[4]R. E. Behrends, R. J. Finkelstein, and A. Sirlin, Phys. Rev. 101, 866 (1955).

[5]T. Kinoshita and A. Sirlin, Phys. Rev. 107, 593, 638 (1957); 113, 1652 (1959).

[6]S. M. Berman, Phys. Rev. 112, 267 (1958).

[7]S. M. Berman and A. Sirlin, Ann. Phys. (N.Y.) 20, 20 (1962).

[8]J. D. Bjorken, Phys. Rev. 148, 1467 (1966).

[9]The symbols $\not{\pi}^0$, $\not{\pi}$, etc., stand for $\gamma\cdot p$, where p is the momentum of the indicated particle. Our pion states are normalized so that $\langle\pi|\pi'\rangle = (2\pi)^3 2E\,\delta_3(\vec{p}-\vec{p}')$.

[10]S. Fubini and G. Furlan, Physics 1, 229 (1965).

[11]The equal-time commutator $[t_{+0}(\vec{x},t), t_{-0}(\vec{y},t)] = 2t_{30}(\vec{x},t)\delta_3(\vec{x}-\vec{y})$ has been used to obtain the first term on the right-hand side of Eq. (4). The correct expression includes a factor of Z_3 in this term, which we have omitted. The diagrams to which it corresponds have also been omitted, so that our calculation is in fact correct. We shall explain this fine point elsewhere.

[12]We are assuming here that A is real, which follows from TP conservation. Since the proof of Eq. (6) [see S. L. Adler, Phys. Rev. 139, B1638 (1965)] depends upon minimal electromagnetic coupling, which implies C invariance, we have assumed TP symmetry from the beginning.

[13]Simply set $D_{\mu\nu}(k) = a(k^2)k_\mu k_\nu$ in (11). The first term can be evaluated using $k_\mu k_\nu(\partial/\partial k^0)T_{\mu\nu} = 2\sqrt{2}E$, which follows from (9) and (12). Then the three terms proportional to e^2 vanish.

[14]R. P. Feynman and G. Speisman, Phys. Rev. 94, 500 (1954).

[15]H. Harari, Phys. Rev. Letters 17, 1303 (1966); R. E. Norton and G. H. Thomas, to be published; S. Coleman and H. J. Schnitzer, Phys. Rev. 136, B223 (1964).

SPIN AND PARITY OF THE $K^*(1420)$ MESON†

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The existence of the $I=\frac{1}{2}$ $K^*(1420)$ meson has been established in many experiments.[1-8] Studies of the $K^*(1420)$ decay angular correlations[1,2,4] have ruled out $J^P=0^+$ and suggested 2^+ as the likely J^P value. However, uncertainties due to large background and/or the absence of independent information of the $K^*(1420)$ alignment do not permit one to rule out 1^- and 3^-. We report here an analysis of a relatively clean $K^*(1420)$ sample, in which we make use of the production dynamics to ascertain the resonance alignment. Although model-dependent assumptions are used, the inherent discrimination among spin-parity values is so marked that we consider the analysis sufficient to rule out 1^- conclusively, and to make 3^- unlikely.

The data discussed below come from 4.6- and 5-BeV/c K^-p interactions, obtained in an exposure of ~300 000 pictures in the Brookhaven National Laboratory 80-inch hydrogen chamber.[9] The production of the $K^*(1420)$ is observed in the two readily identifiable reactions

$$K^- + p \to \bar{K}^0 + \pi^- + p \tag{1}$$

and

$$K^- + p \to \bar{K}^0 + \pi^+ + \pi^- + n, \tag{2}$$

containing 1180 and 1500 events, respectively. Investigation of all two- and three-particle mass combinations reveals that there is little N^*, ρ, or Y_0^* formation, both final states being dominated by $K^*(890)$ production. Moreover, there appear to be no kinematically induced complications[10] (e.g., Deck mechanisms) in Reaction (2). These circumstances simplify the interpretation of the mass spectra relevant to the identification of the $K^*(1420)$, i.e., the $M(K\pi)$ spectrum from Reaction (1) and the $M(K\pi\pi)$ spectrum from Reaction (2). These spectra are shown in Figs. 1(a) and 1(d), respectively. From these figures one sees that Reactions (1) and (2) contain the quasi-two-body reactions

$$K^- + p \to K^{*-}(1420) + p, \quad K^{*-}(1420) \to \bar{K}^0 + \pi^- \tag{3}$$

and

$$K^- + p \to K^{*0}(1420) + n, \quad K^{*0}(1420) \to \bar{K}^0 + \pi^+ + \pi^- \tag{4}$$

with about 70 $K^*(1420)$ events in each channel. The combined enhancements yield a mass and

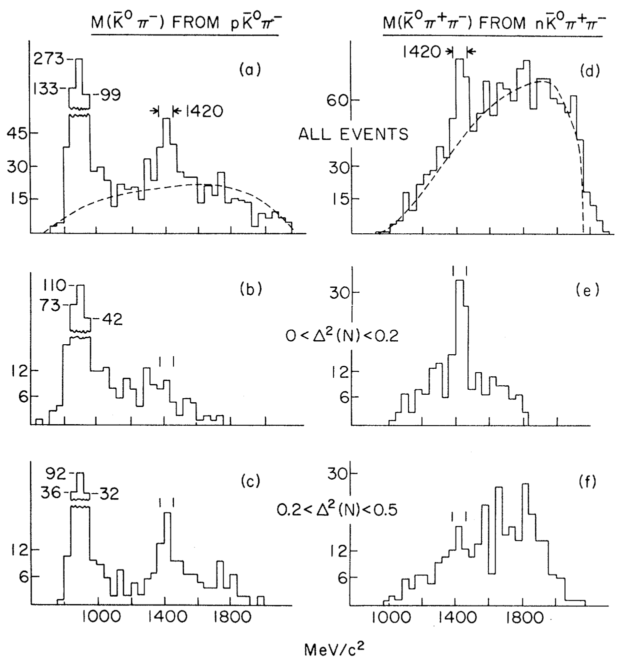

FIG. 1. Invariant-mass spectra $M(K\pi)$ and $M(K\pi\pi)$ from Reactions (1) and (2), respectively. (a) $M(\bar{K}^0\pi^-)$ from $p\bar{K}^0\pi^-$, for all events; (b) for $0<\Delta^2(p)<0.2$; and (c) for $0.2<\Delta^2(p)<0.5$; (d) $M(\bar{K}^0\pi^+\pi^-)$ from $n\bar{K}^0\pi^+\pi^-$, for all events; (e) for $0<\Delta^2(n)<0.2$; and (f) for $0.2<\Delta^2(n)<0.5$. The dotted curves are phase-space distributions.

width of $M=1425\pm5$, $\Gamma=70\pm10$ MeV, consistent with estimates obtained in other experiments.[11]

The production angular distributions of Reactions (3) and (4) can be inferred from Fig. 1, where we exhibit the mass spectra for various regions of momentum transfer (Δ^2) to the nucleon.[12] The forward peaking of both reactions is evident, and suggestive of the presence of meson-exchange production mechanisms. The neutral $K^*(1420)$ production is very strongly peaked, being essentially confined to the region $\Delta_{\min}{}^2\leq\Delta^2(n)\leq0.2$ (BeV)^2. On the other hand, the charged $K^*(1420)$ production is large in the region 0.2 (BeV)$^2\leq\Delta^2(p)\leq0.5$ (BeV)^2. This pattern is similar to that observed in $K^*(890)$ production in the intermediate energy range,[13] and has been successfully interpreted[14] in terms of a peripheral model involving only π and ω exchange.[15] In the $K^*(890)$ case, it is found that in final states requiring the exchanged particle to be charged, only π exchange is necessary, whereas both π and ω (with ω dominant) contribute when the exchanged particle is neutral; no other exchanges are required. In Fig. 2 we exhibit data on $K^{*-}(890)$ production[16] at our energy which are relevant to the validity of the simple $\pi+\omega$ exchange model. One sees that the Δ^2 distribution is consistent with expected ω dominance.[17] More importantly, the polar and azimuthal decay angular distributions agree quite remarkably with the distributions expected from ω dominance in the region $\Delta^2>0.2$. The predicted distributions do not include any modifications due to absorption.

Since $K^*(1420)$ and $K^*(890)$ production appear to have similar behavior, as discussed above, we shall assume for purposes of further analysis that Reaction (3) proceeds via $\pi^0+\omega^0$ exchange while Reaction (4) proceeds via pure pion exchange.[16] We emphasize, however, that conclusions of the ensuing analysis hold even with a much weaker version of the model, in which ρ and A_2 exchange are permitted. The essential assumption is that the dominant isospin-0 exchange contribution is due to the ω.

Since the π and ω have different spins as well as isospins, their individual contributions to $K^{*-}(1420)$ production are incoherent (ignoring absorptive effects). With such incoherence, the relative rate of $K^{*0}(1420)$ vs $K^{*-}(1420)$ production as a function of Δ^2 can be written in terms of general isospin-0 (vector) and isospin-1 (pseudoscalar) exchange amplitudes,

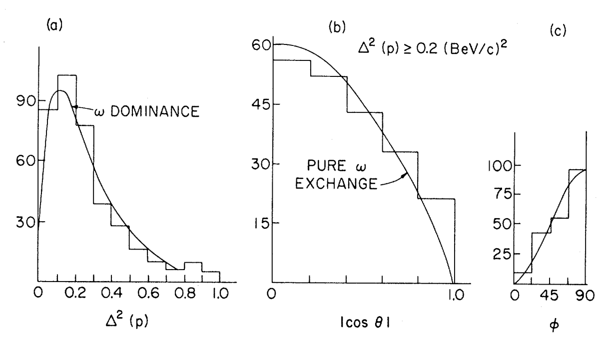

FIG. 2. $K^{*-}(890)$ production in $K^-+p\to p+\bar{K}^0+\pi^-$. (a) Distribution of momentum transfer $\Delta^2(p)$ between target proton and outgoing proton[17]; (b) distribution of $\cos\theta$ folded about $\cos\theta=0$, where the Jackson angle (Ref. 14) θ is the angle between the decay $\bar{K}^0$ and the incident K^- taken in the center of mass of the $K^*(890)$; and (c) distribution of the Yang-Treiman angle φ, folded successively about $\varphi=180°$ and 90°. The angular distributions are symmetrical before being folded. The solid curves are for pure ω exchange.

say $a_0(\Delta^2)$ and $a_1(\Delta^2)$, as follows:

$$R(\Delta^2) \equiv \frac{[K^- + p \to K^{*0}(1420) + n]}{[K^- + p \to K^{*0}(1420) + p]}$$

$$= 4 \frac{|a_1(\Delta^2)|^2}{|a_1(\Delta^2)|^2 + |a_0(\Delta^2)|^2} \equiv 4\gamma(\Delta^2).$$

Here $\gamma(\Delta^2)$ represents the fraction of pseudoscalar exchange in Reaction (3). It is, therefore, equivalent to the standard density matrix element $\rho_{00}{}^3$ for Reaction (3).[18] In practice, of course, we shall consider the above relation averaged over a range of Δ^2 and denote the averaged quantities by $\langle R\rangle$, $\langle\rho_{00}{}^3\rangle$, etc. Now, the ratio $\langle R\rangle$ may be obtained from the directly measurable ratio

$$\bar{r} = \left[\begin{array}{l} K^- + p \to K^{*0}(1420) + n \\ \qquad\qquad \llcorner\!\to \bar{K}^0 + \pi^+ + \pi^- \end{array}\right] \Bigg/ \left[\begin{array}{l} K^- + p \to K^{*-}(1420) + p \\ \qquad\qquad \llcorner\!\to \bar{K}^0 + \pi^- \end{array}\right]$$

with the use of appropriate Clebsch-Gordan coefficients and the known[5,6] branching ratio $\beta = [K^*(1420) \to K + \pi]/\{[K^*(1420) \to K^* + \pi] + [K^*(1420) \to K + \rho]\} = 0.6 \pm 0.2$.[19] One finds in this way

$$\langle\rho_{00}{}^3\rangle \approx \tfrac{1}{4}(3\beta/2)\bar{r} \qquad (5)$$

for Reaction (3).[19] In addition, by limiting the possible exchanges to π and ω we have required that $\langle\rho_{00}{}^4\rangle = 1$ for Reaction (4). These conditions on $\langle\rho_{00}{}^i\rangle$ essentially determine the $K^*(1420)$ alignment.

We now consider the decay angular distributions of the $K^*(1420)$ from Reactions (3) and (4), using the coordinate system of Jackson.[14] For the $K\pi\pi$ decay of the $K^{*0}(1420)$ we use the angles of the normal to the decay plane,[20] while for the two-body decay of the $K^{*-}(1420)$ we use the direction of one of the decay products.

The experimental distributions in θ and φ for the $K^*(1420)$'s produced with $\Delta^2 < 0.2$ (BeV)^2 in Reaction (4) are shown in Figs. 3(a) and 3(b), respectively. The distribution of background events, inferred from a study of neighboring mass bins, has been subtracted. The solid curves, normalized to the total number of events, show the predicted angular distributions (assuming $\langle\rho_{00}{}^4\rangle = 1$) for the various J^P assignments.[21] The comparisons in Figs. 3(a) and 3(b) show that the φ distribution is isotropic, consistent with the model, but that the θ distribution is not very sensitive to the assumed J^P value.[22]

The situation is quite different for Reaction (3). Here we use Eq. (5) to determine $\langle\rho_{00}{}^3(\Delta^2)\rangle$. In Table I we show the measured values of $\langle\rho_{00}{}^3\rangle$ for the intervals $\Delta^2 < 0.2$ (BeV)^2 and 0.2 (BeV)^2 $< \Delta^2 < 0.5$ (BeV)^2. We note that in the region of low momentum transfer $\langle\rho_{00}{}^3\rangle$ is poorly determined; it is, nevertheless, consistent with

Table I. Measured values of $(1420)^-$ alignment parameter.

Δ^2 Interval	$\bar{r}$	$\langle\rho_{00}{}^3\rangle$
Δ^2_{min}-0.2	7_{-4}^{+00}	1.6_{-1}^{+00}
0.2–0.5	<0.7	<0.2

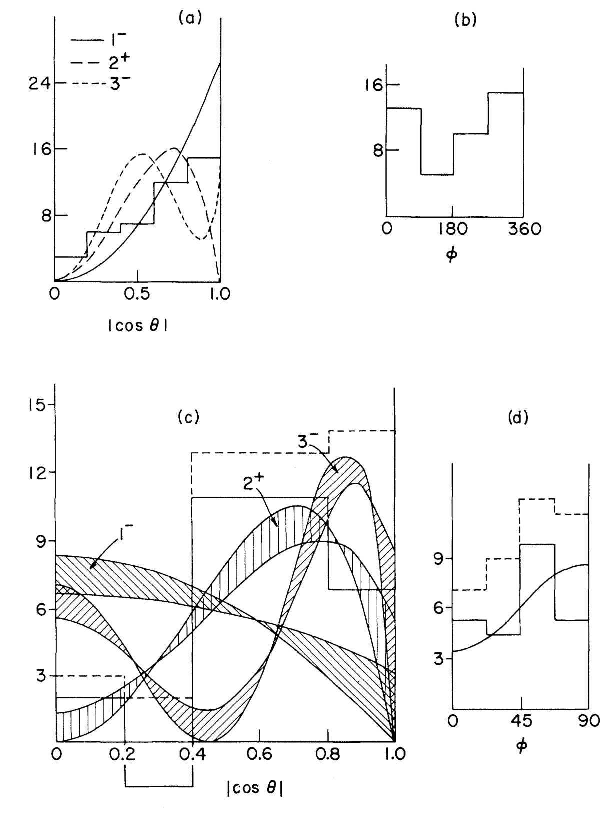

FIG. 3. Decay distributions for the $K^*(1420)$. (a) and (b) Decay angles for the normal to the three-body decay plane for the $K^{*0}(1420)$ selected with $0 < \Delta^2(n) < 0.2$. (c) and (d) Decay angles for the $K^{*-}(1420)$ selected with $0.2 < \Delta^2(p) < 0.5$. Before folding, the distributions are symmetrical. The curves are normalized to the solid-line histograms which have background subtracted; the dashed histograms do not have any background subtraction.

Table II. χ^2 values for J^P analysis.

	Reaction (4)[a] Background subtracted		Reaction (3)[b] Background subtracted			No background subtracted		
			$\chi^{2\,c}$			χ^2		
J^P	χ^2	Degrees of freedom	$\langle\rho_{00}{}^3\rangle=0$	$\langle\rho_{00}{}^3\rangle=0.2$	Degrees of freedom	$\langle\rho_{00}{}^3\rangle=0$	$\langle\rho_{00}{}^3\rangle=0.2$	Degrees of freedom
1^-	5	4	31	22	4	101	72	4
2^+	5	4	7	7	4	11	8	4
3^-	10	3^d	17	15	4	31	22	4

[a] $1380 < M(K^0\pi^+\pi^-) < 1460$, $\Delta^2(n) < 0.2$.

[b] $1360 < M(K^0\pi^-) < 1480$, $0.2 \le \Delta^2(p) \le 0.5$.

[c] The χ^2 fits corresponding to the best estimate of $\langle\rho_{00}{}^3\rangle$, i.e., $\langle\rho_{00}{}^3\rangle \approx 0$, correspond to probabilities of $\sim 10^{-6}$, $\sim 10^{-2}$, and 20% for 1^-, 3^-, and 2^+, respectively. For the sake of comparison we also give the χ^2's corresponding to the 2-standard-deviation upper limit of $\langle\rho_{00}{}^3\rangle = 0.2$.

[d] The distribution of the normal in Reaction (4) contains one undetermined parameter for the case $J^P = 3^-$ (see Refs. 22 and 4). To obtain a χ^2 we adjust this parameter to its most favorable value.

our model which requires $\langle\rho_{00}{}^3\rangle \approx 1$. On the other hand, for the region $0.2\ (\text{BeV})^2 \le \Delta^2 \le 0.5\ (\text{BeV})^2$ the ratio $\bar{r}$, and thus the corresponding $\langle\rho_{00}{}^3\rangle$, is very small. In fact, since the signal corresponding to the numerator of $\bar{r}$ is insignificant here [see Fig. 1(f)], we use the value $3\times[\text{No. events in } K^*(1420) \text{ band}]^{1/2}$ to obtain the limit $\langle\rho_{00}{}^3\rangle < 0.2$. With this condition, the polar and azimuthal distributions of the decay kaon in the $K^{*-}(1420)$ rest frame take on the approximate forms

$$f_J(x) \approx (1-x^2) \quad \text{for } J^P = 1^-,$$
$$\approx x^2(1-x^2) \quad \text{for } J^P = 2^+,$$
$$\approx (5x^2-1)^2(1-x^2) \quad \text{for } J^P = 3^-, \tag{6}$$

and $f(\varphi) \approx 1 - 2\rho_{1,-1}\cos 2\varphi$ for $J^P = 1^-$, 2^+, and 3^-. Here $\rho_{1,1} \lesssim \frac{1}{2}$ and $x = \cos\theta$. It is clear that the functions $f_J(x)$ have very different behavior and thus afford sensitive discrimination among the various J^P values,[23] whereas the φ distributions provide little information. The comparison with experiment is given in Figs. 3(c) and 3(d). The shaded areas represent the variation of $f_J(x)$ for the permissible range of $\langle\rho_{00}{}^3\rangle$. One sees quite clearly that the 2^+ hypothesis fits well, while the 1^- and 3^- hypotheses fit poorly. χ^2 values to test the goodness of fit of each of the curves are summarized in Table II. Even considering the systematic uncertainties, the discrimination among spin-parity values is so pronounced that, if it were not for model dependence, these results would conclusively rule out 1^- and would make 3^- very unlikely.

With regard to the model dependence, we may call attention to the large body of evidence from other experiments[24] which testifies to the essential validity of the peripheral model, especially insofar as angular distribution predictions are concerned. Of particular importance is the evidence both from our own experiment and others indicating that ω exchange is expected to be dominant in the Δ^2 region of interest. Given this background (even if ρ and A_2 exchange are admitted), the results of Table II constitute very strong evidence that the $K^*(1420)$ does indeed have $J^P = 2^+$.

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[1] N. Haque et al., Phys. Letters 14, 338 (1965).

[2] L. M. Hardy et al., Phys. Rev. Letters 14, 401 (1965).

[3] S. Focardi et al., Phys. Letters 16, 351 (1965).

[4] J. Badier et al., Phys. Letters 19, 612 (1965).

[5] S. U. Chung et al., Phys. Rev. Letters 15, 325 (1965).

[6] J. Bishop et al., Phys. Rev. Letters 16, 1069 (1966).

[7] P. Dornan et al., Bull Am. Phys. Soc. 11, 342 (1966).

[8] B. Shen et al., Phys. Rev. Letters 17, 726 (1966).

[9] V. E. Barnes et al., in Proceedings of the Twelfth International Conference on High Energy Physics, Dubna, 1964 (Atomizdat., Moscow, 1966), p. 662. For details of the beam see I. Skillicorn and M. Webster, Brookhaven National Laboratory report No. H-10 (unpublished).

[10] R. T. Deck, Phys. Rev. Letters 13, 169 (1964).

[11] Using Figs. 1(c) and 1(e), the mass and width were estimated by visual fitting of various Breit-Wigner curves on a smooth background. A study of the branching ratio $\alpha = [K^*(1420)\to K^*+\pi]/[K^*(1420)\to K+\rho]$ from

Reaction (4) events yields $\alpha \gtrsim 0.8$, in agreement with other experiments.

[12]At our energy $\Delta_{min}^2 = 0.03$ and $\Delta_{max}^2 = 6$ (BeV)^2, for the $K^*(1420)$ region.

[13]S. Goldhaber et al., Phys. Rev. Letters 15, 737 (1965); J. Friedman and R. Ross, Phys. Rev. Letters 16, 485 (1966).

[14]J. D. Jackson, Rev. Mod. Phys. 37, 484 (1965); J. D. Jackson et al., Phys. Rev. 139, B428 (1965).

[15]We use the terms η, ω, and f exchange to represent all $I(J^P) = 0(0^-)$, $0(1^-)$, and $0(2^+)$ exchanges, respectively (mixing effects are ignored).

[16]We have not studied $K^*(890)$ production in this experiment; we accept the evidence from lower energy investigations.

[17]The predicted Δ^2 distribution is obtained with the use of a form factor phenomenogically equivalent to the effects of absorption at lower energies. See J. D. Jackson and H. Pilkuhn, Nuovo Cimento 33, 906 (1964).

[18]The density-matrix element ρ_{00} represents the fraction of pseudoscalar exchange provided that the (nonpseudoscalar) exchanged meson and the produced meson both have natural (or both unnatural) parities.

[19]We make use of the approximation $[K^*(1420) \rightarrow K^* + \pi] \gg [K^*(1420) \rightarrow K + \rho]$. (See Ref. 11.) However, we wish to emphasize that the error introduced by this assumption is negligible compared with other errors.

[20]This avoids ambiguity due to the existence of both $K^*\pi$ and $K\rho$ decay modes.

[21]S. M. Berman and M. Jacob, Phys. Rev. 139, B1023 (1965).

[22]The sensitivity is even weaker if one admits ρ and A_2 exchange as well as π exchange.

[23]If we include the exchange of all allowed and well-established mesons (i.e., ρ, A_2, η, and f) Eq. (5) becomes

$$\langle \rho_{00}^{\ 3} \rangle = \tfrac{1}{4}(3\beta/2)\bar{r}[|\bar{a}_1^{\ \pi} + \bar{a}_0^{\ \eta}|^2/(|\bar{a}_1^{\ \pi}|^2 + |\bar{a}_1^{\ \rho}|^2 + |\bar{a}_1^{\ A_2}|^2)],$$

where, for example, $\bar{a}_1^{\ \pi}$ is the pion contribution to the isospin-1 amplitude. The density-matrix element $\langle \rho_{22}^{\ 3} \rangle$ will also appear in the expressions for $f_J(x)$:

$$\langle \rho_{22}^{\ 3} \rangle \leq \tfrac{1}{4}(3\beta/2)\bar{r}[|\bar{a}_1^{\ A_2} + \bar{a}_0^{\ f}|^2/(|\bar{a}_1^{\ \pi}|^2 + |\bar{a}_1^{\ \rho}|^2 + |a_1^{\ A_2}|^2)].$$

The arguments for eliminating $J^P = 1^-$ clearly carry through the same as in the "$\pi + \omega$" model as long as the η-exchange amplitude is small compared to the sum of π, ρ, and A_2 amplitudes. The same requirement is necessary to eliminate $J = 3^-$, with the additional proviso that f exchange be relatively small.

[24]See Refs. 15 and 14, and G. London et al., Phys. Rev. 143, 1034 (1966).

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STIMULATED EMISSION AND Rb SPIN-EXCHANGE CROSS SECTION. Jacques Vanier [Phys. Rev. Letters 18, 333 (1967)].

Equation (1) should read as follows:

$$\Delta_0 = \Gamma'/(5\Gamma' + 8).$$

On page 334, the third sentence after Eq. (3) should read, "The experimental data agreed well with the prediction of Eq. (3) $\cdots$."