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SPIN DEPENDENCE OF WEAK INTERACTION IN $\mu^- + p \rightarrow n + \nu$

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The asymmetry coefficient $\bar{a}_0$ of μ-e decay electrons averaged over the two hfs states has been measured with scintillation counters for mesonic atoms of silver and of red and black phosphorus. The meson lifetime τ in these two modifications of phosphorus has also been measured. The relative values of a_0 for red (nonconductive) and black (conductive) phosphorus indicate directly that meson spin relaxation time in mesonic atoms is decreased by the presence of conduction electrons. The values of $\bar{a}_0$ and τ in phosphorus are used to determine the level populations for $F = 1$ and 0, and the probabilities λ_1 and λ_0 for meson capture by the nucleus from these states. The results indicate directly that $\lambda_1 \neq \lambda_0$ (the weak interaction is spin dependent) and $\lambda_0 > \lambda_1$ (capture occurs more rapidly from the $F = 0$ state than from the $F = 1$ state). The lower limit obtained for $\Delta\lambda/\lambda = (\lambda_1 - \lambda_0)/(\frac{3}{4}\lambda_1 + \frac{1}{4}\lambda_0)$ is direct evidence for the A − xV type of interaction.

1. INTRODUCTION

It has been noted in [1] that the measurement of muon capture from the two hfs states can furnish evidence regarding the spin dependence of weak interaction in the process $\mu^- + p \rightarrow n + \nu$. If the capture probabilities for the two states are different, the time dependence of the number of electrons from μ-e decay in isolated mu-mesonic atoms will not be a simple exponential function and the logarithm of the decay curve should exhibit positive curvature. This theory can be checked experimentally only by mu-mesonic atom production in matter. However, mu-mesonic transitions between the hyperfine levels, due to the presence of the medium, can complicate the picture. Telegdi[2] has shown that the existence of transitions and the spin dependence of the interaction can be used in experimental investigations of the type of interaction involved. When the transition probability R is known, the sign and magnitude of the curvature K of the logarithmic decay curve determine the interaction type uniquely. However, the determination of R is very complicated[3-5] and has not yet been accomplished experimentally.[6] It is therefore impossible to arrive at final conclusions regarding the interaction type solely on the basis of the experimental value of K.[6]

Überall[5] and Primakoff[7] have shown that the interaction type can also be determined uniquely by measuring n_1 and n_0, the populations of the states with total angular momenta $F = 1$ and 0, respectively, and $\Delta\lambda$, the difference between muon capture probabilities from these states. The nucleus of phosphorus, having spin $I = 1/2$, is a convenient object for such investigations. Among the allotropic modifications red (nonconductive) phosphorus and black (conductive) phosphorus are of greatest interest, since conduction electrons perform a "catalytic" function by reducing the relaxation time of nuclear spin. It is expected[2,5,7] that because of conversion associated with conduction electrons the difference between n_1 and n_0 for these modifications at the time of muon capture will be sufficient to permit the measurement of these quantities and of $\Delta\lambda$.

In the present work we have determined n_1, n_0, and $\Delta\lambda$ by measuring the asymmetry of the angular distribution of electrons from μ-e decay and the μ^--meson lifetime, in red and black phosphorus.

2. EXPERIMENT

a) Asymmetry of the μ-e decay electron distribution. When the method of [8] is used for the asymmetry measurement the experimental precession curve for nuclei with $I \neq 0$ will represent the superposition of the precession curves of muons decaying from both hfs states. Therefore $\bar{a}_0$, the asymmetry coefficient in the angular distribution $1 + a_0 \cos\theta$ integrated over electron energies, will be the average for the two states. $\bar{a}_0$

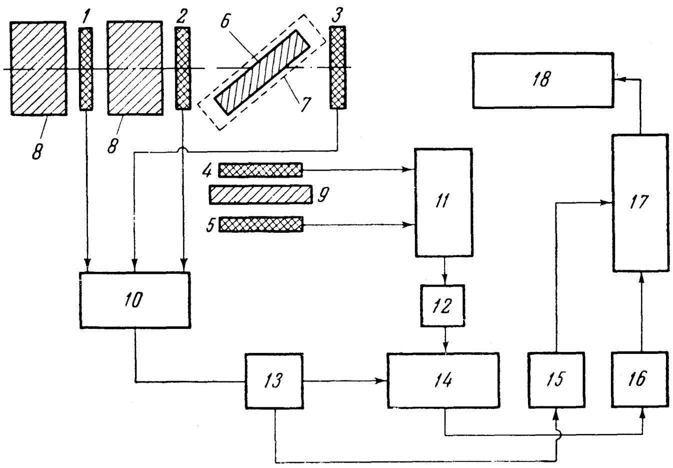

FIG. 1. Block diagram of apparatus. 1 – 5 – scintillation counters; 6 – target; 7 – magnetizing coil; 8 – copper absorbers; 9 – paraffin absorber; 10 – anticoincidence circuit; 11 – coincidence circuit; 12 – delay line; 13 – gate trigger; 14 – gate; 15, 16 – pulse shapers; 17 – converter; 18 – amplitude analyzer.

will be time dependent because of transitions.[5,6] Relative measurements[9,10] averaged over the entire spectrum of a_0 for $I = 0$ show that a_0 is independent of time and the atomic number Z.

If a_0 is independent of Z, a comparison of $\bar{a}_0$ for silver and phosphorus can indicate the populations of the levels $F = 1$ and 0 at the time of muon capture by phosphorus nuclei. In mesonic silver atoms having $I = 1/2$ and nuclear magnetic moment $\mu_N < 0$, transitions will proceed from $F = 0$ to $F = 1$. Since muons are depolarized in the state $F = 0$, while the state $F = 1$ "remembers" the spin direction, transitions do not affect $\bar{a}_0$, which will be constant and equal to $1/2\, a_0$.[11] In mesonic phosphorus atoms having $I = 1/2$ and $\mu_N > 0$, the state $F = 0$ lies lower and conversions will reduce $\bar{a}_0$ with time. For phosphorus at time $t = 0$ we have $a_0 = \bar{a}_{Ag} = 1/2$. Then the effective mean level populations $\bar{n}_1$ and $\bar{n}_0$ for the time interval from 0 to t can be determined (taking $\bar{n}_1 + \bar{n}_0 = 1$ into account) from the relation

$$\bar{a}_P/\bar{a}_{Ag} = \bar{a}_P/\bar{a}_0 = (\bar{n}_1 a_1 + \bar{n}_0 a_0)/\left(\tfrac{3}{4} a_1 + \tfrac{1}{4} a_0\right), \quad (1)$$

where $\bar{a}_P$ and $\bar{a}_{Ag}$ are the values of $\bar{a}_0$ for phosphorus and silver measured during the time from 0 to t, and a_1 and a_0 are the asymmetry coefficients in the $F = 1$ and 0 states depending only on the nuclear spin.[11]

Sulfur and cadmium, which have $I = 0$ and Z close to phosphorus and silver, respectively, can be used as controls to determine whether a_0 is actually independent of Z. Mann and Rose[12] have predicted theoretically that a_0 should be independent of Z for $Z \geq 15$, when the absolute

Element	I	ξ
Cadmium	0	1.10±0.01
Silver	1/2	1.05±0.01
Sulfur	0	1.10±0.01
Red phosphorus	1/2	1.04±0.01
Black phosphorus	1/2	1.00±0.01

quantum yields of the K and L series in mesonic atoms are constant[13] and Auger conversions play only an insignificant role. a_0 and $\bar{a}_0$ can be determined by measuring the numbers of electrons N_{max} and N_{min} for two values of the magnetic field $\pm H$ within which the target is located[14] corresponding to

$$t_1 + \Delta t = T/2 = \pi mc/eH,$$

where t_1 is the delay time, Δt is the gate width, and T is the spin precession period of a "free" meson (for sulfur and cadmium) or of a mesonic nucleus (for phosphorus and silver).

The experimental conditions and apparatus were the same as those used in earlier work.[9,14] Figure 1 is a block diagram of the apparatus. Negative muons stopping in the target 6 were registered by the 1 + 2 – 3 anticoincidence circuit 10. Pulses from 10, delayed 0.1 μsec, opened the gate 12 for the time $\Delta t = 1.2$ μsec. Pulses due to μ-e decay electrons from the 4 + 5 coincidence circuit 11 were transmitted and were registered by a scaler.

We used 15×15 cm targets that were 8 g/cm² thick. In the experiments with sulfur and phosphorus a 7 g/cm² paraffin absorber 9 was placed between counters 4 and 5; for silver and cadmium this was replaced with an aluminum absorber of the same thickness. The registration efficiency for γ rays under 10 Mev emitted from the target as a result of meson absorption was reduced to under 10^{-3} by the aluminum absorber. We used targets and a paraffin absorber of considerable thickness to measure asymmetry at the end of the decay-electron spectrum, where the asymmetry coefficient is larger than a_0.

The values of $\xi = N_{max}/N_{min}$ are given in the third column of the table, after correction for the delay time t_1, the gate width Δt, the muon lifetime τ, and the solid angle of the electron detector. In correcting for meson decay and capture we used values of τ for red and black phosphorus obtained in the present work (see below), while for sulfur, cadmium, and silver we used the values given by Sens.[15]

b) Measurement of the μ^--meson lifetime in phosphorus. When the lifetime is measured conventionally the muon decay curve observed for

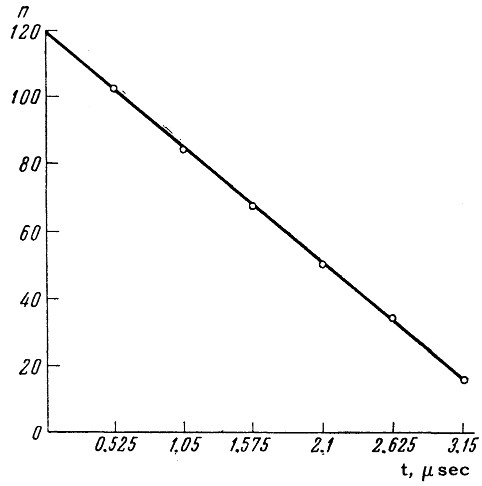

FIG. 2. Analyzer channel number n vs the delay time t between the first and second pulses in the converter.

phosphorus will represent the superposition of the muon decay curves from the two hfs states. Then the measured sum $S = \Sigma t_i n_i / \Sigma n_i$ (where n_i is the number of electrons at time t_i) will be the average over the states F = 1 and 0, since it is easily shown that $S = \bar{n}_1 S_1 + \bar{n}_0 S_0$ (see Appendix I). If the level populations $\bar{n}_1$ and n_0 are known for red and black phosphorus, the measurement of S will obviously determine S_1 and S_0 uniquely and also, consequently, τ_1 and τ_2, the muon lifetimes in the states F = 1 and 0.

Figure 1 is a block diagram of our apparatus. The magnetizing coil 7 compensated the stray magnetic field of the synchrocyclotron. The electronic circuitry functioned as follows. Pulses from the 1 + 2 − 3 anticoincidence scheme 10 actuated the trigger 13, which formed positive rectangular pulses of stable 5 μsec duration. Pulses from the 4 + 5 coincidence circuit 11 were fed through the 5 μsec gate 14; these pulses were delayed 0.2 μsec in 12 before triggering the pulse shaper 16. The delay 12 was introduced in order to register "zero" time between the pulses on the screen of the analyzer 18. Pulses designed to trigger the converter 17 reached its first input from 16 and its second input from the pulse shaper 15, which was triggered by the trailing edge of the pulse from the trigger 13. At the converter output pulses with amplitudes proportional to the time interval between the two pulses to the respective inputs were analyzed with a type AMA-3S 128-channel amplitude analyzer 18.[16]

Linearity of the apparatus was checked with a set of RKZ-401 delay cables producing a 0.52 μsec delay. Delay equality was checked within 0.5% by the resonance method. Figure 2 shows the analyzer channel number n vs the delay t between the two pulses at the converter. Nonlinearity is seen to be under 1%. The calibration was stable to within 1% during 15 hours of operation. The "zero" analyzer channel was determined by placing scintillation counters 1 — 5 along the meson beam axis, with the anticoincidence channels switched off.

The experiments with red and black phosphorus were performed under identical conditions. With black phosphorus during the time interval from 0 to 2.4 μsec (corresponding to 80 analyzer channels) 19 272 electrons were registered, compared with 12 088 in the case of red phosphorus. The time interval from 2.4 to 3.3 μsec was used to determine the background. At t = 0 the electron-to-background ratio was 23. There were 600 gate openings per second, i.e., 6 openings for each accelerator pulse.

For the calculation of S, pulses from four channels were added (for the time interval 0.127 μsec). The results were $S_b = 0.540 \pm 0.007$ μsec for black phosphorus and $S_r = 0.590 \pm 0.012$ μsec for red phosphorus.

3. DISCUSSION OF RESULTS

The table gives equal values of ξ for sulfur and cadmium within statistical error limits. The values of a_0 obtained from ξ agree within error limits with earlier results.[9] Equal values were also obtained for a_0 from our results for ξ for silver and red phosphorus and on the basis of a large number of points on the precession curve for red phosphorus in [17]. In the experiments with black phosphorus the electron counting rate was not observed to depend on the magnet coil current. In the cases of silver and red phosphorus the fact that maximum electron asymmetry is observed at a spin precession frequency of mesonic nuclei that is one-half the spin precession frequency of a free muon again [17] indicates directly that negative muons have spin ½.

The equality of the measured values of a_0 for sulfur and cadmium is in agreement with the theory.[12] Therefore ξ for silver and phosphorus can be used to determine the effective mean populations $\bar{n}_1$ and $\bar{n}_0$ of the F = 1 and 2 levels in the two modifications of phosphorus, using Eq. (1),

$$\bar{a}_P/\bar{a}_{Ag} = (\bar{n}_1 a_1 + \bar{n}_0 a_0) \,/\, \left(\tfrac{3}{4}\, a_1 + \tfrac{1}{4}\, a_0\right),$$

where a_1 and a_0 equal $(2I+3)/3(2I+1)$ and $(2I-1)/3(2I+1)$, respectively.[11] For asymmetry measurements we used the time interval from 0 to 1.3 μsec (two lifetimes τ for red phosphorus[15]). In this time interval we had $\bar{n}_1 \sim 0$,

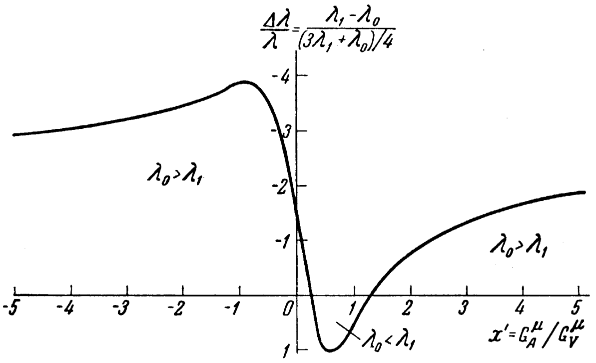

FIG. 3. $\Delta\lambda/\lambda = (\lambda_1 - \lambda_0)/(\frac{3}{4}\lambda_1 + \frac{1}{4}\lambda_0)$ vs $x' = G_A^\mu/G_V^\mu$ for hydrogen.

$\bar{n}_0 \sim 1$ for black phosphorus and $\bar{n}_0 \sim 2/5$, $\bar{n}_1 \sim 3/5$ for red phosphorus. These values of $\bar{n}_1$ and $\bar{n}_0$ indicate considerably different transition probabilities of muons between the hyperfine levels of mesonic atoms in these two modifications. This in turn is a direct indication that the presence of conduction electrons reduces the meson spin relaxation time in mesonic atoms.[2,7,5]

Let us now consider the measurements of S for black and red phosphorus, performed in the time interval from 0 to 2.4 μsec, which corresponds to 4τ for red phosphorus. In virtue of the fact that approximately equal numbers of μ-e decay electrons appeared in the intervals 2τ and 4τ, S can be expressed as follows for the two modifications:

$$S_r = \bar{n}_{1r}S_1 + \bar{n}_{0r}S_0, \quad S_b = \bar{n}_{1b}S_1 + \bar{n}_{0b}S_0. \qquad (2)$$

Deriving S_1 and S_0 from these relations and using the tables of coefficients given by Peierls,[18] we obtain τ_1 and τ_0, the meson lifetimes in the states F = 1 and 0 and, consequently, λ_1 and λ_0, the meson capture probabilities from these states.

In the present work S_b was found to be smaller than S_r. The difference exceeds three standard deviations and is therefore significant. This fact, together with the values of $\bar{n}_1$ and $\bar{n}_0$ for red and black phosphorus, indicates directly by means of (2) that $\lambda_1 \neq \lambda_0$ (the weak interaction is spin dependent) and $\lambda_0 > \lambda_1$ (capture from the state F = 0 proceeds more rapidly than from the state F = 1).

The measurements of S_b and S_r provide a basis for definite conclusions regarding the type of weak interaction in the process $\mu^- + p \rightarrow n + \nu$, if we obtain the lower limit of

$$\Delta\lambda/\lambda = (\lambda_1 - \lambda_0)/\left(\tfrac{3}{4}\lambda_1 + \tfrac{1}{4}\lambda_0\right). \qquad (3)$$

This limit is obtained from (2) with $\bar{n}_1 = \frac{3}{4}$, $\bar{n}_0 = \frac{1}{4}$ for red phosphorus and $\bar{n}_1 = 0$, $\bar{n}_0 = 1$ for black phosphorus (Appendix II). In this case we obtained

$S_1 = 0.61 \pm 0.016$ μsec, $\quad S_0 = 0.54 \pm 0.007$ μsec,
upper limit $\Lambda_1 = \lambda_1 + \lambda_{decay} = 1.42 \pm 0.035$ μsec^{-1},
lower limit $\Lambda_0 = \lambda_0 + \lambda_{decay} = 1.72 \pm 0.022$ μsec^{-1},
lower limit $(\Delta\lambda/\lambda)_{min} = -0.29 \pm 0.04$;

the meson decay probability $\lambda_{decay} = 1/\tau$ was here taken to be 4.505×10^5 sec^{-1}.

Figure 3 shows the dependence of $\Delta\lambda/\lambda$ on $x' = G_A^\mu/G_V^\mu$ for hydrogen, calculated for the interaction type A + xV + P (taking the effect of weak magnetism into account) using Primakoff's formulas.[7] For meson capture by phosphorus $\Delta\lambda/\lambda$ was calculated similarly with $x' = -1.21$ on Schmidt's model, and also on the Mayer-Jensen model, as given by Überall.[5] The results for $\Delta\lambda/\lambda$ were -0.25 and -0.45, respectively. A comparison of these values with Fig. 3 indicates that $\Delta\lambda/\lambda$ for hydrogen is 15 or 9 times greater, respectively, than for phosphorus. $(\Delta\lambda/\lambda)_{min}$ in Fig. 3, allowing for twice the statistical error, indicates that all values $x' > 0$ (on the Schmidt model) and $x' < 0$ in the interval $0 < x' < +5$ (on the Mayer-Jensen model) are excluded, since for $x' \rightarrow +\infty$ we have $\Delta\lambda/\lambda \rightarrow -2.5$.

Our results therefore furnish direct evidence for the interaction type A − xV if we take $|x'| = 1.25$ for β decay. $\Delta\lambda/\lambda$ for phosphorus is found on the basis of S and the effective mean values of $\bar{n}_1$ and $\bar{n}_0$. A comparison with theory[3,5,19] then makes it possible to obtain information regarding the probability of meson absorption by protons in different nuclear shells. We were unable to accomplish this comparison since the error in $\Delta\lambda/\lambda$ was very large as a result of the fact that much uncertainty remained regarding the values of $\bar{n}_1$ and $\bar{n}_0$ obtained by our present method.

In conclusion the authors wish to thank D. Chultém for assistance.

APPENDIX I

We shall prove that $S = \bar{n}_1S_1 + \bar{n}_0S_0$.

Let the sums $S_1 = \Sigma n_{1i}t_i/N_1$ and $S_0 = \Sigma n_{0i}t_i/N_0$ calculated from 0 to t correspond to the exponential functions e^{-t/τ_i} and e^{t/τ_0}. We introduce the notation $N_1 + N_0 = N$, $N_1/N = a$, and $N_0/N = 1 - a$. Adding the sums S_1 and S_0, we obtain

$$S = aS_1 + (1 - a)S_0 = \Sigma(n_{1i} + n_{0i})t_i/N,$$

where $n_i = n_{1i} + n_{0i}$ is the total number of decays at time t_i. If τ_1 and τ_0 do not differ greatly, a and $1 - a$ will obviously equal the level populations $\bar{n}_1$ and $\bar{n}_0$, respectively.

APPENDIX II

S for the two modifications of phosphorus is expressed by

$$a_1 S_1 + (1 - a_1) S_0 = S_{\rm I}, \qquad a_2 S_1 + (1 - a_2) S_0 = S_{\rm II}.$$

We now have the difference

$$S_1 - S_0 = (S_{\rm I} - S_{\rm II})/(a_1 - a_2).$$

The derivatives of the difference $S_1 - S_0$ with respect to a_1 and a_2 are

$$\frac{\partial (S_1 - S_0)}{\partial a_1} = -\frac{S_{\rm I} - S_{\rm II}}{(a_1 - a_2)^2}, \quad \frac{\partial (S_1 - S_0)}{\partial a_2} = \frac{S_{\rm I} - S_{\rm II}}{(a_1 - a_2)^2}.$$

These expressions show that $S_1 - S_0$ decreases as a_1 increases and as a_2 decreases. The minimum of $S_1 - S_0$ will obviously be found at $a_1 \sim \bar{n}_1 = \frac{3}{4}$ and $a_2 \sim \tilde{n}_2 = 0$. Taking $|S_1 - S_0| \sim |\Lambda_1 - \Lambda_0|$, we also obtain the minimum of $|\Lambda_1 - \Lambda_0|$ for $\bar{n}_1 = \frac{3}{4}$ and $\bar{n}_2 = 0$.

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