analogs). In this note we have restricted our discussion to the strongest, statistically well established peak in each spectrum; the understanding of possible subsidiary structures must await better data.

We wish to acknowledge discussions with A. Kerman regarding strangeness analog resonances, over the past decade, as well as recently. Thanks are also due to Professor B. Povh for calling the authors' attention to these recent experimental results.

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Gamma Decay of the 9.042- and 9.805-MeV States in ^{23}Na†

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^{12}C(^{12}C,$p\gamma$)^{23}Na proton-γ angular correlations were measured at $E_B = 38.82$ MeV for the 9.042- and 9.805-MeV states in ^{23}Na which decay to levels at 7.270, 6.235, and 5.534 MeV with branching ratios of 20%, 60%, and 20%, respectively, for the 9.042-MeV state, and 30%, 50%, and 20%, respectively, for the 9.805-MeV state. Angular correlations and lifetime data eliminate $\frac{17}{2}$ assignments for either state.

The 9.042- and 9.805-MeV states in ^{23}Na have recently been shown to be populated with unusual strength at a number of resonant energies in the reaction ^{12}C(^{12}C,p)^{23}Na.[1] It has been suggested that these two states are the $\frac{15}{2}^+$ and $\frac{17}{2}^+$ members of the ground-state rotational band in ^{23}Na.[2] Verification of these assignments would help to clarify both the nature of the resonance phenomena which favors their formation and the nuclear structure of ^{23}Na. If these are high-spin states, they should show γ decay, even though they are unbound to proton emission. A proton escaping from a state at this excitation energy in ^{23}Na can only go to the ground state of ^{22}Ne. Such a decay from a $\frac{15}{2}$ state in ^{23}Na would therefore require $7\hbar$ units of orbital angular momentum to be associated with the proton emission, and the centrifugal barrier associated with this angular momentum, in combination with the Coulomb barrier, greatly hinders proton emission.

In order to study the details of the γ decay of the 9.042- and 9.805-MeV states, a ^{12}C(^{12}C,$p\gamma$)^{23}Na particle-γ angular-correlation experiment has been performed at an incident ^{12}C beam energy of 38.82 MeV. The ^{12}C beam was obtained from the Florida State University super FN tandem Van de Graaff accelerator with an inverted sputter source.[3] The beam entered a particle-γ angular-correlation chamber and after bombarding a 60-μg-cm^2 carbon target was stopped in a gold foil. The protons were detected at zero degrees to the beam by ΔE-E solid-state counters which subtended a solid angle of 50 msr with an angular acceptance of ± 7°. Proton-γ angular correlations were determined from γ-ray spectra obtained at angles of 54°, 70°, 90°, 144°, and 160° to the beam. The γ rays were detected by three Ge(Li) detectors. Coincidence events between γ rays and protons were identified by time gates in an on-line computer. Coincidences were accumulated in a four-parameter list mode and stored on magnetic tape for subsequent playback and analysis.

Included in this experiment were states from 2.0 to 16.0 MeV excitation in ^{23}Na. The resultant γ-ray spectrum, gated on the 9.805-MeV state in ^{23}Na taken at 160° to the beam, is shown in Fig. 1. Doppler-broadening effects were observed in

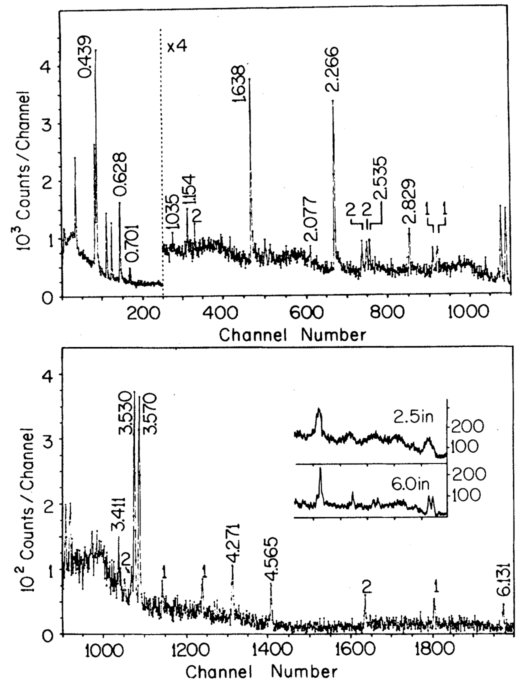

FIG. 1. γ-ray spectrum at 160° to the beam, gated on the 9.805-MeV state. γ rays are labeled by the unshifted transition energy. First and second escapes are labeled (1) and (2), respectively. The 6.131-MeV γ ray is due to accidental coincidences from oxygen inelastic scattering. Unlabeled low-energy γ rays are due to accidentals from competing reactions. The inset illustrates the effect of the target to the Ge(Li) detector distance on Doppler broadening.

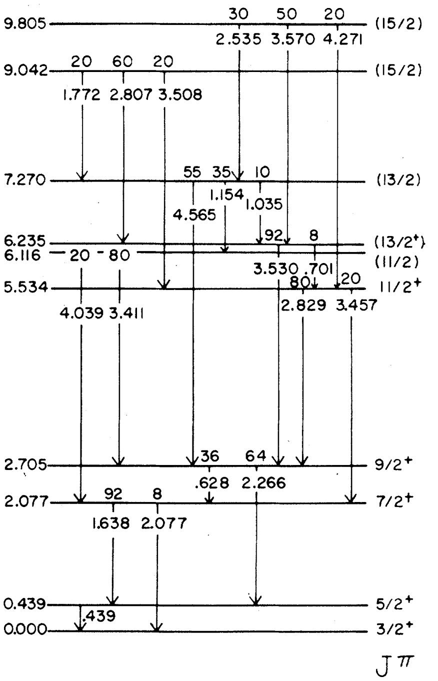

FIG. 2. Decay scheme for ^{23}Na showing the branches from the 9.805- and 9.042-MeV states.

this experiment due to the short lifetimes of the excited states, typically less than 150 fsec,[4,5] and the recoil velocities ($v/c \leq 0.035$) of the ^{23}Na residuals. These effects were minimized by placing the Ge(Li) detectors 6 in. from the target in order to limit their solid angles. To emphasize the resulting improvement, an inset is included in the spectrum of Fig. 1 showing the region of the doublet at 3.50-MeV γ energy for target-to-detector distances of 2.5 and 6.0 in. with the Ge(Li) detector at 90° to the beam.

In the present work particle-γ angular correlations have been analyzed for a few of the stronger key transitions. These angular correlations were performed in the "method II geometry" of Litherland and Ferguson,[6] and were fitted with even-order Legendre polynomials up to and including $l=4$. Mixing-ratio calculations were performed for quadrupole and dipole or octopole and quadrupole contributions assuming only population of $M_z = \pm\frac{1}{2}$ magnetic substates. The mixing ratio was varied from $\tan\delta = -90.0°$ to $90.0°$, and a standard χ^2 analysis was performed for each value of δ. The branching ratios, indicated above each transition in the decay scheme of Fig. 2, were determined from γ-ray yields at 54°, where angular-correlation effects for typical dipole and quadrupole transitions are minimal.

The spins and parities of states in ^{23}Na have been previously established up to about 5.0 MeV excitation.[7] States belonging to the ground-state rotational band have been identified up to a proposed $(\frac{13}{2}^+)$ state at 6.235 MeV excitation.[8] In an earlier ^{12}C(^{12}C,$p\gamma$)^{23}Na angular-correlation study at $E_B = 28.2$ MeV,[4] the 9.042-MeV state was observed to decay to the $(\frac{13}{2}^+)$ state at 6.235 MeV with a mean lifetime of less than 30 fsec, and its spin was limited to $\frac{11}{2}$, $\frac{13}{2}$, or $\frac{15}{2}$. More recently,[5] a new branch of 28% was observed to the $\frac{11}{2}^+$ state at 5.534 MeV. The results of the present work, shown in Fig. 2, indicate yet another branch of 20% to a state at 7.270 MeV, which in turn decays to a state at 6.115 MeV excitation. An angular correlation analysis has been performed on the 9.042–6.235 transition and the results are shown in Table I. The $a_2/a_0 = -0.18 \pm 0.05$ and $a_4/a_0 = -0.08 \pm 0.08$ coefficients are typical of a stretched dipole transition and this is substantiated by the mixing-ratio calculations shown in Table I. The $\frac{17}{2}$-$\frac{13}{2}$ transition is excluded at the 0.1%

TABLE I. Angular correlation results.

Transition	a_2/a_0	a_4/a_0	$J_i \to J_f$	δ^a	χ^2
9.042-6.235	-0.18±0.05	-0.08±0.08	17/2-13/2	+ 4.7 ± 2.1	5.9
			15/2-13/2	- 0.05± 0.08	0.8
				+ 7.1 ± 2.4	16.7
			13/2-13/2	- 2.4 ± 0.8	8.4
				+ 0.87± 0.22	2.1
			11/2-13/2	-57.0 ±28.0	5.6
				+ 0.00± 0.09	0.8
			9/2-13/2	- 0.33± 0.13	0.9
9.805-6.235	+0.19±0.05	+0.14±0.09	17/2-13/2	+ 0.05± 0.07	6.9
			15/2-13/2	- 9.5 ± 2.9	5.9
				- 0.24± 0.12	0.8
			13/2-13/2	- 0.96± 0.37	7.2
				+ 0.36± 0.23	2.0
			11/2-13/2	+ 0.24± 0.12	1.0
				+ 3.5 ± 2.0	0.7
			9/2-13/2	- 0.02± 0.12	1.6

[a] The sign convention is that of Rose and Brink, Ref. 10.

confidence level ($\chi^2 = 5.4$), and the $\frac{9}{2}$-$\frac{13}{2}$ transition is excluded because of an unreasonably high implied $M3$ strength of at least 0.6×10^6 Weisskopf units (W.u.). These results favor the $\frac{11}{2}$, $\frac{13}{2}$, or $\frac{15}{2}$ assignments for the 9.042-MeV state, which is good agreement with the results of Ref. 4.

In recent studies,[2,5] the 9.805-MeV state was observed to decay only to the ($\frac{13}{2}^+$) state at 6.235 MeV with a mean life of less than 30 fsec. Our results indicate two new branches of 30% to the state at 7.270 MeV and 20% to the $\frac{11}{2}^+$ state at 5.534 MeV. The 20% branch to the $\frac{11}{2}^+$ state makes the proposed $\frac{17}{2}^+$ assignment very doubtful. As a pure $M3$ transition, a transition strength of greater than 1×10^6 W.u. is implied. If this were a pure $E2$ transition, implying a ($\frac{15}{2}^+$) assignment, a more reasonable transition strength of 2.9 W.u. is obtained. The particle-γ angular-correlation data support this same conclusion. As is shown in Table I, the 9.805-6.235 transition has a positive a_2/a_0 coefficient which is consistent with a quadrupole transition. However, the a_4/a_0 coefficient is also positive within the error of the measurement. This positive a_4/a_0 coefficient eliminates the $\frac{17}{2}$-$\frac{13}{2}$ possibility at the 0.1% confidence level. None of the remaining possibilities can be strictly eliminated, but the $\frac{15}{2}$-$\frac{13}{2}$ and $\frac{11}{2}$-$\frac{13}{2}$ are the best candidates at the 50% confidence level ($\chi^2 = 0.8$).

Analysis of γ-ray spectra, gated on proton-populated states with excitation energy below 10.0 MeV, indicates that only the states at 2.077, 2.705, 5.534, 6.235, 6.116, 7.270, 9.042, and 9.805 MeV are populated with significant strength at this beam energy. Since the first four of these states are yrast states, it appears that this reaction selectively populates high-spin states. The population of high-spin states is also expected from grazing-angular-momentum considerations.[9] It is therefore reasonable to assume that the 6.116-, 7.270-, 9.042-, and 9.805-MeV states are also high-spin states, and they have been labeled in Fig. 2 with the highest spin consistent with the present work.

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Anomalous ϵ/β^+ Decay Branching Ratios: A Theoretical Explanation

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Anomalous ϵ/β^+ branching ratios for hindered allowed transitions in ^{145}Gd and ^{143}Sm decay are explained in terms of second-order corrections to normal allowed theory. These calculations lead to correction factors as large as 1000 in nuclei near $Z=80$, and explain a smaller anomaly for ^{22}Na decay. A simplified equation is presented to estimate skew ratios, $(\epsilon/\beta^+)_{\mathrm{expt}}/(\epsilon/\beta^+)_{\mathrm{theor}}$, for moderately hindered transitions.

In a previous Letter[1] we reported two large ϵ/β^+ branching-ratio anomalies relative to calculated values for allowed transitions.[2] Our subsequent Comment[3] on absolute measurements of these ratios showed that all twelve measurable transitions from ^{145g}Gd decay were substantially anomalous. These results are presented in Table I along with results from ^{143g}Sm decay which were relative measurements. A value for ^{22}Na decay[4] is also included in Table I. This is, perhaps, the most accurately measured ϵ/β^+-decay branching ratio in the literature, and, although it was studied looking for Fierz interference effects, the discrepancy was never adequately explained. We now believe that we can explain these anomalous ratios in terms of second-order (off-center) corrections to allowed decay. Calculations of these corrections are explained below, and they qualitatively describe the magnitude of the anomalies.

The second-order corrections to allowed β decay are proportional to $(pR)^2$ or $(pR)(v_N/c)$ and are normally about (1–2)% of the allowed matrix elements $\int 1$ and $\int \sigma$. For heavier nuclei these contributions become increasingly important because $R \approx 0.426 \alpha A^{1/3}$. A general correction term to the positron-decay probability can be written as[5]

$$\begin{aligned} C(W_e) = {} & [M_0(1,1)]^2 + [m_0(1,1)]^2 - \frac{2\mu_1\gamma_1}{W_e}[M_0(1,1)][m_0(1,1)] \\ & + \lambda_1 \left\{ [M_1(1,1)]^2 + [m_1(1,1)]^2 - \frac{2\mu_1\gamma_1}{W_e}[M_1(1,1)][m_1(1,1)] \right\} \\ & + \lambda_1 \left\{ [M_1(1,2)]^2 + [M_2(1,2)]^2 - \frac{2\mu_1\gamma_1}{W_e}[M_1(1,2)\, m_1(1,2) + M_2(1,2)\, m_2(1,2)] \right\} \\ & + \lambda_2 \left\{ [M_1(2,1)]^2 + [M_2(2,1)]^2 - \frac{\mu_2\gamma_2}{W_e}[M_1(2,1)\, m_1(2,1) + M_2(2,1)\, m_2(2,1)] \right\}. \end{aligned} \tag{1}$$