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# Two-Nucleon Interactions of $K^-$ Mesons in Deuterium*

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Direct measurements of all two-nucleon interactions of stopping $K^-$ mesons in deuterium have been made in a bubble-chamber experiment. The production rates relative to the single-nucleon interactions of $K^-$ are $R(K^-d\to\Sigma^-p)=(0.505\pm0.036)\%$, $R(K^-d\to\Sigma^0n)=(0.337\pm0.070)\%$, and $R(K^-d\to\Lambda n)=(0.387\pm0.041)\%$. The ratio of the rates $R(K^-d\to\Sigma^-p)$ and $R(K^-d\to\Sigma^0n)$ is consistent with the prediction of isotopic-spin invariance for the strong interactions. The total two-nucleon production rate is $(1.22\pm0.09)\%$ and is compared with current theoretical predictions.

IN this paper we report a precise measurement of the total two-nucleon interaction production rate for stopping $K^-$ mesons in deuterium, the first detailed measurements of two-nucleon interaction branching ratios, and a comparison of these rates with the predictions of isotopic-spin invariance for the strong interactions. Our results are based on a sample (which is $\sim$85 times larger than previous data[1]) of 120 000 interactions of $K^-$ mesons at rest in deuterium.

The two-nucleon interaction events were produced by a beam of $K^-$ mesons[2] stopping in the Brookhaven National Laboratory 30-in. bubble chamber[3] filled with liquid deuterium. The two-nucleon production reactions are

$$K^-+d\to\Sigma^-+p \quad (1a)$$
$$\to\Sigma^0+n \quad (1b)$$
$$\to\Lambda+n\,. \quad (1c)$$

The production rates for these rare ($\sim$1%) two-nucleon interactions are measured relative to the single-nucleon interactions which occur in the following channels:

$$K^-+d\to\Sigma^-+\pi^++n \quad (2a)$$
$$\to\Sigma^-+\pi^0+p \quad (2b)$$
$$\to\Sigma^0+\pi^0+n \quad (2c)$$
$$\to\Sigma^-+\pi^0+p \quad (2d)$$
$$\to\Sigma^++\pi^-+n \quad (2e)$$
$$\to\Lambda+\pi^0+n \quad (2f)$$
$$\to\Lambda+\pi^-+p \quad (2g)$$
$$\to\Lambda+\pi^-+\pi^++n\,. \quad (2h)$$

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[1] Data of O. I. Dahl, N. Horwitz, D. H. Miller, J. J. Murray, and P. G. White, reported by L. Alvarez, in Proceedings of the Ninth International Conference on High-Energy Physics, Kiev, USSR, 1959 (unpublished); L. Alvarez, UCRL Report No. UCRL-9354, 1959 (unpublished). We quote the total two-nucleon production rate from the above references. However, in O. I. Dahl *et al.*, Phys. Rev. Letters **6**, 142 (1961), this rate is reported as $\sim$1.2%.

[2] D. Berley, BNL AGS Internal Report No. DB-1, 1963 (unpublished).

[3] C. Alff, N. Gelfand, U. Nauenberg, M. Nussbaum, J. Schultz, J. Steinberger, H. Brugger, L. Kirsh, R. Plano, D. Berley, and A. Prodell, Phys. Rev. **137**, B1105 (1965).

The characteristic feature of the two-nucleon interaction of $K^-$ mesons is the nonproduction of $\pi$ mesons. Therefore the $Q$ is $\sim$140 MeV higher than for the single-nucleon interactions, and hence the two-nucleon $\Sigma$'s and $\Lambda$'s have higher momenta. This fact simplifies and makes feasible the detection of all of the individual two-nucleon production reactions.

The scanning involved a sample of 37 000 pictures with three to four stopping $K^-$ per frame. Two different views of the chamber were used in the search for events. Examples of reaction (1a), $K^-d\to\Sigma^-p$, were found by scanning along beam tracks for $K^-$ which interact and produce an outgoing positive particle ($p$) which is collinear with a heavy particle ($\Sigma^-$) which decays negatively. Collinearity of the two outgoing tracks ensured that the $K^-$ interacted at rest, and eliminated most single-nucleon events. Since the two-nucleon $\Sigma^-$ have high momenta, the $\Sigma^-$ track was required to have a projected length greater than 0.8 cm, which eliminated many examples of the single-nucleon $\Sigma^-$ production reactions (2a) and (2b) which appeared during scanning to be collinear. This projected-length cut reduced the number of $\Sigma^-p$ candidates from $\sim$2800 collinear events to $\sim$800.

Examples of reactions (1b), $K^-d\to\Sigma^0n$, and (1c), $K^-d\to\Lambda n$, were found by searching for high-momentum $\Lambda$ decays $\Lambda\to\pi^-p$. For these reactions, the only tracks which are observed in the bubble chamber are the incoming $K^-$ and $\pi^-p$ pair from the decay of the directly produced $\Lambda$, or from the secondary $\Lambda$ from $\Sigma^0$ decay, $\Sigma^0\to\Lambda\gamma$. In order to identify high-momentum $\Lambda$ hyperons on the scanning table and thereby reduce the number of events to be measured, a cut was made on the proton from the observed $\Lambda$ decays. Events were accepted only if the proton had a projected track length greater than 15 cm or if the proton left the bubble chamber. This scanning cut reduced the number of $\Lambda$'s to be measured from about 25 000 to about 5000, and correction factors were later calculated to compensate for the high-momentum $\Lambda$ events that were eliminated.

The scanning efficiency for all two-nucleon interactions was found to be $(96\pm1)\%$, as determined from an independent rescan of 75% of the film. A record of $\tau$ decays ($K\to\pi^-\pi^-\pi^+$) was made during the frame-by-frame scan of the film. In addition, the scanning also involved searching on every tenth frame of the film for all $K^-$ events which corresponded to single- or two-nucleon interaction topologies or to one of the $K^-$ decay topologies.

Events were measured on a standard film-plane measuring machine, and the measurements were processed in the geometric reconstruction program TVGP[4] and the kinematic fitting program SQUAW.[4] Kinematic fits to all of the $\Sigma^-$ production hypotheses, reactions (1a), (2a), and (2b), were attempted for all of the events in the $\Sigma$ topology which passed the scanning rules. The $\Sigma^- p$ fit, reaction (1a), was a 4- or 5-constraint fit, while the single-nucleon $\Sigma^-$ productions were 1- or 2-constraint fits. Due to the high momentum of the two-nucleon interaction $\Sigma^-$, $p_{\Sigma^-}=510$ MeV/$c$, the $\Sigma^- p$ events were unambiguously separated from the single-nucleon interactions which have $\Sigma^-$ momenta less than 345 MeV/$c$. For each fitted two-nucleon $\Sigma^- p$ event, a weight was calculated to correct for events lost because either the projected length of the $\Sigma^-$ track was short or the $\Sigma^-$ left the chamber without decaying. In this way it was found that our data contain $572\pm37$ $\Sigma^- p$ events. The uncertainty includes the statistical error, the error in the scanning efficiency, and other minor corrections.

The two-nucleon $\Sigma^0 n$ and $\Lambda n$ events from stopping $K^-$ interactions, reactions (1b) and (1c), were found by observing $\Lambda$ hypersons in the high-momentum portion of the entire $\Lambda$ momentum spectrum, which extends from $\sim 0$ to $\sim 650$ MeV/$c$ and includes the single-nucleon interactions, reactions (2c) and (2f). The $\Lambda$'s from $K^- d\rightarrow \Lambda n$ are centered about 587.8 MeV/$c$, which is a consequence of the two-body production kinematics. For the reaction $K^- d\rightarrow \Sigma^0 n$, the $\Sigma^0$ has a momentum of 513 MeV/$c$, and it decays into a $\Lambda$ with $p_\Lambda=75$ MeV/$c$ in the $\Sigma^0$ rest frame. In the laboratory, this secondary $\Lambda$ has a known distribution ranging between 400 and 562 MeV/$c$. The single-nucleon interaction $\Lambda$'s have generally lower momenta, which are peaked well below their kinematic maximum of 442 MeV/$c$, as illustrated by an impulse-model calculation[5] of the spectrum in Fig. 1. The observed $\Lambda$ spectrum in Fig. 1 shows that our scanning cut strongly rejects events below about 350 MeV/$c$. In the region of interest for the two-nucleon interactions, that is, at $\Lambda$ momenta higher than the single-nucleon kinematic limit, the scanning cut caused a small loss of events, ranging from 0% at 650 MeV/$c$ to $\sim$20% at 455 MeV/$c$. The actual $\Lambda$ momentum spectrum between 400 and 650 MeV/$c$ is reconstructed in Fig. 2 by means of a weighting procedure which calculates the probability that an event passes the scanning and analysis cuts. It is important to note that the $\Lambda$'s came from the interactions of $K^-$ at rest.[6]

[4] T. B. Day, University of Maryland Technical Report No. 649, 1966 (unpublished).

[5] R. A. Burnstein, W. C. Cummings, D. L. Swanson, and V. R. Veirs, Phys. Rev. **177**, 1945 (1969).

[6] At low momenta when the rate of energy loss is high, a small uncertainty in the length of a track implies a large momentum error. As a result, the measured momenta unfitted for stopping tracks form a distribution which peaks at positive and negative momenta, symmetric about zero. By studying the measured $K^-$ momentum distribution from a sample of stopping events (400, 4-constraint fits at rest), it was found that $(96\pm1)$% of the total number of stopping $K^-$ are included in the sample of events with measured momenta less than 150 MeV/$c$.

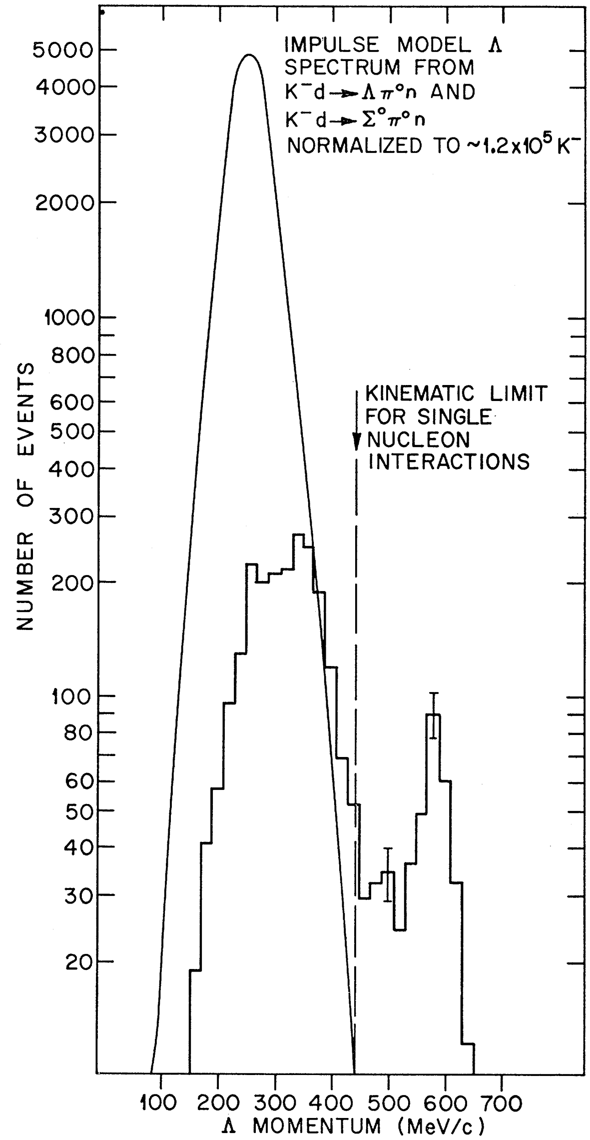


FIG. 1. The histogram represents the unweighted spectrum of fitted $\Lambda$ momenta observed in this experiment from events with $P_{K^-}<150$ MeV/$c$. The superimposed curve is derived from an impulse-model calculation of the expected $\Lambda$ momentum spectrum from the at-rest reactions $K^- d\rightarrow \Lambda\pi^0 n$ and $K^- d\rightarrow \Sigma^0\pi^0 n$, $\Sigma^0\rightarrow\Lambda\gamma$. This single-nucleon spectrum is normalized to the number of stopping $K^-$ in this experiment, $\sim 1.2\times10^5$.

The number of two-nucleon interactions in the $\Sigma^0 n$ and $\Lambda$ channels is determined directly from the spectrum of Fig. 2 by studying the region of $\Lambda$ momenta higher than 500 MeV/$c$, which is significantly above the kinematic maximum $\Lambda$ momentum possible from single-nucleon interactions of $K^-$ mesons at rest, 442 MeV/$c$. There is a negligible probability that measuring errors

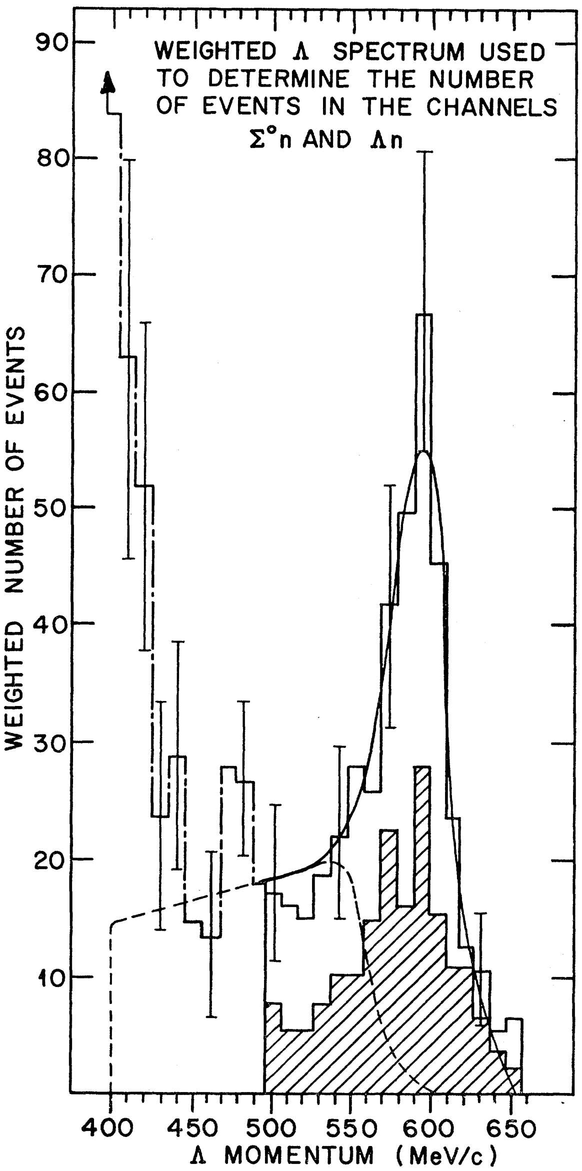


FIG. 2. The fitted Λ momentum spectrum (unshaded histogram) represents the observed spectrum of Fig. 1, after weighting the events for detection efficiencies. The smooth curve is a fit to the Λ spectrum expected for $K^-d\rightarrow\Lambda n$ and $K^-d\rightarrow\Sigma^0 n$, $\Sigma^0\rightarrow\Lambda\gamma$ (above 500 MeV/$c$) and this determines the number of events in each channel. The shaded histogram corresponds to events for which the measured (unfitted) $K^-$ momentum was negative ($p_{K^-}<0$ MeV/$c$) rather than $p_{K^-}<150$ MeV/$c$.

could lead to single-nucleon events with fitted momenta higher than 500 MeV/$c$. This follows since the standard deviation for fitted Λ momenta near 500 MeV/$c$ is ~15 MeV/$c$, and, assuming a Gaussian distribution (which agrees well with observations[7]), single-nucleon events with Λ momenta near the kinematic limit of 442 MeV/$c$ have a probability of $<10^{-3}$ per event of being measured with momenta above 500 MeV/$c$. Therefore, there is a negligible contamination of the two-nucleon interaction sample by events with Λ momenta greater than 500 MeV/$c$ (a total of ≪1 event).

We have investigated the possibility that a small number of in-flight $K^-$ events, which pass the cut $p_{K^-}<150$ MeV/$c$, result in Λ's with $p_\Lambda\geq 500$ MeV/$c$ and thereby contaminate the two-nucleon interaction sample. Under the assumption of maximal $s$-wave inelastic scattering, for $K^-$ with momenta between 0 and 150 MeV/$c$, it has been calculated that approximately 200 events out of ~109 000 interactions take place in which a $K^-$ interacts in flight and produces a single nucleon Λ or $\Sigma^0$ which leads to a charged Λ decay. From studying the impulse-model prediction for the Λ momenta spectrum of these in-flight events, it was found that none of these in-flight events has Λ momenta higher than 500 MeV/$c$. The conclusion, that a negligible number of single nucleon Λ's are measured with momenta higher than 500 MeV/$c$, was checked by plotting the momentum spectrum of Λ's produced by $K^-$ which were "overstopped" (whose momenta had been measured negative). The Λ spectrum from this pure sample of stopping events is shown as the shaded region in Fig. 2. By comparing the two spectra in Fig. 2, it is seen that there is no observable excess of events in the complete spectrum compared to the shaded spectrum near the momentum cutoff of 500 MeV/$c$. This implies that the complete spectrum contains a negligible contamination of in-flight single-nucleon events caused by $K^-$ with momenta between 0 and 150 MeV/$c$.

The analysis of the two-nucleon interaction Λ spectrum of Fig. 2 involved combining the Λ spectrum expected from the decay of $\Sigma^0$ hyperons from isotropic $\Sigma^0 n$ production (the broken curve in Fig. 2), with a Gaussian distribution representing the observed $\Lambda n$ production. The solid curve is the total spectrum, and a fit was performed[8] to the histogram of events with momenta higher than 500 MeV/$c$. The fit had three parameters: the normalization of the Λ spectrum from $\Sigma^0 n$ production, and the normalization and the width of the Gaussian which represents the $\Lambda n$ events. The upper limit of the secondary Λ momentum spectrum was modified by the same Gaussian function to account for the errors in measuring Λ momenta from the $\Sigma^0 n$ sample. The fit has a minimum $\chi^2$ of 8.6 which implies a confidence level of 74%, and the fit determines the number of $\Sigma^0 n$ and $\Lambda n$ events which occurred with associated charged Λ decays. The total number of

[7] We have examined the high-momentum portion of the Λ momentum spectrum (Fig. 2) and find that the data are accurately described by a Gaussian function centered at 587.8 MeV/$c$ (the expected mean value for direct $\Lambda n$ production). Furthermore, the measured $\chi^2$ distribution for the 3-constraint Λ decay events agrees with the theoretical distribution and therefore supports the assignment of Gaussian errors.

[8] The $\chi^2$ fits are performed with the aid of a general minimizing computer program MINIMZ, which was designed by E. West and J. Boyd (private communication).

[9] N. Barash-Schmidt, A. Barbaro-Galtieri, L. Price, A. Rosenfeld, P. Söding, C. Wohl, and M. Roos, Rev. Mod. Phys. **41**, 1 (1969).

events in each channel is found by dividing by the charged $\Lambda$ decay branching ratio $0.653\pm0.012$.[9] This results in a total of $491\pm80$ $\Sigma^0 n$ events and $448\pm46$ $\Lambda n$ events. We have repeated the above analysis and determined the number of $\Sigma^0 n$ and $\Lambda n$ events for different $\Lambda$ momentum cutoffs, and find that the results are substantially unchanged for momentum cutoffs chosen somewhat higher than the kinematic limit of 442 MeV/$c$ (that is, above 455 MeV/$c$).

The total number of $K^-$ interactions at rest was determined in order to calculate the absolute production rates. This number was found by counting, on every tenth frame, all $K^-$ which produced one or more visible prongs such as charged pions or $\Sigma$'s, and all $K^-$ for which the interaction vertex had zero prongs and an associated charged $\Lambda$ decay. The only events which were omitted by this procedure were zero-prong events ($\Lambda\pi^0 n$, $\Sigma^0\pi^0 n$, $\Lambda n$, $\Sigma^0 n$) in which the $\Lambda$ decays neutrally. These events were corrected for by scaling up the observed number of zero-prong events with $\Lambda$ decays by the charged $\Lambda$ decay branching ratio.[9] The $K^-$ decays were removed from the sample by computing the total expected number of decays from the observed number of $\tau$ decays ($K^-\to\pi^-\pi^-\pi^+$). After subtracting the decays and correcting for the scanning efficiency, the resulting sample is the total number of interactions of $K^-$ mesons both at rest and in flight. To determine the fraction of $K^-$ interaction events at rest, a sample of 605 randomly selected $K^-$ tracks was measured. By comparing the unfitted $K^-$ momentum spectrum to the corresponding spectrum from 400, 4-constraint fits at rest, it was found that $(88\pm2)\%$ of all of the $K^-$ interactions occurred at rest. In this way the number of stopping interactions was found to be $115\,900\pm3200$.

We obtain the following two-nucleon production rates relative to the number of single-nucleon interactions:

$$R(K^-d\to\Sigma^-p)=0.505\pm0.036\% \quad (572\pm37 \text{ events}),$$

$$R(K^-d\to\Sigma^0n)=0.337\pm0.070\% \quad (391\pm80 \text{ events}),$$

$$R(K^-d\to\Lambda n)=0.387\pm0.041\% \quad (448\pm46 \text{ events}),$$

$$R(K^-d\to\Sigma^0n)/R(K^-d\to\Sigma^-p)=0.68\pm0.15,$$

$$R(K^-d\to\Lambda n)/R(K^-d\to\Sigma^-p)=0.78\pm0.09.$$

The total two-nucleon production rate is $(1.22\pm0.09)\%$. This result agrees with a previous measurement of Dahl *et al.*[1] of $(0.90\pm0.22)\%$, based on $\sim$15 events. These results can also be compared with measurements of the $\Sigma^-p$ and $\Lambda n$ production cross sections for in-flight $K^-$ interactions by Cline *et al.*,[10] which imply that the $\Lambda n$ to $\Sigma^-p$ ratio is $1.2\pm0.6$ at 340 MeV/$c$ and is $1.0\pm0.2$ at 400 MeV/$c$.

The assumption of isotopic-spin invariance for the two-nucleon interaction leads to the prediction that the $\Sigma^0 n$ to $\Sigma^-p$ branching ratio should be $\frac{1}{2}$, which is about 1 standard deviation from the value of $0.68\pm0.15$ measured in this experiment. Small departures from the expected value of $\frac{1}{2}$ could be attributed to the kinematic effect of the mass differences ($\Sigma^0$-$\Sigma^-$, $n$-$p$) between the final states ($\sim\frac{1}{2}\%$ increase in the ratio), the possibility of isotopic-spin mixing between the $\Sigma^0$ and $\Lambda$ hyperons[11] [$\lesssim(6\pm2)\%$ increase in the ratio], and the effect of the $K^-$-$\bar{K}^0$ mass difference on the initial-state isotopic-spin wave function.[12]

Our rates can be compared to the rates predicted by several theoretical calculations which deduce the two-nucleon absorption rates in deuterium by combining one-pion and one-kaon exchange amplitudes to obtain the total scattering amplitudes. The phase difference between these two single-particle exchange amplitudes is unknown, and therefore these calculations only yield maximum and minimum limits on the rates. Burhop *et al.*[13] obtain the results $R(K^-d\to\Sigma^-p)=0.094$–$0.400\%$, $R(K^-d\to\Sigma^0n)=0.049$–$0.236\%$, $R(K^-d\to\Lambda n)=0.067$–$0.378\%$, and $R_{\text{tot}}=0.21$–$1.01\%$. Fowler and Poulopoulos,[14] in a more recent calculation, set a small upper limit on the total two-nucleon rate $R_{\text{tot}}=0.29$–$0.87\%$. Also, Fowler and Poulopoulos[14] attempt to include the effect of a $Y^*$ resonance and obtain the limits $R_{\text{tot}}=0.82$–$1.64\%$. Reitan[15] calculates limits on the two-nucleon branching ratios for six different sets of $K^-$ nucleon scattering lengths. For example, the scattering-length solution (II) of Kim[16] yields the result that the ratio $(K^-d\to\Lambda n$ or $\Sigma^0 n)/(K^-d\to\Sigma^-p)$ has a minimum value of 0.2 and a maximum of 3.7 (we find $1.47\pm0.17$). Our measured rates are in basic agreement within the broad limits of these calculations. However, our precise measurements of the two-nucleon interaction production rates and branching ratios for $K^-$ mesons in deuterium suggest the need for more accurate theoretical predictions. In addition, our measurements could be useful for calculations of two-nucleon production in heavier nuclei.

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[10] D. Cline, R. Laumann, and J. Mapp, Phys. Letters **27B**, 577 (1968).

[11] R. Dalitz and F. Von Hipple, Phys. Letters **10**, 153 (1964); M. Wellner, *ibid.* **7**, 355 (1963).

[12] The $K^-$-$\bar{K}^0$ mass difference is found to change the prediction for the single-nucleon interaction branching ratios from $K^-$ in deuterium by inducing an $I=\frac{3}{2}$ component into the initial-state wave function [R. H. Dalitz and R. Chand, Ann. Phys. (N.Y.) **20**, 1 (1962)], and this may also change the two-nucleon interaction branching ratio prediction [R. H. Dalitz (private communication)].

[13] E. Burhop, A. Common, and K. Higgins, Nucl. Phys. **39**, 689 (1966).

[14] G. Fowler and P. Poulopoulos, Nucl. Phys. **77**, 689 (1966).

[15] A. Reitan, Nucl. Phys. **B11**, 170 (1969).

[16] J. K. Kim, Phys. Rev. Letters **14**, 29 (1965).