the pion-deuteron breakup reactions by using the same relativistic three-body theory which has worked well in explaining the elastic cross sections. However, in the case of the kinematically complete experiment at 228 MeV, if the invariant mass of the pion-proton subsystem is larger than the mass of the delta, some discrepancies still remain which cannot be explained by the theory.

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Intense Coherent Submillimeter Radiation in Electron Storage Rings

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Energetic electron bunches in storage rings produce pulsed bursts of *incoherent* synchrotron radiation. It is pointed out that they should also produce a roughly comparable power output of *coherent* radio-frequency radiation. Thus electron storage rings might additionally serve as pulsar simulators, producing a similar spectrum of coherent emission, the properties and modification of which could be studied in the laboratory. A spontaneous bunching of electrons (artificially bunched here) might be evidenced as "superbunching."

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In electron storage rings, small (~ 1 cm) bunches of ~ 10^{11} electrons circulate at high energies (several gigaelectronvolts) around relatively small (~ 12 m radius) rings. The resultant synchrotron radiation then extends into the several-kilovolt x-ray region and provides a valuable source of such radiation [e.g., the Stanford Synchrotron Radiation Laboratory (SSRL)]. Moreover, this radiation is pulsed, because the electrons are bunched together, and is narrowly beamed, because of the extreme relativistic motion of the electrons.

It has been much less widely noted that the (deliberate) electron bunching has quite a different effect on the low-frequency part of the spectrum. At high frequencies the electrons radiate incoherently since they are more or less randomly located a large number of x-ray wavelengths from one another. But the flux density in the synchrotron spectrum falls rather slowly as one goes to low frequencies (essentially as $\omega^{1/3}$) and remains substantial even at wavelengths as long as the size of the bunch. For example, going from x-ray wavelengths (~ 10^{-8} cm) to the bunch size (~ 1 cm) reduces the flux density by less than 10^3. In contrast, once the bunch is less than about a wavelength in size, all the electrons radiate coherently. That is to say, the "bunch" might as well be a single particle with a charge of $10^{11}e$ insofar as radiation at such long wavelengths is concerned. As a consequence of the coherence at low frequencies, the intensity is boosted by a factor equal to the number of electrons in the bunch, 10^{11}. This factor can be vastly larger than the decline in intensity at low frequencies, as is the case here, leading to the double-peaked spectrum shown in Fig. 1.

One can compare the power output at the two peaks simply by multiplying the flux density (energy output per hertz or, equivalently, photons per unit bandwidth) by the characteristic frequency at the peak. Thus if the x-ray peak is taken to represent unit power output, the low-frequency power output (at wavelengths comparable to the bunch size) is weaker by the factor of 10^3 because of the decline in (incoherent) output, but up by 10^{11} as a result of the bunch coherence, and then down by 10^8 in frequency. In other words, the two energy outputs are roughly the same for these particular parameters.

The rapid drop in coherence (Fig. 1) for wavelengths shorter than the bunch size can be understood by imagining the bunch to be subdivided into cubes half a wavelength on a side. On the average, one cube will then destructively interfere with a neighboring cube and the total coherence factor will be no more than roughly the number of particles within one single ("left over") cube, hence falling off as ω^{-3} (but slightly softened by the $\omega^{+1/3}$ increase in flux density to $\omega^{-8/3}$). As rapid as this drop is expected to be, it still leaves some remnant of a 10^{11} coherence factor even out to wavelengths roughly 10^4 times smaller than one bunch size (i.e., into the far infrared). At yet shorter wavelengths, there is not even one particle per "cube," and hence there is no coherence left to lose.

These considerations are familiar to machine designers[1]; however, since the coherent wavelengths are not very much shorter than the cavity size, much of the radiation is strongly modulated by the machine itself. Consequently, this feature of the synchrotron radiation has come to be lumped under "machine physics" because it strongly influences the performance of the storage ring; at high bunch densities sudden disappearance of the bunches are experienced, etc. This aspect is somewhat neglected by those mainly interested in the physics that the machines were designed for, namely the collision of energetic particles or, more recently, the production of intense (but incoherent) synchrotron radiation. The point here

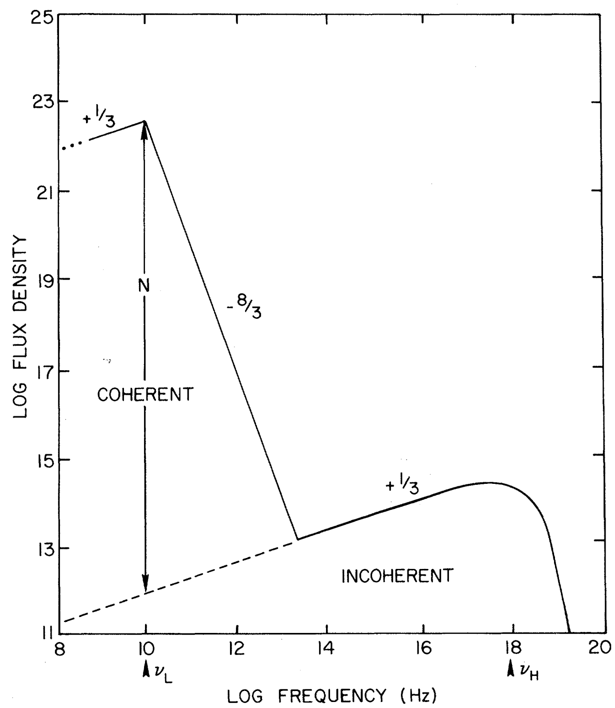

FIG. 1. Synchrotron spectrum showing coherent modifications at low frequencies (adapted from Fig. 1 of Ref. 4). Interference within a bunch may give oscillations (not illustrated) near the low-frequency peak, depending upon the electron distribution within each bunch. At *very* low frequencies the ring cavity should further modify the spectrum (shown dotted). The coherence factor (N) is taken to be 10^{11}, corresponding to a time-averaged beam current of about 65 mA at SSRL. The units of flux density are photons $\sec^{-1}$ mrad^{-1} (10% bandwidth)$^{-1}$ for this current at SSRL (the incoherent spectrum is shown for 3.0 GeV electrons; however, the very low frequencies are insensitive to this energy).

is that this coherent component of the radiation provides in itself an interesting and fundamental topic of investigation that transcends its nuisance role in storage ring design.

The point of this Letter is twofold: (1) to point out that the same analysis has also been made for the case of pulsars instead of electron storage rings; and (2) to point out the experimental possibilities offered by such machines. Goldreich and Keeley[2] have discussed the complementary problem, namely the spontaneous bunching of a uniform circulating beam of electrons as a consequence of their mutual radiation reaction, and suggested that this bunching mechanism might be applicable in pulsars. It is somewhat difficult to study this process in actual storage rings because the electrons are already bunched and maintained as bunches. Consequently, the storage rings could simulate the coherent radiation but not necessarily the bunch formation mechanism. If one inserts storage ring parameters into the growth rate formula[2] [their Eq. (27); $r_c = 3\times 10^{-13}$ cm, $a = 1.2\times 10^3$ cm, $N_0 = 10^{11}$, $\gamma = 6\times 10^3$, and $n \sim 120$] one obtains a growth rate of less than a second, which opens the possibility of "superbunching," wherein the bunch or parts of it become bunched to even higher density. Unfortunately the conducting walls plus a multitude of perturbations modify both the radiation field and the bunch dynamics in a real storage ring, so that superbunching is simply a possibility, one which could be investigated experimentally.

Although no completely satisfactory quantitative pulsar model yet exists, it is widely theorized that the basic source of coherent radio emission from pulsars is from energetic electrons that have been accelerated off the neutron surface (by the rotationally induced electric field). The existing (semiphenomenological) theories account for the radio emission by having the electrons incoherently radiate curvature radiation at γ-ray energies and coherently radiate (because of some bunching mechanism, such as suggested above, although this point remains controversial) at low frequencies to give the observed radio-frequency pulses.[3-6] Pulsed γ rays are, in fact, observed from at least the Crab and Vela pulsars.[7] Whether such phenomenology correctly accounts for the pulsar phenomenon is irrelevant here—the point is that exactly the same argument can be scaled to apply to electron storage rings, in which case we have the (nonastrophysical) luxury of knowing that the electrons are bunched, are energetic, and are emitting synchrotron radiation.

The radio emission from pulsars is characterized by a number of interesting phenomena such as microstructure and a very wide range of polarization variations. There are all the usual difficulties in sorting out which variations are intrinsic to the source and which represent modifications due to propagation. It would therefore be interesting to study the properties of the coherent radiation from the bunches to see if any of these effects might appear spontaneously. Density structure within the bunches and geometrical effects (the bunches are actually pencil shaped) may introduce interesting interference effects. These effects can also be treated with some confidence theoretically, of course. However, if we now go to the next plausible step and suppose that these bunches are radiating *within* a plasma, the theory becomes a bit more difficult. The generally accepted estimate[8] of the charge density near pulsars gives plasma frequencies centered at about 3×10^{10} rad/sec. The observed pulsar radiation is almost all below such frequencies. In many theoretical models, the above fact poses no problem because the plasma frequency is either Doppler down shifted because of plasma flow in the direction of emission or because the dispersion relation is modified by the intense magnetic field. Other models propose quite dense pair-production magnetospheres, however, and the situation with actual pulsars seems rather open at present. Near the plasma frequency, the interference effects are strongly modified by the change in phase velocity. And below the plasma frequency one would naively predict that no radiation could escape. However, for a storage ring the bunches produce fairly strong coherent wave fields (~ 1 V/m), and this radiation could be significantly boosted with strong local perturbing magnets (e.g., wigglers) to, say, ~ 1 V/cm. The plasma can be significantly perturbed by such radiation pressures. In other words, filamentation, inhomogeneities, parametric instabilities, nonlinear effects, etc., may be induced in the plasma which in turn permit emission to occur below the apparent plasma frequency. Such processes would certainly enrich the likely coherent emission properties from such a system.

The obvious types of experiment would then be to take the radiating electron beam and attempt to modify emission within an ambient plasma. A rather high plasma density of about 10^{13} cm^3 would be required to place most of the coherent radiation below the plasma frequency, but at those centimeter wavelengths the plasma volume need not be large to have a scale large compared to these wavelengths. Undoubtedly exploratory experiments should first be made at more readily available plasma densities such as 10^9/cm^3 where the coherence factor would be no less although the wavelengths may become a limiting factor (now ~ 1 m). It is not, of course, necessary to suppress all of the coherent emission and there may be experimental advantages in not doing so (e.g., for calibration purposes). The immediate questions then would be (a) is the radiation completely suppressed below the plasma frequency, or (b) if not, how does it get out? Plus there are other obvious follow-up questions: Is the coherent emission steady or sporadic (i.e., micropulses), or are there unusual polarization effects (i.e., orthogonal mode changing)? Note that these are not just propagation experiments. The issue is what happens if the particles try to radiate within a plasma instead of a vacuum. (The propagation properties at high-power flux densities could, of course, be studied directly with conventional sources of microwaves.) Since the electrons are artificially bunched, one does not expect to be able to simulate that aspect of the phenomenon, although superbunching might even shed some light there as well.

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Charge Form Factors and Charge Densities of ^{3}He and ^{3}H

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Results are presented for the effect of the three-body force on the charge form factors of the $A = 3$ nuclei. Mesonic exchange currents, isobaric processes, and other effects of relativistic order are included in the present calculation. The evaluation of the form factors is extended to values of momentum transfer $q = 10.0$ fm^{-1}, and their model dependence is explored.

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A genuine three-nucleon ($3N$) interaction is incorporated in the nuclear wave functions employed in the present calculation. Hence, for the first time we can explore the role of this interaction in the charge form factor $F_{ch}(q^2)$ and the charge density $\rho(r)$ of ^{3}He and ^{3}H, in the framework that also includes the effects of mesonic exchange currents (MEC), isobaric processes, and relativistic pieces of the one-body charge density (spin-orbit and Darwin-Foldy terms). These relativistic pieces have been traditionally ignored in most of the past work.

As a result, we find that within the conventional framework for evaluating MEC, we are now in a position to resolve long-standing discrepancies with experimental data for F_{ch} of ^{3}He in the intermediate range of momentum transfer q, e.g., in the region of the second maximum. Furthermore, we find that at higher q values the form factors are strongly sensitive to theoretical input such as the nucleon electromagnetic structure, aspects of the strong meson-nucleon interaction, and the exchange processes. Given that our knowledge of this input is rather imperfect, the results of the