Positron polarization from the decay of ^{25}Al relative to ^{26}Al^m

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A comparison of the positron polarization from the decays of ^{25}Al and ^{26}Al^m is reported. A new instrument to perform these measurements has been installed on-line at a cyclotron and is described. The theoretical motivation for this experiment is discussed. Polarization data and results of systematic tests are reported. No difference in polarization was found at the level of 0.48%.

I. INTRODUCTION

We present the first on-line measurements of longitudinal β^+ polarization made with a new system that we call the Positron Polarization Comparator (PPC). The instrument is intended to make comparisons between different isotopes rather than absolute measurements. It has been installed on-line at the Princeton Cyclotron to give access to isotopes having half-lives as short as a few seconds.

The motivation for our work is an exploration of fundamental aspects of the weak interaction. Here theoretical studies[1–3] have shown that departures of order 0.1% from the simple v/c law for polarization as a result of the presence of any of the following effects: (a) Fierz interference terms, (b) the existence of right-handed W bosons having masses of order 0.5 TeV, (c) second-class currents, and (d) time-reversal invariance (T) violation, cannot be excluded on the basis of existing data.

In addition, effects of nuclear structure on beta decay can give rise to similar departures from the v/c law,[2] and must be fully taken into account if the fundamental effects are to be identified or if correct limits on their existence are to be set.

The way that the experiments proceed is that pairs of isotopes are selected for which several of the listed effects are to be nil, or are safely predicted to be the same for both isotopes. An observed result must therefore be due to one or a combination of the remaining effects. Sometimes one of the effects can reliably be calculated, further reducing the range of possible interpretations of the experimental results.

We have investigated the decays of ^{25}Al (mixed Fermi and Gamow-Teller) and ^{26}Al^m (pure Fermi) for a number of technical reasons (see the following) as well as because these isotopes could reveal a polarization difference arising from (a), (b), or (d) above, but are not expected to exhibit second-class currents. There will be a polarization difference arising from the weak magnetism term in ^{25}Al decay, but we have calculated that this will amount to only 3.5×10^{-4} of the polarization.

Polarization comparisons of pure Gamow-Teller decays with pure Fermi decays have greater sensitivity to effects of (b) compared to a mixed/Fermi comparison. In our particular case, ^{25}Al/^{26}Al^m, a factor of 2.5 dilution in sensitivity to right-handed currents is obtained (see Sec. III). Naturally we would have preferred to use a pure Gamow-Teller transition in our comparison; however, we have experienced great difficulty in producing the appropriate enriched ^{30}Si targets that would be necessary to activate the pure Gamow-Teller isotope ^{30}P. We therefore commenced our research with the more simply fabricated ^{25}Mg target so as to gain experience in running our system on-line, as well as to investigate the ^{25}Al nucleus for its own sake. Work with ^{30}P is, in fact, now commencing (Sec. III).

The isotopes ^{25}Al and ^{26}Al^m are readily produced using a proton beam incident upon enriched magnesium targets. Further pragmatic reasons for the choice of these particular isotopes are their similar beta end-point energies and half-lives (Table I). The results reported here are preliminary, but only in the sense that our general type of instruments offers the long-term possibility of precision below the level of 0.1%, which is not likely to be achieved by other known means in the foreseeable future.

The precision of the result presented here, 0.48%, is comparable to that of the work of Wicher *et al.*[4] Their result had a precision of 0.4% in the β^+ polarization comparison of the decays of ^{30}P and ^{26}Al^m. The method of polarization analysis that was used to obtain the Wicher *et al.* result is Bhabha scattering, a technique considerably less statistically efficient than ours, based on positronium formation. The Bhabha-scattering result of 0.4% is considered by those authors[4] to be the most precise achievable with their technique.

TABLE I. Decay data on ^{25}Al and ^{26}Al^m.

Isotope	$T_{1/2}$	$E_{\beta^+}^{max}$ (MeV)	% β^+	logft	Transition
^{25}Al	7.18 s	3.211	99.1	3.57	mixed
		~2.2	0.05	6.2	*G-T*
		~1.6	0.84	4.3	*G-T*
^{26}Al^m	6.36 s	3.256	100	3.48	Fermi

Another project similar to ours is the work of Girard *et al.*[5] They use a β^+ polarimeter like ours, exploiting the properties of positronium formation in a magnetic field. A comparison of the β^+ polarization from the decays of ^{14}O and ^{10}C with a precision of 5.6% has been published by this group.[5] These authors believe that eventual precisions of 0.1% are achievable.

II. THE EXPERIMENT

Our new PPC system is the successor to several earlier instruments[1,6–8] that exploited the phenomenon of positronium formation in a magnetic field. A major drawback to this technique, when applied to β-decay positrons, is the β^+ depolarization in slowing down to positronium formation energies ($\approx$10 eV). We avoid this problem by comparing the β^+ polarization from two sources, but using positrons of the same energy. In the PPC, positrons from a radioactive source are momentum selected by a magnetic spectrometer and directed into the aperture of a polarimeter magnet. Within the field of the magnet, they enter a pellet of magnesium-oxide powder (grain size 5 nm) in which they slow down to energies of a few electron volts, at which a quarter of them form positronium. The relationship between the magnetic induction and the relative formation fractions of the positronium substates has been studied in detail by Gerber *et al.*[7] It is this relationship that we continue to use in our new instrument, which, however, incorporates several major changes since the pioneer researches of Skalsey.[8]

Our new equipment is illustrated in Fig. 1. The PPC includes a 30 cm Varian nuclear magnetic resonance (NMR) electromagnet, which we have operated at 8.8 kG, coaxial with a two-lens magnetic momentum selector (the spectrometer). The Varian magnet has had its yoke and one pole piece bored out axially to permit transmission of particles into the pole gap (see Fig. 2). Parallel to the bored pole face there is a 1-mm-thick transmission plastic scintillator (to time the arrival of positrons) and beyond, against the second pole face, is the pellet of compressed MgO. Positrons from the source with an average energy of 930 keV and energy resolution of 12% are focused into a nearly parallel beam at the entrance to the polarimeter. Since the properties of the spectrometer have been described in detail by Holdsworth and Paul,[9] they will not be repeated here. In the PPC, the velocities of positrons entering the polarimeter are inclined at angles up to 3 deg to the spectrometer axis. Within the pole gap of the polarimeter, we have overcome some of the geometrical problems experienced with a previous polarimeter[8]: Shielding between the transmission counter and the annihilation detectors has proved a major advantage of the PPC, reducing the fraction of observed positron decays not from the MgO target from 7% to less than 0.1%. The larger volume of scintillator in the new detectors has increased detection efficiency to about 13% of all positron annihilations in the MgO pellet, provided the detector outputs are summed through an OR gate. All photomultiplier tubes are magnetically shielded and located far enough away from the magnet (50 cm from photocathode to magnet gap) so that there is no change in gain when the field is reversed. Field reversals are per-

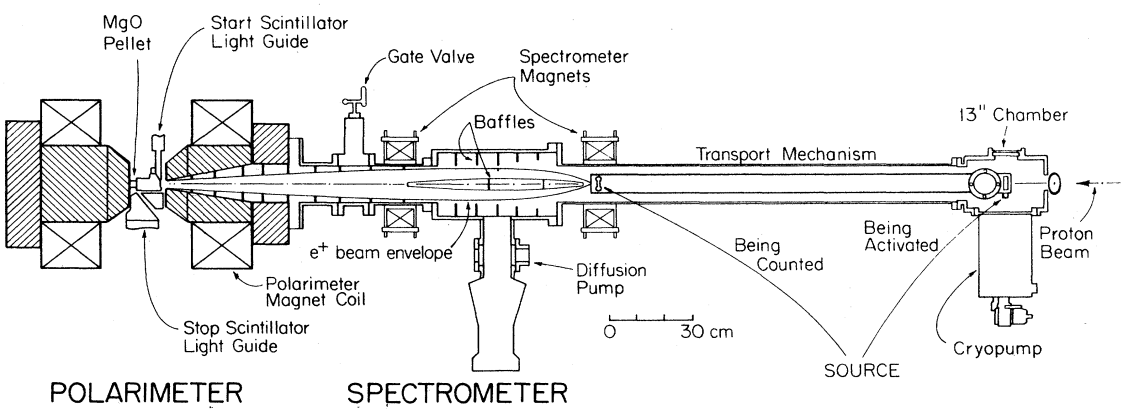

FIG. 1. Positron Polarization Comparator (PPC). The main elements of the PPC are the positron polarimeter and the two-lens, β-ray spectrometer. The source transport mechanism allows one source to be counted while another is being activated. Rapid interchange is programmed as desired with up to eight targets on the transport chain.

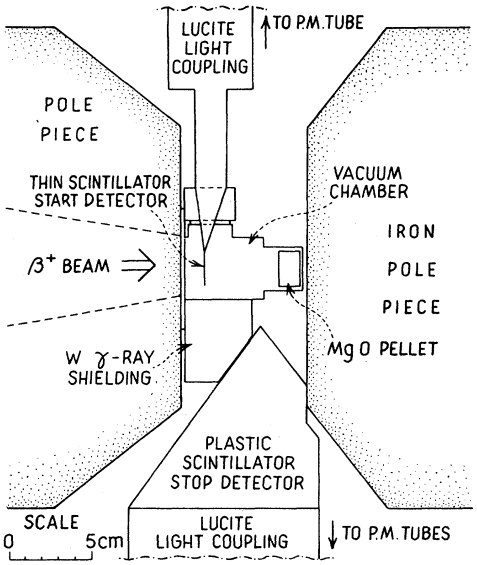

FIG. 2. MgO/detector region. Positrons from the β-ray spectrometer are focused onto the thin scintillator start detector through an axial hole in the magnet pole piece. About 80% of the positions stop in the MgO, and their annihilations are observed in the plastic scintillator stop detectors (one of two shown). The other 20% of the positrons backscatter from the MgO pellet and most stop in the start detector. The tungsten γ-ray shielding prevents these annihilations from being observed by the stop detectors.

formed at approximate 12 h intervals. When we reverse the polarimeter field, we also reverse the fields in the two spectrometer coils. This procedure is used to equalize, as closely as possible, the counting rates at the polarimeter for the two field directions. We observe about 20% fewer counts when the polarimeter field and positron spin are antiparallel as opposed to parallel.

An entirely new feature of the PPC is the chain-driven vacuum transfer mechanism developed to interchange radioactive samples between source position in the spectrometer and irradiation position in the target chamber. The importance of the transfer mechanism in this research is the short transfer time of 1.1 s (recall the 6–7-s half-lives of ^{25}Al and ^{26}Al^m) over the distance of about 1.5 m and the accurate positioning which is reproducible to about 0.003 cm. Since the positioning is of equal accuracy at each end of the transfer, the placement of the radioactive sources in the spectrometer is remarkably constant except in the event of a shifting proton beam. However, our 10-s interchanges of target should average over small random position shifts of proton beam. The transfer mechanism has been described elsewhere by Holdsworth and Paul.[10]

The PPC is operated with the accelerator beam on, so that one target is being irradiated while the other is being counted. We thus halve the required cyclotron time at the high price of having to collect data in the presence of a substantial neutron flux. We were obliged to install extensive shielding around our target chamber, the beam dump, and the polarimeter detectors, but we still detect enough proton beam-related pulses to increase our overall statistical error in $\Delta P/P$ by 33% in the worst case, where P is the polarization.

The raw data consist of time distributions of positrons and positronium obtained using a Lecroy model 4202 CAMAC time digitizer. Start pulses are provided by the transmission counter and stop pulses by the summed annihilation pulses. The entire experiment is controlled by an LSI 11/02 computer. The method of extracting the polarization difference from the time distributions is detailed in Ref. 8.

The Mg targets are typically irradiated with about 2 μA of 10-MeV protons from the Princeton Cyclotron. The proton beam is focused at the target position to a roughly elliptical spot of 1-mm width and less than 2-mm height as viewed from the spectrometer. The Mg targets[11] were prepared by rolling of the enriched metallic material to a thickness of 2 mg/cm^2. The isotopic enrichments of the materials were $>99.7\%$ for ^{26}Mg and $>98.8\%$ for ^{25}Mg. After rolling the Mg foils, both sides were covered with an evaporated, 200-μg/cm^2 Au coating to stabilize the level of oxygen contamination. Directly below the target activation site on the cyclotron beam line, a cryopump is installed to provide the cleanest possible vacuum conditions (typically below 10^{-6} Torr). The well-known phenomenon[12] of carbon accumulation on the foil where the proton beam strikes the target was observed. This carbon gives a negligible effect on our results. The rate of carbon buildup was so slow that only two sets of Mg targets were required to perform these polarization measurements. Also, there is no evidence for the significant loss of Mg material from the targets by sputtering during the proton-beam irradiations. Contaminant activities, primarily ^{13}N, contribute less than 0.5% of the positrons during our polarization measurement. This level of contamination gives a systematic uncertainty of less than 4×10^{-4} in P_L, the longitudinal polarization.

A typical rate of incidence of positrons on the polarimeter is 30 kHz for ^{25}Al and 40 kHz for ^{26}Al^m, measured immediately after a target transfer occurred. The positron arrival rate is measured by the 1-mm thick transmission "start" detector. The proton-beam-related room background in this detector amounted to less than 10% of the observed rate during a typical run.

The positronium (Ps) decay γ rays are observed in two large-volume ($\approx10^3$ cm^3) plastic "stop" scintillators, each coupled to two Amperex XP-2020 photomultiplier tubes (PMT's). Lucite light guides, approximately 50 cm long, couple the scintillator light to the PMT's outside the strong polarimeter field. The four PMT output signals are linearly summed, yielding about 13% efficiency for detecting a Ps decay event. The time-resolution curve is exponential in the flanks with an observed optimized lifetime of 450 ps for promptly annihilating positrons. During a cyclotron run, the proton-beam-related, room background events dominate the stop detector rate and account for about 90% of the pulses. Typical total stop rates are about 40 kHz and are the same at the 3% level for both sources. Corrections for the accidental coincidences that are caused by the background events are made by counting the coincidence rate after the posi-

tronium has decayed. In these experiments, a time window is set starting 750 ns after positronium formation and extending to 1500 ns. The counting rate in this window is used to subtract out the accidental contribution in the perturbed and unperturbed positronium windows. The signal-to-noise ratios for the two sources differ by the same amount as the stop-rate difference, i.e., 3%. The correction procedure for accidental coincidences introduces systematic uncertainty into the polarization comparison at the level of 5×10^{-4}.

The polarization data were taken in a series of cyclotron runs spread over an interval of a year. When all equipment is performing optimally, a statistical uncertainty below 2% is obtained in 24 h for the quantity $\Delta P/P$. Our averaged result for the polarization comparison, including statistics only, is

$$\frac{P(^{25}\mathrm{Al})-P(^{26}\mathrm{Al}^m)}{\bar{P}}=\frac{\Delta P}{P}=-0.0010\pm0.0046\ . \quad (1)$$

A number of tests were performed to study the influence of all of the identified systematic shifts which could occur in the polarization measurements. These include the effects of contaminant activities, differences in count rates, source-positioning errors, room background, proton beam steering, distortion in the Ps lifetime decay spectrum, etc. The correction for the β^+ depolarization in the target foils is calculated using the prescription of Muhlschlegel.[13] We have intentionally made as many parameters as possible to be similar or identical when comparing the two isotopes. For example, the two β^+ distributions have end-point energies that differ by only 1.4%. Hence, the scattering of β^+ from surfaces in the spectrometer will be similar, and the systematic uncertainty in the polarization comparison due to scattered β^+ will be small (0.06%). The 0.06% systematic uncertainty for scattered β^+ is an upper limit derived from an experimental study using the conversion electron line source ^{207}Bi. Even more precise, albeit more indirect limits, were set by studying the off-axis transmission from a long-lived β^+ source (^{68}Ge–^{68}Ga). Combining these results with known scattering distributions[14] yielded a less than 10^{-4} systematic uncertainty due to β^+ scattering in the spectrometer for our polarization measurement. However, we prefer to use the more conservative and more direct conversion electron results in specifying our upper limit of systematic uncertainty arising from scattering. Table II specifies all of the systematic effects for this measurement. The systematic effect with the largest uncertainty is due to the deflections of the positron trajectories when entering the magnetic field of the polarimeter. This effect is discussed in detail in Sec. V of Ref. 8.

Combining the results of the systematic tests and the statistics from the cyclotron runs yields the final result

$$\frac{\Delta P}{P}=-0.0016\pm0.0048\ . \quad (2)$$

This is consistent with equal β^+ polarizations for ^{25}Al and ^{26}Al^m decays.

III. DISCUSSION AND CONCLUSIONS

With a purely $(V-A)$ coupling, there are normal, recoil order corrections to the simple v/c law for polarization. These corrections are expected at a level of $\lesssim10^{-3}$ of the β^+ polarization for ^{25}Al decay ($\lesssim10^{-4}$ for ^{26}Al^m) and have been discussed in detail by Holstein[2] and Girard.[15] The dominant recoil order term in our case is the so-called "weak magnetism" term. Using the conserved vector current (CVC) hypothesis, one can predict the weak magnetism term (b) from normal, electromagnetic properties of the parent/daughter nuclei.[16] For ^{25}Al decay, the difference in the nuclear magnetic moments[17] yields

$$b=-133.14\ . \quad (3)$$

The CVC relation between weak magnetism and moments has been shown in other experiments to be reliable at about the 10% level.[18] Using that uncertainty as the error in b, we expect a polarization deviation[2] from β for ^{25}Al decay of

$$\frac{P-\beta}{P}=3.6(4)\times10^{-4}\ . \quad (4)$$

TABLE II. Systematic effects in the ^{25}Al/^{26}Al^m β^+ polarization comparison.

Systematic effect	$\frac{\Delta P}{P}(^{25}\mathrm{Al}\text{-}^{26}\mathrm{Al}^m)$
Source depolarization	$(0\pm2)\times10^{-4}$
Spectrometer β^+ scattering	$(6\pm6)\times10^{-4}$
Proton beam drift	$(0\pm2)\times10^{-5}$
Source holder positioning	$(0\pm3)\times10^{-5}$
Contaminant β^+ emitters	$(0\pm4)\times10^{-4}$
β^+-trajectory deflections	$(0\pm9)\times10^{-4}$
Lifetime spectra $t=0$ shifts	$(0\pm2)\times10^{-5}$
Proton-beam generated background	$(0\pm5)\times10^{-4}$
Temperature instability	$(0\pm2)\times10^{-5}$
2-ns lifetime component	$(0\pm5)\times10^{-5}$
Count rate difference	$(0\pm3)\times10^{-4}$
Total	$(6\pm13)\times10^{-4}$

We conclude that recoil order corrections are completely negligible at our present level of uncertainty.

As mentioned in the Introduction, there are several non-$(V-A)$-type couplings which, if they exist, could be identified by this polarization experiment. We will discuss the quantitative limits which can be set by our work on the strength of such couplings; however, we first note that there have been numerous other experiments performed to place limits on each of these couplings. While this experiment does not surpass any one of the most restrictive limits for each interaction, it does provide useful, systematically different input for each. The individual limits that are set on each interaction require the assumption that the sum of the contributions from the other interactions is negligible.

The first non-$(V-A)$ coupling we consider is time-reversal (T) violation, which is of interest because of the observed charge conjugation-parity (CP) violation in the decay of neutral kaons.[19] As shown previously,[3,20] while β^+ longitudinal polarization is, in leading order, T even, sensitivity to T violation is obtained through the so-called Coulomb correction terms proportional to αZ. Pure Fermi transitions are sensitive to scalar T-violating couplings, while pure Gamow-Teller transitions are sensitive to tensor T-violating couplings.[3,20] Since the ^{25}Al decay is a mixed transition, there is sensitivity to a combination of scalar and tensor T-violating couplings.[20] Because the tensor T-violating couplings have much more restrictive limits than the scalar T-violating couplings,[3] our $^{25}\mathrm{Al}/^{26}\mathrm{Al}^m$ result sets a limit on the imaginary (and hence T-violating) coupling combination:

$$|\mathrm{Im}(C_S C_V'^* + C_S' C_V^*)| < 0.29 \ . \tag{5}$$

This should be contrasted with the best published limit[21] on T-violating scalar couplings:

$$|\mathrm{Im}(C_S C_A'^* + C_S' C_A^*)| \leq 0.26 \ . \tag{6}$$

Since C_A is 25% larger than C_V, our result sets a different limit which is less restrictive by 38% than that of Eq. (6), but nevertheless confirms the absence of the T-violating effect.

The next coupling is Fierz interference, that is, the admixture of real scalar (C_S) and/or tensor (C_T) couplings into the canonical $(V-A)$ theory.[22] Briefly, the limit that comes from our $^{25}\mathrm{Al}/^{26}\mathrm{Al}^m$ experiment,[2]

$$|\mathrm{Re}(C_S C_V^* + C_S' C_V'^*) - 0.65\,\mathrm{Re}(C_T C_A^* + C_T' C_A'^*)| \leq 0.028 \ , \tag{7}$$

is about 50% less restrictive than the best published limits on Fierz interference.[22] Again, our experimental technique is quite different from those that set the previous limits and so provides a useful check on those previous experiments.

The final coupling is the possible existence of right-handed currents, the so-called $(V+A)$ couplings.[23] Right-handed currents can be described with a right-handed W_R boson having a mass much larger than the normal W_L boson (80 GeV). Theory also allows for a mixing between W_R and W_L, described by a mixing angle, ζ. Our $^{25}\mathrm{Al}/^{26}\mathrm{Al}^m$ experiment is one-third as sensitive to the W_R parameters as the recent polarization work of Wichers *et al.*[4] In their work, a β^+ polarization comparison of a pure Gamow-Teller decay (^{30}P) and a pure Fermi decay ($^{26}\mathrm{Al}^m$) was performed to about the same level of uncertainty as our $^{25}\mathrm{Al}/^{26}\mathrm{Al}^m$ result. The increased sensitivity of $^{30}\mathrm{P}/^{26}\mathrm{Al}^m$ to W_R parameters can be seen from the relation

$$P = \beta \left[1 - 2\delta^2 - 2\zeta^2 + \frac{4(a^2 - c^2)}{a^2 + c^2} \delta\zeta \right] , \tag{8}$$

where δ is the W-boson mass ratio squared,

$$\delta = \left[\frac{M(W_L)}{M(W_R)} \right]^2 , \tag{9}$$

and a and c are, respectively, the Fermi and the Gamow-Teller matrix elements (for ^{25}Al decay, $a=1$ and $c=0.81$). A polarization comparison using $^{30}\mathrm{P}/^{26}\mathrm{Al}^m$ yields

$$\frac{\Delta P}{\beta} = -8\delta\zeta \ , \tag{10}$$

and a $^{25}\mathrm{Al}/^{26}\mathrm{Al}^m$ comparison yields

$$\frac{\Delta P}{\beta} = -3.17\delta\zeta \ . \tag{11}$$

While our result is not as restrictive as that of Wichers *et al.*, both experiments offer useful corroborations of the sophisticated, μ-decay experiment[24] that recently investigated right-handed currents. All of these experimental tests for right-handed currents, using μ and β decay, require the assumption that the associated right-handed neutrino has a mass less than the decay energy.

At present, as a result of the experience gained by the successful operation of the $^{25}\mathrm{Al}/^{26}\mathrm{Al}^m$ β^+ polarization comparison described above, the PPC apparatus at Princeton is being used for a similar comparison between the decays of ^{30}P and $^{26}\mathrm{Al}^m$, the same isotopes used by Wichers *et al.*[4] This new experiment is virtually identical to the one described here. The replacement of the enriched ^{25}Mg foil with an enriched ^{30}Si target[25] is the only major difference between the experiments. We hope to obtain an accuracy commensurate with the Wichers *et al.* result in this comparison, with the principal error being due to statistical uncertainty. The motivation for doing this experiment is twofold: (1) to provide a systematic check on the results of Wichers *et al.* and (2) to investigate questions related to the feasibility of performing a similar experiment with an improved instrument (and adequate ^{30}Si target) at a level of precision which we estimate can be appreciably better than 10^{-3}. A result at this level would cause each of the limits on the non-$(V-A)$ couplings discussed above to be improved beyond the existing sensitivity provided by any other experiment.

In conclusion, we have installed on-line at the Princeton Cyclotron a new β^+ polarimeter capable of performing several interesting experiments with uncertainties below 0.5%. The first experiment, a $^{25}\mathrm{Al}/^{26}\mathrm{Al}^m$ comparison, is now complete and progress on a second experiment has begun.

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[1]M. Skalsey, T. A. Girard, D. Newman, and A. Rich, Phys. Rev. Lett. **49**, 708 (1982).
[2]B. R. Holstein, Phys. Rev. C **16**, 1258 (1977).
[3]M. Skalsey and M. S. Hatamian, Phys. Rev. C **31**, 2218 (1985).
[4]V. A. Wichers *et al.*, Phys. Rev. Lett. **58**, 1821 (1987).
[5]T. A. Girard *et al.*, Z. Phys. A **330**, 51 (1988).
[6]L. A. Page and M. Heinberg, Phys. Rev. **106**, 1220 (1957); A. Bisi *et al.*, *ibid.* **128**, 2195 (1962); L. Dick *et al.*, Phys. Lett. **7**, 150 (1963); J. R. Gilleland and A. Rich, Phys. Rev. A **5**, 38 (1972).
[7]G. Gerber, D. Newman, A. Rich, and E. Sweetman, Phys. Rev. D **15**, 1189 (1977).
[8]M. Skalsey, T. A. Girard, and A. Rich, Phys. Rev. C **32**, 1014 (1985).
[9]D. Holdsworth and D. Paul, Nucl. Instrum. Methods **223**, 79 (1984).
[10]D. W. Holdsworth and D. A. L. Paul, Nucl. Instrum. Methods **A235**, 431 (1985).
[11]Enriched Mg targets prepared by Chalk River National Laboratory from material obtained from Oak Ridge National Laboratory.
[12]G. Blondiaux *et al.*, Nucl. Instrum. Methods **277**, 19 (1984).
[13]B. Muhlschlegel, Z. Phys. **155**, 69 (1959).
[14]H. H. Seliger, Phys. Rev. **88**, 408 (1952); M. S. Hatamian, T. A. Girard, and M. Skalsey, Nucl. Instrum. Methods **222**, 584 (1984).
[15]T. A. Girard, Phys. Rev. C **27**, 2418 (1983).
[16]B. R. Holstein, Rev. Mod. Phys. **46**, 789 (1974).
[17]T. Minamisono *et al.*, Phys. Rev. C **14**, 376 (1976); F. Alder and F. C. Yu, Phys. Rev. **82**, 105 (1951).
[18]H. Brandle *et al.*, Phys. Rev. Lett. **41**, 299 (1978); R. E. Tribble, D. P. May, and D. M. Tanner, Phys. Rev. C **23**, 2245 (1981).
[19]J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. **13**, 138 (1964).
[20]M. Skalsey and M. S. Hatamian, Bull. Am. Phys. Soc. **30**, 1277 (1985).
[21]M. B. Schneider *et al.*, Phys. Rev. Lett. **51**, 1239 (1983).
[22]B. R. Holstein, Phys. Rev. C **16**, 753 (1977).
[23]M. A. B. Beg, R. V. Budny, R. Mohapatra, and A. Sirlin, Phys. Rev. Lett. **38**, 1252 (1977); B. R. Holstein and S. B. Treiman, Phys. Rev. D **16**, 2369 (1977).
[24]A. Jodido *et al.*, Phys. Rev. D **34**, 1967 (1986).
[25]H. J. Kaper *et al.*, Nucl. Instrum. Methods **A254**, 210 (1984); J. van Klinken *et al.*, Phys. Rev. Lett. **50**, 94 (1983).