events with $\Lambda_c^+ \to \Lambda\pi^+$ since this sample has the smallest background. The values obtained are

$$m(\Lambda_c^+) = 2257 \pm 10 \text{ MeV},$$

$$m(\Sigma_c^{++}) - m(\Lambda_c^+) = 168 \pm 3 \text{ MeV}.$$

It is interesting to note that one of the 20 events is probably an example of quasielastic charmed-baryon production. Kinematics and track identification suggest that the reaction is $\nu_\mu \text{Ne} \to \mu^- \Lambda\pi^+\pi^+\pi^+\pi^-$ with no missing particles. The event thus has the $\Delta S = -\Delta Q$ signature of charm production. Examination of the masses then indicates that the event is another example of the reaction

$$\nu p \to \mu^- \Sigma_c^{++},\ \Sigma_c^{++} \to \Lambda_c^+\pi^+,$$

$$\Lambda_c^+ \to Y^{*+}\pi^+\pi^-,\ Y^{*+} \to \Lambda\pi^+.$$

Two of the three π^+'s in this event are overstopped as K^+ and the interpretation of the third positive track heavily favors π^+ over K^+ by geometrical reconstruction, ionization, and longitudinal-momentum balance. Transverse momentum is balanced to within 70 MeV/c. There is no visible evidence for stubs at the primary vertex or additional neutrals in the downstream 7 radiation lengths and 2.5 interaction lengths. The probability that this event is associated strange-particle production with a missing K_L has been calculated to be less than 3%. The two relevant masses are $m(\Lambda_c^+) = 2276 \pm 25$ MeV and $\Delta m = 163 \pm 5$ MeV.

In summary, we have presented evidence for the existence of both the Σ_c^{++} and Λ_c^+ baryons, a measurement of their masses, as well as the first observations of two-body decay modes of the Λ_c^+: $\Lambda_c^+ \to \Lambda\pi^+$ and, with less significance, $\Lambda_c^+ \to \overline{K}^0 p$.

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[9] Figures show all mass combinations. In Table I we have made correct ions for multiple combinations within an event for both the signal and the background.

Interpretation of *p-p* Dibaryon Resonances at 2140, 2260, and 2430 MeV

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Recent elastic p-p C_{LL} measurements and other p-p data indicate the existence of $^1D_2$, $^3F_3$, and $^1G_4$ resonances at energies of about 2140, 2260, and 2430 MeV, respectively. These resonances accurately correspond to nuclear-physics–type rotational levels of a virtual $pp\pi(2020)$ bound state.

In a recent paper,[1] Auer *et al.* reported the possible existence of $^1D_2$, $^3F_3$, and $^1G_4$ proton-proton dibaryon resonances at energies of approximately 2140, 2260, and 2430 MeV. These energies correspond to the positions of dips in the elastic C_{LL} spin-correlation data.[1] Other evidence for this p-p resonant structure is obtained from cross-section differences between parallel and antiparallel longitudinal ($\Delta\sigma_L$) and transverse ($\Delta\sigma_T$) total cross sections, and from Legendre expansions of differential-cross-section and polarization data.[2] The central C_{LL} dip was first identified as a $^3F_3$ resonance by Hidaka *et al.*[3] The resonant nature of this structure in the p-p data is also indicated by the phase-shift analyses of Hoshizaki,[4] the dispersion-relation analysis of Grein and Kroll,[5] and the early work of Arndt.[6] Structure has also been observed in the neutron-proton amplitudes.[2,7,8] These experimental results were unexpected, because phase-shift analyses of lower-energy p-p and n-p elastic scattering data[9] failed to reveal any dinucleon resonances.

The reported $^1D_2(2140)$, $^3F_3(2260)$, and $^1G_4(2430)$ p-p dinucleon resonances[1] correspond to $j=l=2$, 3, and 4 excitations, respectively, where j and l are the total and orbital angular momentum quantum numbers, and where the notation $^{2s+1}l_j$ is used to define the dinucleon phase shifts. The observed correlation between increasing energies and increasing angular momentum values suggests a form of rotational motion. Since the dinucleon state is the lightest example of a multinucleon (nuclear) system, we logically expect the excitations of this p-p system to follow the rotational systematics of nuclear physics. In order to pursue this idea in detail, we must first consider the *nonadiabatic* nature of the rotations that take place in very light nuclei. Quantum mechanically, the rotational energy of a rotating system is characterized by the Hamiltonian $H=(\hbar^2/2I)\hat{L}^2$, where $\hat{L}$ is the orbital angular momentum operator and I is the effective moment of inertia.[10] In nuclear physics, it is customary[10,11] to write $\hat{L}=\hat{J}-\hat{S}$, where $\hat{J}$ is the total angular momentum operator and $\hat{S}$ is the spin angular momentum operator. Thus the rotational energy is given (schematically) by the expectation value of operator $\hat{L}^2=(\hat{J}-\hat{S})^2=\hat{J}^2+\hat{S}^2-2\hat{J}\cdot\hat{S}$. The usefulness of this representation lies in the fact that the "Coriolis term" $\hat{J}\cdot\hat{S}$ tends to vanish if the rotating system satisfied the following conditions: (A) The system is markedly aspherical, so that the rotational axes are clearly delineated; (B) the rotational velocity is "slow" (the *adiabatic* approximation[12]); (C) the spin $\vec{S}$ does not have the value $\frac{1}{2}$. If the Coriolis term vanishes, which is often the case for *heavy* atomic nuclei, then the rotational energies follow an equation of the general form

$$E(j)=E_0+(\hbar^2/2I)j(j+1)\equiv E_0+E_{\rm rot}\,j(j+1). \quad (1)$$

However, near closed shells, where condition (A) fails, and for nuclei with $\vec{S}=\frac{1}{2}$, where condition (C) fails, the $j(j+1)$ interval rule of Eq. (1) is no longer valid.

In the case of *light* atomic nuclei, where the small masses lead to very rapid rotations, condition (B) is violated. Also, the broad widths of some of the low-mass rotational levels indicate that these levels last for very brief periods of time,[13] so that the rotational motion (condition A) is not well defined. Thus the $\hat{J}\cdot\hat{S}$ Coriolis term does *not* vanish for rotational levels in very light nuclei, and the rotational energies depend essentially just on the quantum number l, as given by the equation

$$E(l)=E_0+(\hbar^2/2I)l(l+1)\equiv E_0+E_{\rm rot}\,l(l+1). \quad (2)$$

The three p-p resonances that have been reported[1] (and also the one possible n-p resonance[7,8]) are all $j=l$ excitations, so that in this special case Eq. (1) and (2) reduce to the same equation.

If the $^1D_2$, $^3F_3$, and $^1G_4$ p-p resonances are members of a nonadiabatic nuclear-physics-type rotational band, then their energies $E(l)$, as defined in Eq. (2), should yield a linear curve when plotted against an $l(l+1)$ abscissa. This plot is shown in Fig. 1, where the observed linearity of the curve demonstrates that these resonances do in fact obey the $l(l+1)$ energy interval rule of Eq. (2).

The C_{LL}, $\Delta\sigma_L$, and $\Delta\sigma_T$ measurements reported in Ref. 1 unfortunately extend down only to 1.0 GeV/c, which corresponds to a center-of-mass p-p energy of 2082 MeV. Thus the $j=l=0$ and 1 excitations that correspond to the $^1S_0$ and $^3P_1$ levels in this p-p rotational band are not observed (see Fig. 1). However, by using the $F-D=D-S$ equal-energy-interval rule of Eq. (2) to extrapolate to $l=0$, as shown in Fig. 1, we can pinpoint the mass of the p-p S-state bandhead at the value 2020 MeV. Since the mass of two unbound protons is 1877 MeV, the excitation energy of this p-p bandhead is about 143 MeV, which is just the mass of a pion. Hence the three observed p-p resonances phenomenologically correspond to the $j=l=2,3$, and 4 rotational levels of a virtual $pp\pi$ dibaryon bound state. In support of this conclusion, we note that a similar dibaryon excitation, $\Lambda\Lambda\pi$, accurately reproduces the mass value of a weak strangeness $S=-2$ dibaryon resonance, $\Xi^*(\sim 2367)$, that has been observed in two experiments.[14] Furthermore, the occurrence of the π as a mass-shell (zero binding energy) excitation quantum has also been observed in a completely different hadronic system—the "charmed" D and D^* kaon system—as is demonstrated by the following strikingly similar decay modes[14]:

$$\begin{aligned} &pp\pi(2020) \to pp(1877) + 143 \text{ MeV kinetic energy};\\ &D^{*+}(2009) \to D^{+}(1868) + \pi^0(135) + 6 \text{ MeV kinetic energy};\\ &D^{*+}(2009) \to D^{+}(1868) + \gamma(141). \end{aligned} \tag{3}$$

In the $pp\pi$ decay a virtual pion is transformed into kinetic energy, whereas in the D^* decays the pion is either emitted directly or else transformed into a photon.

In addition to its mass, there is one other piece of information about the $pp\pi$ bandhead that we can obtain from Fig. 1 and Eq. (2)—namely, its moment of inertia I, or equivalently its rotational energy parameter $E_{\rm rot} = \hbar^2/2I$. The experimental ${}^3F_3$-${}^1D_2$ mass difference of 120 MeV corresponds to the value $E_{\rm rot} = 20$ MeV. We can compare this p-p $E_{\rm rot}$ value with the $E_{\rm rot}$ values of neighboring light nuclei by using Eq. (2) to obtain experimental $E_{\rm rot}$ values for nonadiabatic rotational bands in light nuclei as a function of the atomic weight A. The rotational bands that we select for this purpose are the following: the "molecular" ^{12}C + ^{12}C rotational band[13] in ^{24}Mg; the $J^P = 0^+, 2^+, \ldots$ ground-state yrast bands[15,16] in ^{28}Si, ^{28}Mg, ^{24}Mg, ^{22}Mg, ^{22}Ne, ^{20}Ne, ^{12}C, and ^{8}Be; two "excited-state" yrast bands in ^{16}O and ^{4}He; four rotational bands (including the yrast band) in ^{20}Ne; two yrastlike rotational bands in ^{9}B and ^{9}Be; and several fragmentary rotational bands in ^{5}Li, ^{5}He, and ^{3}He. Applying Eq. (2) to these experimental[16] rotational bands gives the average values for $E_{\rm rot}$ that are displayed in Fig. 2. We can obtain a scaling law for the rotational energies in these light nuclei by noting that $E_{\rm rot} = \hbar^2/2I \propto 1/I \propto 1/MR^2 \propto A^{-5/3}$. Two different $A^{-5/3}$ curves are shown in Fig. 2; one that corresponds to expanded "molecular-type" geometries[13], and one that corresponds to compact or prolate geometries. These two curves

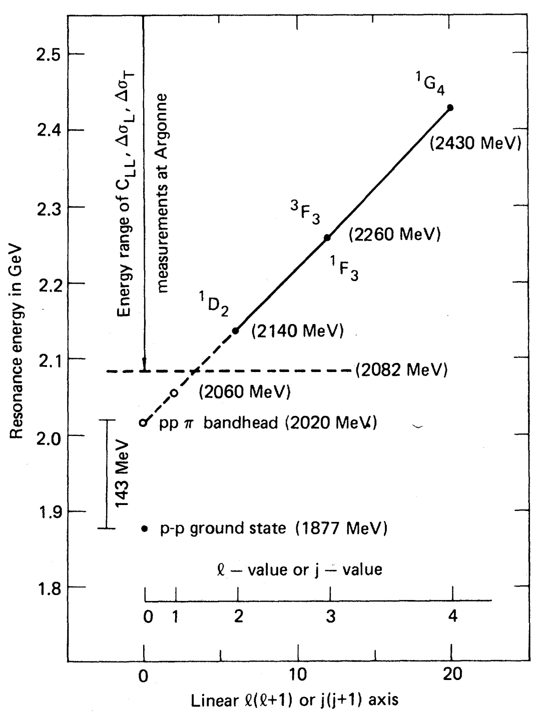

FIG. 1. The experimental p-p rotational band, plotted against an $l(l+1)$ or $j(j+1)$ axis [Eqs. (2) and (1)]. The slope of the curve corresponds to an $E_{\rm rot}$ value of 20 MeV.

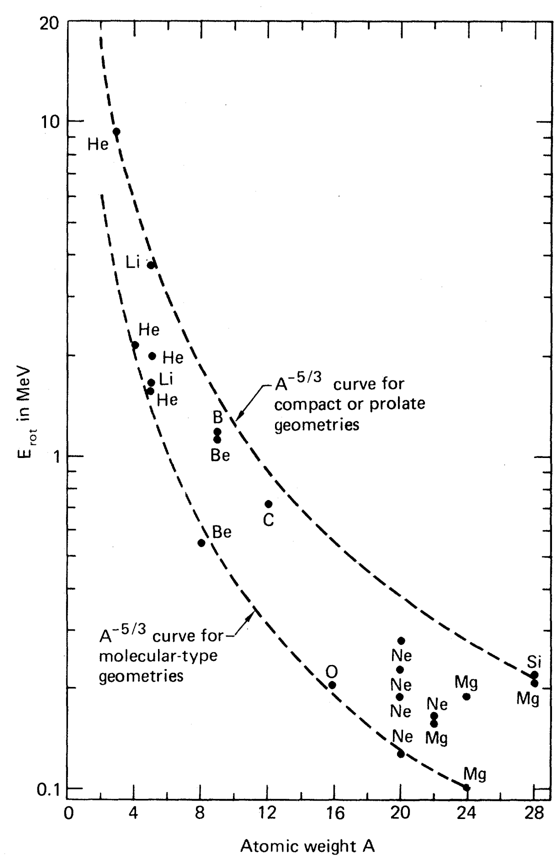

FIG. 2. Average experimental values of the rotational energy parameter $E_{\rm rot} \equiv \hbar^2/2I$ for nonadiabatic [Eq. (2)] rotational bands in light atomic nuclei (Ref. 16), plotted as a function of atomic weight A.

serve as an envelope that brackets the observed values of E_{rot}.

It can be shown[17] that the results displayed in Fig. 2 follow from Eq. (2), but not in general from Eq. (1). Thus a knowledge of the *nonadiabatic* nature of the rotations in light nuclei is essential for a proper understanding of these results.

Figure 2 can be used to delimit the value of E_{rot} that is expected in the case of the $A=2$ dinucleon system. However, we can obtain a more precise value if we extend Fig. 2 so as to include nonadiabatic rotational bands in baryons and mesons, which lie in the mass range that corresponds to $A<2$. These hadronic rotational bands can be formally defined,[18,19] and their E_{rot} values, together with those of the light nuclei of Fig. 2 and the p-p rotational band of Fig. 1, are displayed in Fig. 3. As can be seen in Fig. 3, all of these experimental values for E_{rot} are in agreement with one another.[20]

Preliminary experiments[2,7] show some structure in the n-p amplitudes. If this structure is interpreted in the context of an isotopic spin $I=0$ resonance, then it indicates a mass, width, and elasticity that closely resemble those of the ${}^3F_3$ p-p resonance,[7] and its quantum numbers seem to be either ${}^1P_1$ or ${}^1F_3$. From the systematics of Eq. (2), we expect ${}^3F_3$ and ${}^1F_3$ resonances, if they exist, to appear at the same mass value (as we have indicated in Fig. 1). Thus the phase-shift assignment ${}^1F_3$ is suggested for this $I=0$ structure in the n-p amplitudes.

Uncertainties still exist in the p-p data analysis. However, it seems apparent from the results achieved thus far that the p-p resonances serve as a direct and unique experimental link between the domains of nuclear physics and hadron physics: *The p-p rotational levels, which are nuclear in origin, can be used to pinpoint the mass of the p-p bandhead excitation, which is hadronic in origin.*

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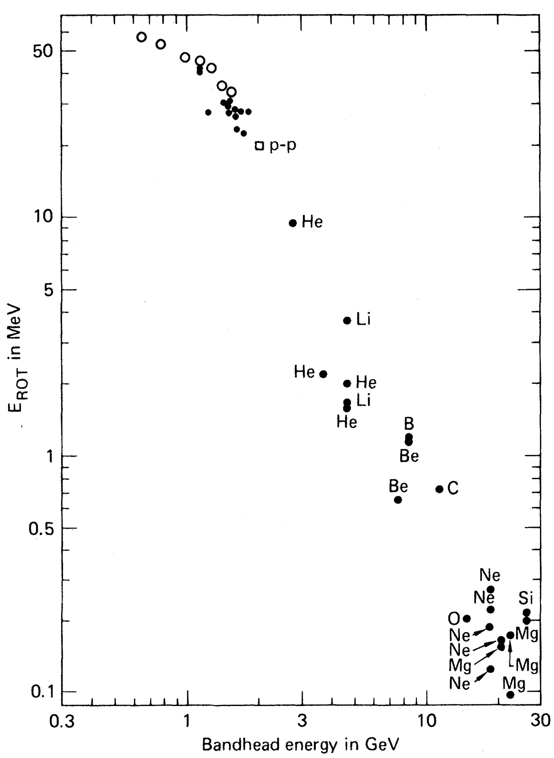

FIG. 3. Average experimental values of E_{rot} for nonadiabatic [Eq. (2)] rotational bands in mesons (open circles), baryons (small solid circles), the p-p dibaryon system (square), and light atomic nuclei (large solid circles) (see Refs. 18–20 and Figs. 1 and 2), plotted as a function of the mass of the rotating bandhead.

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Angular Momentum Transfer in Deeply Inelastic Collisions from Exclusive Sequential-Fission Experiments

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Kinematically complete experiments have been performed on the three-body exit channels in 7.5 MeV/amu ^{208}Pb and ^{238}U on ^{58}Ni and ^{90}Zr. The bulk of the events (> 99%) can be interpreted as sequential fission following deeply inelastic collisions. From the angular correlations, oriented-spin values up to $45\hbar$ are deduced for the heavy fissioning fragment. Their constancy at large energy losses points to strong fluctuations in the correlation between energy loss and angular momentum.

One of the outstanding problems in the mechanism of deeply inelastic heavy-ion collisions is associated with the angular momentum transferred from orbital to intrinsic rotation. Besides γ and light-particle emission, sequential fission has already proven a useful probe sensitive both to the magnitude and orientation of the spin transfer.[1-4] We report in this Letter results from the first exclusive experiments in this field.[5,6] By use of heavy-particle beams and large-area detectors, the two- and three-body exit channels in the reactions ^{208}Pb, ^{238}U $\rightarrow$ ^{58}Ni, ^{90}Zr have been investigated in a way which is complete both kinematically and in the total phase-space distribution of the events, including all correlations between the observables. We show that the bulk of the three-particle data can, in fact, be interpreted as sequential fission following quasielastic and deeply inelastic collisions. From the fission-fragment angular correlations, oriented-spin values up to $45\hbar$ and rather isotropically distributed nonoriented components of $(10-15)\hbar$ are deduced for the heavy fissioning nucleus. Following an initial rise, the former are observed to remain constant up to the largest energy losses, possibly indicating strong fluctuations in the correlation between energy loss and angular momentum.

Ni and Zr targets of 100–200 μg/cm^2 were bombarded with Pb and U beams of 7.5 MeV/amu from the UNILAC at Gesellschaft für Schwerionenforschung. The targetlike fragments were analyzed in a 40×12 cm^2 position-sensitive ΔE-E gas ionization chamber.[7] A lab acceptance angle of ~30° in the reaction plane together with the kinematic concentration for forward c.m. angles and the focusing property of the deeply inelastic reaction allowed us to measure the major part of the cross section with one angle setting for each system. The beamlike surviving fragment or its two fission products were detected in coincidence in a 1×1 m^2 position-sensitive parallel-plate avalanche counter[8] with an overall time-of-flight resolution (in connection with the bunched beam)

