays are therefore almost certainly allowed. Now the ground-state spin of Na^{23} has been measured to be 3/2 and its parity is undoubtedly even.[15] The first excited state is known from Coulomb excitation studies[16] to have the same parity as the ground state. These data therefore suggest an assignment of 1/2+, 3/2+, or 5/2+ for the ground state of Ne^{23}. Of these, the 5/2+ is that derived from the simple shell theory which would give Ne^{23} a configuration with one neutron less than a closed $d_{\frac{5}{2}}$ subshell. We therefore adopt 5/2+ for the Ne^{23} ground state.

We turn our attention to the first excited state of Na^{23} at 0.436 Mev which can now have any one of the assignments 3/2+, 5/2+, or 7/2+. Since the ground-state spin of 3/2 for Na^{23} is anomalous, and explanations[17] of the anomaly predict a nearby 5/2 state, the assignment of 5/2+ to the first excited state is reasonable. This assignment is consistent with the lifetime measurements for this state by Swann and Porter[18] which show that the 436-kev radiation must be a mixture of $M1$ and $E2$. Our data is consistent with spins 3/2, 5/2, or 7/2, whereas Swann and Porter's work is consistent with 1/2, 3/2, or 5/2. The assignment of 5/2+ is also the one suggested by Krone and Read[19] from an analysis of the angular distribution of the gamma rays which resulted from the inelastic scattering of protons from this state.

The weak beta transition to the second excited state of Na^{23} at 2.08 Mev has a log *ft* value of 5.88. Hence, this decay is also probably allowed. Again, with a 5/2+ state for Ne^{23}, we can say that the second level in Na^{23} must be 3/2+, 5/2+, or 7/2+. On the basis of the upper limit set on the intensity of a direct ground-state transition we conclude that if the state were 3/2+ or 5/2+, then the resulting $M1$ transition must be inhibited by a factor of at least 20 over that to the first excited state. It is therefore tempting to cite this as evidence for an assignment of 7/2+ to the second level. However, in view of the wide range in magnitude of transition probabilities for $M1$ transitions[20] no restriction on the spin assignment has been imposed on this basis.

We find no evidence for a superallowed transition to the 3.01-Mev level as had been reported by Brown and Perez-Mendez.[3] Further, we find no evidence for a superallowed transition to any known level of Na^{23}. From the experimental upper limits set on the intensity of higher energy gamma radiation we can set a lower limit of 4.5 on the log *ft* value to any level in Na^{23} up to an excitation of approximately 4.2 Mev. Thus, not only is there no evidence for a superallowed transition in the decay of Ne^{23} but it is extremely unlikely that one exists. This does not eliminate the possibility that lighter nuclei of the $N-Z=3$ series may exhibit such transitions by the mechanism proposed by King[1] and by Feenberg.[2]

We wish to thank T. J. Morgan and the crew of the University of Washington 60-in. cyclotron for their able assistance in this work. We acknowledge especially the help of H. Fauska with the complex electronic equipment.

[14] Van Patter, Sperduto, Endt, Buechner, and Enge, Phys. Rev. **85**, 142 (1952).

[15] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley and Sons, Inc., New York, 1955), p. 83.

[16] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **96**, 426 (1954).

[17] D. Kurath, Phys. Rev. **80**, 98 (1950); I. Talmi, Helv. Phys. Acta **25**, 185 (1952); A. Bohr, and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).

[18] C. P. Swann and W. C. Porter, Bull. Am. Phys. Soc. Ser. II, **1**, 29 (1956).

[19] R. W. Krone and W. G. Read, Bull. Am. Phys. Soc. Ser. II, **1**, 212 (1956).

[20] M. Goldhaber and J. Weneser, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1955), Vol. 5, p. 1.