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Resonance Neutron Capture in the Even-A Isotopes of Tungsten*

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The γ-ray spectra following neutron capture in the 4.14- and 21.2-eV resonances of W^{182} and the 18.8-eV resonance of W^{186} have been observed with a 6-cc Ge(Li) detector. Transitions corresponding to the $W^{182}(n,\gamma)W^{183}$ reaction have also been observed in the 115- and 250-eV resonances. In a special experiment, using a NaI detector, the absolute width of the ground-state transition for the 4.14-eV in resonance W^{182} was determined relative to the ground-state transition for the 7.62-eV resonance in W^{183}.

I. INTRODUCTION

THE low-lying level structure of odd-A nuclei in the deformed region is generally well described by rotational spectra built upon intrinsic Nilsson orbits.[1] The capture of an s-wave neutron by an even-even target leads to compound states in the odd-neutron nucleus with spin $\frac{1}{2}$ and positive parity. Since for initial states at excitations near the neutron separation energy the radiative strength to low-lying levels is primarily $E1$, the capture process will selectively populate $\frac{1}{2}^-$ and $\frac{3}{2}^-$ final states. These can be described in the unified model as the two lowest-spin members of a rotational band built upon a $K=\frac{1}{2}^-$ Nilsson orbit, and the lowest spin (or quasi-ground-state) member of a $K=\frac{3}{2}^-$ band. Other states that are members of the $(\frac{1}{2}^-,\frac{3}{2}^-)$ subset of levels may have their dynamical origin in vibration or core-excitation modes, and these normally will occur at energies greater than 1 MeV.

The eigenstates of the odd-neutron isotopes of tungsten, W^{183}, W^{185} and W^{187} have been studied in detail by several workers[2-4] through analysis of (d,p) angular distributions and reduced strengths. In particular, they have identified the lowest-lying states of $\frac{1}{2}^-$ and $\frac{3}{2}^-$ members of the $K=\frac{1}{2}^-$,[510] orbital and the $K=\frac{3}{2}^-$,[512] orbital. Erskine concludes that the $J=\frac{3}{2}^-$ states are, in fact, mixtures of the shell-model states.

Recently, work on the capture γ-ray spectra for both tungsten and hafnium isotopes has been reported. Martin, Harvey, and Slaughter[5] have measured the thermal-capture spectra of W^{183}, W^{185}, and W^{187}; and the spectra associated with capture in the 4.14-eV resonance in W^{182} and the 18.8-eV resonance in W^{186} have been measured by Faler, Spencer, and Dixon.[6] The thermal-capture spectra of hafnium have been measured by Namenson *et al.*[7,8] The results obtained show systematic effects, which would not be expected for a statistical compound state. The first regularity is observed among the primary transitions to the [510] band; the ratio of the intensity of the transition to the $\frac{3}{2}^-$ state to that to the $\frac{1}{2}^-$ state has similar values in the thermal spectra of W^{183} and Hf^{179} and in the 4.14-eV spectrum of W^{183}. Second, for these same spectra, the radiative strength to the [512] band appears to be consistently less than that to the [510] band.

In the investigation reported upon here, the relative radiative widths for the above-mentioned final states have been determined for capture in higher-energy resonances of W^{182}. In addition, the absolute radiative width for the ground-state transition following capture in the W^{182} 4.14-eV resonance has been measured.

II. EXPERIMENTAL ARRANGEMENT AND RESULTS

A. The Ge(Li) Spectra

A 1-kg sample of natural tungsten sheet was placed in the pulsed beam of the Argonne fast chopper[9] at a flight path of 6.43 m. Pulse-height spectra corresponding

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **29**, No. 16 (1955).
[2] A. Iosaya, Phys. Rev. **130**, 234 (1963).
[3] J. R. Erskine, Phys. Rev. **138**, B66 (1965).
[4] R. H. Siemssen and J. R. Erskine, Phys. Rev. Letters (to be published).
[5] M. J. Martin, J. A. Harvey, and G. G. Slaughter, Bull. Am. Phys. Soc. **11**, 336 (1966).
[6] K. T. Faler, R. R. Spencer, and D. R. Dixon, Bull. Am. Phys. Soc. **11**, 336 (1966).
[7] A. Namenson, H. E. Jackson, and R. K. Smither, Phys. Rev. **146**, 844 (1966).
[8] A. I. Namenson and H. H. Bolotin, Phys. Rev. **158**, 1206 (1967).
[9] L. M. Bollinger, R. E. Coté, and G. E. Thomas, in *Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 14, p. 239.

to γ rays detected in a 6-cc Ge(Li) diode coupled to a low-noise linear system were recorded as a function of neutron time of flight. Two-parameter events were recorded serially in the form of 512 time-of-flight channels (each 1 μsec wide) and 1024 pulse-height channels (each spanning 4.6 keV of γ-ray energy) on the magnetic tape of the Argonne 3-parameter analyzer.[10]

Figure 1 is a plot of the γ-ray yield as a function of neutron time of flight. The 18.8-eV resonance in W^{186} is not completely separated from the 21.2-eV resonance in W^{182}, since the resonance line shape is distorted by multiple scattering. In addition, the structure of the cross section at higher energies is complicated by the contributions from resonances in W^{183}.

The spectra associated with capture of neutrons at thermal energy and at several higher energies are shown in Fig. 2. In the case of the 4.14-eV resonance, background corrections were made simply by subtracting the off-resonance contributions. The spectra associated with capture in the 18.8-eV resonance in W^{186} and 21.2-eV resonance in W^{182} were corrected both for off-resonance background and for interfering contributions. Two neutron time-of-flight regions were selected such that the relative amounts of the two isotopic contributions were significantly altered.

The two observed spectra are different linear combinations of the spectra corresponding to each isotope, so that we may write

$$S_1 = S^{182} + A_1 S^{186},$$
$$S_2 = S^{182} + A_2 S^{186}.$$

In these equations S_1 is the intensity at any particular energy in the spectrum corresponding to neutron time-of-flight region 1, which contains contributions mainly from the W^{182} resonance, but also contains a fractional contribution $A_1/(1+A_1)$ from the W^{186} resonance. Similarly, S_2 is the intensity in the spectrum corresponding to the region in which the contribution from the W^{186} resonance is dominant. The values of A_1 and A_2 were determined from the equation

$$A_r = I_r(186)/I_r(182),$$

where the intensity I_r of the indicated W isotope is measured as the area of the double-escape peak of the transition to the $[510]\,\frac{1}{2}^-$ state in spectrum r. For the windows used, 56% of the intensity in W_1 was due to W^{182}, while 100% of the intensity in W_2 was due to W^{186}.

For the two higher-energy regions examined, 88–131 eV, and 150–400 eV, no corrections for background were made. These energy regions of the W^{182} cross section are known[11] to be dominated by resonances at 115 and 250 eV, respectively. The resonances from W^{184} and W^{186} in this region do not interfere with the analysis of the relative intensities of the three transitions under discussion, since their energy exceeds the known binding energy of these two isotopes. It was necessary to assume that the contribution from resonances in W^{183} in this energy region do not give rise to transitions of the same energy as those under consideration. The spectra were analyzed only in the region containing the primary transitions to the known first three excited states of W^{183}, as indicated in Fig. 3.

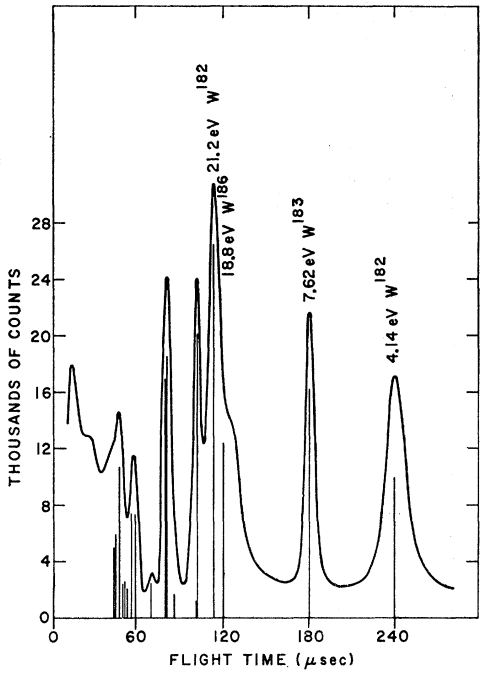

FIG. 1. Capture γ-ray yield as a function of neutron flight time for the experiment that used a lithium-drifted germanium γ-ray spectrometer.

The relative intensities of the transitions, normalized to the intensity of the one whose final state has been identified as the $[510]\,\frac{1}{2}^-$ state, are listed in Table I.

B. The Determination of the Widths

Since the response function of the NaI detector is more thoroughly understood than that of the Ge(Li) diode, the former was used to determine the branching

TABLE I. Partial widths of transitions normalized to the value of Γ_γ for the transition to the $[510]\,\frac{1}{2}^-$ state.

Product isotope	Neutron energy (eV)	Final state $[510]\,\frac{1}{2}^-$	Final state $[512]\,\frac{3}{2}^-$	Γ_n^0 (meV)
W^{183}	Thermal	0.328±0.02	0.029±0.02	
	4.14	0.339±0.03	0.022±0.03	0.71
	22.2	1.48 ±0.2	0.59 ±0.1	8.0
	114	0.23 ±0.25	0.89 ±0.43	27
	220	2.0 ±1.2	2.2 ±1.2	70
W^{187}	Thermal	1.47 ±0.12	0.06 ±0.12	
	18.8	1.98 ±0.23	0.08 ±0.10	

[10] C. C. Rockwood and M. G. Strauss, Rev. Sci. Instr. **32**, 1211 (1961).

[11] J. E. Russell, R. W. Hockenbury and R. C. Block, Reports to the A.E.C. Nuclear Cross Sections Advisory Group, Wash-1064, **161**, 1965 (unpublished).

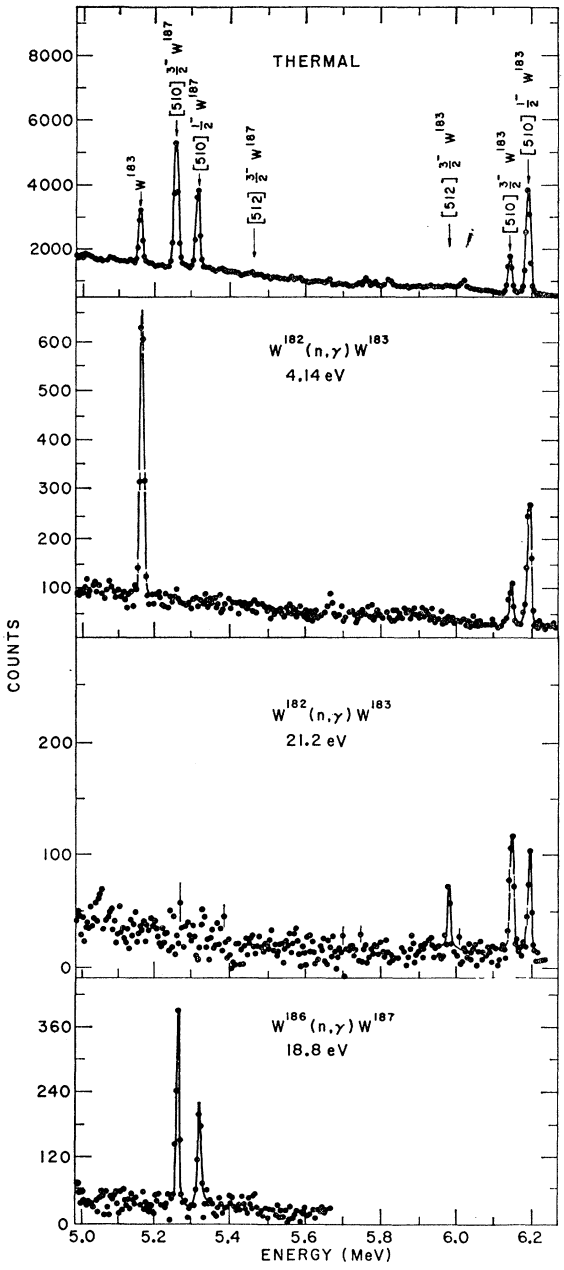

FIG. 2. The capture γ-ray spectra observed with the lithium-drifted germanium spectrometer with thermal neutrons and with resonance neutrons.

ratio of transitions in W^{183}. The measurement was made relative to the intensity of the ground-state transition from the 7.62-eV resonance in W^{183}, for which the branching had already been determinated.[12] The same sample as had been used for the Ge(Li) measurements was placed at a flight path of 25 m. The capture radiation was observed with a NaI detector of 8-in. diam and 6-in. length in an arrangement described in detail elsewhere.[12] A boron-plate neutron detector[13] was placed in the neutron beam at 24 m. Two-parameter events in a data field consisting of 512 time-of-flight channels$\times$256 pulse-height channels were recorded on the magnetic tape of the multiparameter analyzer. Concurrently, the total number of events monitored in each detector was recorded as a function of time of flight in the respective halves of a 4096-channel time analyzer[14] operated in a two-detector mode. In a separate experiment, the transmission of the sample was determined in the energy region of interest.

The counting rate $N_i^{(j)}$ in a particular photopeak corresponding to a transition from resonance j to final state i is given by

$$N_i^{(j)}=\frac{\Gamma_{\gamma_i}^{(j)}}{\Gamma^{(j)}}\mathcal{E}(E_{\gamma_i}^{(j)})\int_{E_j}^{E_j+\Delta_j}\phi(E_n)\times[1-T(E_n)]\,dE_n\left[1+\sum_{r=1}^{\infty}\left(\frac{\Gamma_n^{(j)}}{\Gamma^{(j)}}\right)^r\right],$$

where $\Gamma_{\gamma i}$, Γ, and Γ_n are the partial radiative, total, and neutron widths, $\mathcal{E}(E_{\gamma_i}^{(j)})$ is the efficiency of the detector at peak j; i, $\phi(E_n)$, and $T(E_n)$ are the neutron flux and transmission; $E_j\leqslant E_n\leqslant E_j+\Delta_j$ is the neutron energy region over which the spectrum is determined; and the last term is a correction for multiple-scattering contributions. With the substitution $\beta_i^{(j)}=\Gamma_{\gamma_i}^{(j)}/\Gamma^{(j)}$, with the integral replaced by average quantities, and

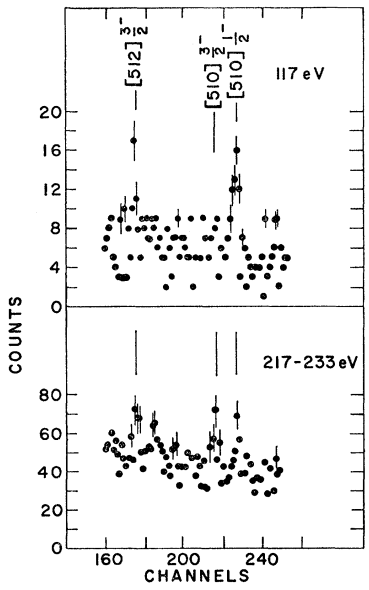

FIG. 3. The capture γ-ray spectra observed with the lithium-drifted germanium spectrometer with neutrons having energies of about 100 eV and about 200 eV.

[12] L. M. Bollinger, R. E. Coté, R. T. Carpenter, and J. P. Marion, Phys. Rev. 132, 1640 (1963).

[13] L. M. Bollinger, R. E. Coté, and G. E. Thomas, in *Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 15, p. 127.

[14] C. C. Rockwood, Rev. Sci. Instr. 36, 1161 (1965).

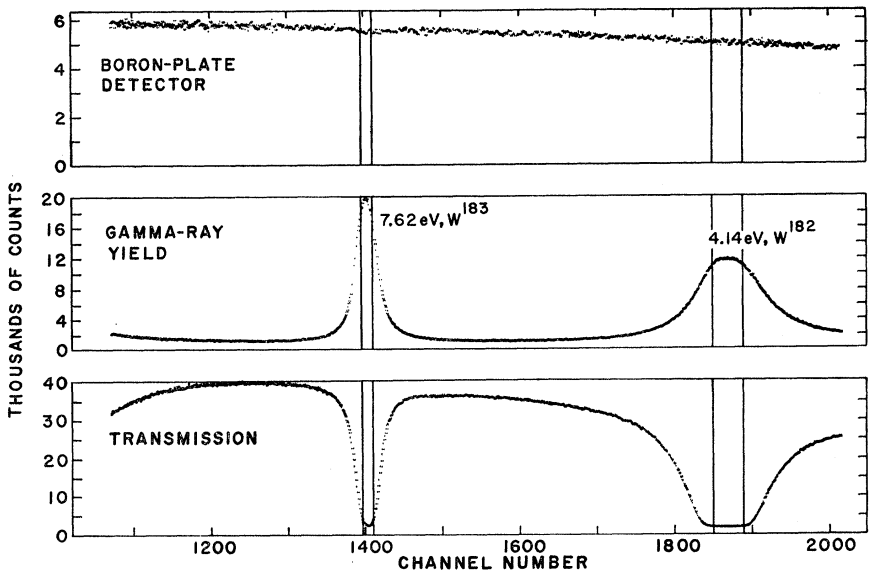

FIG. 4. The variation of neutron flux, the yield of γ rays observed in the NaI(Tl) spectrometer, and the transmission of the sample of natural tungsten as a function of neutron flight time.

with the multiple-scattering term retained to first order, the expression for the counting rate becomes

$$N_i^{(j)}=\beta_i^{(j)}\mathcal{E}(E_{\gamma_i}^{(j)})\langle\phi_j\rangle\langle 1-T_j\rangle\Delta_j\left[1+\frac{\Gamma_n^{(j)}}{\Gamma^{(j)}}\right].$$

For the 4.14-eV resonance ($j=1$), as the Ge(Li) spectra show, the photopeak consists of transitions to the first excited and ground states in the ratio $\alpha=\beta_1^{(1)}/\beta_0^{(1)}$. The photopeak for the W^{184} ground-state transition following capture in the 7.62-eV ($j=2$) resonance of W^{183} is known[12] to correspond nearly to that for a single γ ray. Hence

$$\frac{\beta_0^{(1)}}{\beta_0^{(2)}}=\frac{N_0^{(1)}\mathcal{E}(E_{\gamma_0}^{(2)})\langle\phi_2\rangle\langle 1-T_2\rangle\Delta_2(1+\Gamma_n^{(2)}/\Gamma^{(2)})}{N_0^{(2)}(1+\alpha)\mathcal{E}(E_{\gamma_0}^{(1)})\langle\phi_1\rangle\langle 1-T_1\rangle\Delta_1(1+\Gamma_n^{(1)}/\Gamma^{(1)})},$$

The results of the flux and transmission measurements are shown in Fig. 4. The slight slope in the counting rate-versus-time curve from the boron-plate counter represents a small departure from the $\phi(E)=1/E$ variation for which a correction was made. For the 4.14-eV resonance, $T(E)=0$ over the energy region of interest. A small correction of about 2% was made for the finite transmission at 7.62 eV. The relative peak efficiencies were obtained from Monte Carlo calculations of Miller and Snow,[15] while the observed rate was determined from the photopeak area of the corresponding Na(I) spectra. From these results, together with the known resonance parameters,[16] a value $\Gamma_{\gamma_0}=2.58\pm0.3$ meV was obtained for the partial radiation width of the ground-state transition.

III. DISCUSSION

The relative partial radiative widths to the two levels with well-developed single-particle structure, the [510] $\frac{1}{2}^-$ and [512] $\frac{3}{2}^-$ orbits might be expected to display systematic features if the initial radiating state were simple in structure. The observed data have been compared with the behavior implied in various approximate models. These lead to the considerations that follow. Throughout this discussion, the reader should bear in mind that the various systematic effects being considered are likely to be obscured by Porter-Thomas statistical fluctuation and conversely that the statistical fluctuations may be responsible for what appear to be systematic effects.

(a) Strong coupling: Since capture of an s-wave neutron is involved, one model for the initial state constitutes a $\Lambda=0$ orbit in which the neutron is strongly coupled to the target. In this case, because of the selection rule $\Delta\Lambda=0\pm1$, $E1$ radiation to the [512] orbit is strictly forbidden in the asymptotic limit. The observed data for thermal capture and for capture in the 4.14- and 21.2-eV W^{182} and 18.8-eV W^{186} resonances appear to be qualitatively consistent with this interpretation.

(b) Correlation with (d,p) data: In the direct-capture hypothesis as proposed by Lane and Lynn,[17] significant resonant-channel contributions occur from a radiating state consisting of an s-wave neutron weakly coupled to the target nucleus. For even-even targets,

[15] W. F. Miller and W. J. Snow, Rev. Sci. Instr. **31**, 39 (1960).
[16] *Neutron Cross Sections*, compiled by D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report No. BNL-325, 2nd ed. (U. S. Government Printing Office, Washington, D. C., 1960), Suppl. No. 1.
[17] A. M. Lane and J. E. Lynn, Nucl. Phys. **17**, 563 (1960); **17**, 586 (1960).

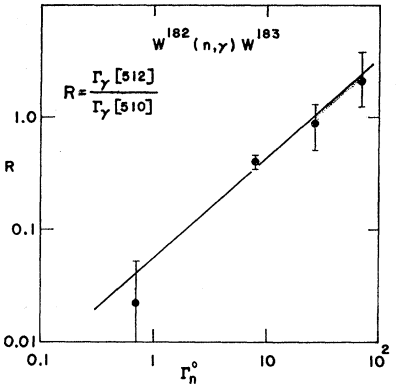

FIG. 5. The ratio $\Gamma_\gamma[512]/\Gamma_\gamma[510]$ for transitions to the $\frac{1}{2}^-$ states of the [512] and [510] bands, plotted as a function of the reduced neutron width Γ_n^0.

for which only one intermediate spin state occurs, the reduced radiative widths should be correlated with the corresponding reduced stripping strengths.[17] For the $W^{182}(d,p)W^{183}$ reaction, the reduced strength to the [510] $\frac{1}{2}^-$ state is two orders of magnitude smaller than that to the [510] $\frac{3}{2}^-$ state.[4] For all cases studied in this work the reduced widths to these two levels are comparable and in no case are they similar to the relative strengths observed in stripping.

(c) Single-particle enhancement: The observed width for the ground-state transition from the 4.14-eV resonance gives a value

$$k=\frac{\Gamma_\gamma}{E_\gamma{}^3 D_0 A^{2/3}}=7.5\times10^{-3}.$$

This value is entirely consistent with the systematics of $E1$ widths throughout this mass region. Thus, the single-particle nature of the [510] orbit does not appear to lead to any significant enhancement for this transition.

(d) Correlation with reduced neutron widths: A resonance-channel contribution displaying selection rules should increase with the reduced neutron width.[17] As can be seen from Fig. 5 the ratio $\Gamma_\gamma[512]/\Gamma_\gamma[510]$ increases with increasing Γ_n^0. It should be stressed that with a sample consisting of only four values, no statistically significant conclusions can be drawn concerning the existence of a correlation between these two quantities. The result is included only to indicate a qualitative consistency with the direct-capture hypothesis. In addition, the widths for the transitions to the two $J=\frac{3}{2}$ levels seem to fluctuate independently whereas if the radiative process occurs from the channel region, these widths would be expected to display correlations.

Finally, we call attention to the strong 5176-keV transition to a final state at $E_x=1029$ keV observed in the thermal and 4.14-eV spectra from capture in W^{183}. One can only speculate on the dynamical origin for this excitation mode. No single-particle Nilsson orbits with $K=\frac{1}{2}^-$ or $\frac{3}{2}^-$ are expected in this region; and consistent with this is the lack of an observable (d,p) cross section to this state. Two possible explanations for this state are that it is either a collective vibration or one of the [521] neutron-hole states. Because of the large corresponding partial width, either hypothesis requires that the initial radiating state contain significant components corresponding to rather complex configurational structures. Moreover, as can be seen from the spectrum at 18.8-eV, these components exhibit strong fluctuations. These properties are more consistent with a compound radiating state than with the simple structure associated with the channel regions of phase space.

The data do seem to display regularities as described in (a) and (d), but these features are not sufficiently well developed to justify any clear conclusions regarding the intrinsic structure of the radiative states or the details of the reaction mechanism.

Note added in proof. Conclusions similar to some of those reported here have been made in a recent publication by E. R. Rae, W. R. Moyer, R. R. Fullwood, and J. L. Andrews [Phys. Rev. **155**, 1301 (1967)].

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