ELECTROSTATIC WAVES AND ANOMALOUS TRANSPORT IN THE SOLAR WIND

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ABSTRACT

In situ measurements of fluctuation spectra and particle distribution functions have now been carried out throughout interplanetary space. The link between these observations is established by theories of wave-particle interaction. Linear instability analysis for the actual non-Maxwellian particle distribution functions and an examination of the velocity dependence of microscopic diffusion coefficients form the basis of such an investigation. It is described in more detail for the short wavelength, ion acoustic like turbulence which is found by linear instability analysis to correspond to the observed electrostatic fluctuations. Of the transport processes associated with these fluctuations, electron heat conduction and electron-ion energy transfer are of particular importance for macroscopic solar wind expansion. These effects are studied with the aid of an anomalous transport theory. This theory (Dum, 1978 a, b) is based on the dominance of elastic scattering of electrons by fluctuations, similar to (enhanced) electron-ion collisions. It has a much wider range of applicability than classical transport theory, which assumes dominance of Coulomb collisions for elastic and inelastic scattering. Nevertheless, a substantial fraction of the heat flux is often carried by strongly anisotropic electrons of elevated energy (Strahl) which should be handled by a nonlocal transport theory, describing the modification of exospheric (collisionless) expansion by residual scattering and the enhancement of the ambipolar electric field by anomalous momentum transfer.

Solar Wind Models and Breakdown of Classical Transport Theory

The solar wind like most plasmas we encounter is both turbulent and nearly collisionless. Macroscopic studies may point to the importance and direction for modifications of classical transport theory but, due to the interdependence of many parameters and the uncertainty of coronal boundary conditions, generally allow no unique conclusions on the underlying microscopic physics (Hundhausen, 1972, p. 81). The rationale and some principal results from microscopic studies that make direct use of the detailed in situ measurements available now for the interplanetary solar wind are outlined in the following.

The need for a modification of classical transport theory as applied to solar wind expansion was recognized at an early stage of theoretical development. (For a review see Hundhausen, 1972.) According to one-fluid theory of radial expansion

$$r^{-2} \frac{d}{dr} r^2 \rho u \left[\frac{u^2}{2} + \frac{5}{2} \frac{p}{\rho} - \frac{GM_o}{r} \right] = -r^{-2} \frac{d}{dr} r^2 q \tag{1}$$

where ρ is the mass density, p the pressure, u the speed and the last term in the bracket is the gravitational potential, the heat flux q provides the major internal source term to which external sources due to hydrodynamic waves propagating beyond the corona may be added. The heat flux predicted by classical transport theory, however, was much too large to fit observations at 1 AU. Various ad hoc

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reductions have been introduced to allow for a more efficient conversion of thermal energy into kinetic energy of expansion. Heat flux is dominated by electrons. Two fluid models, however, brought even more problems. Not only were electron temperatures too high, but ion temperatures were an order of magnitude too low to fit observations at 1 AU. Again, the way out appeared to be an ad hoc increase in the electron-ion energy transfer rate. Both modifications have been carried out in a number of different ways. The introduction of "fudge factors" in the classical transport relations may be interpreted in terms of an increase in the effective collision frequency, typically by a factor of 10-100 over the frequency of Coulomb collisions, which arises presumably by scattering from enhanced fluctuations. Anomalous transport with even larger increases in the effective collision frequency is of course by now a well established fact for many space and laboratory plasmas. It was also recognized very early that solar wind expansion may in turn provide the free energy source for enhanced fluctuations. In fact, the various two fluid models themselves imply the onset of microinstabilities already at heliocentric distances ranging from 3-11 solar radii, using the skewed electron distribution function corresponding to classical heat flux (Forslund, 1970; Singer and Roxburgh, 1977).

Fluid models also imply total breakdown of classical collision dominated transport at about the same heliocentric distances even without account of instabilities, especially for rapidly diverging non-radial flow geometries (Durney and Pneuman, 1975). Clearly, heat flux must remain limited as the plasma becomes nearly collisionless,

$$\hat{q}_e \equiv q_e / (nmv_e)^3 = - \varkappa_T \lambda_{ei} \nabla_\| \ln T_e < \alpha_q , \qquad (2)$$

where n is the electron density, $v_e = (T_e/m)^{1/2}$ the electron thermal velocity, $\lambda_{ei} = v_e \tau_{ei} \propto (T_e^2/n)$ the mean free path for collisions of thermal electrons with ions, $L_T = (\nabla_\| \ln T_e)^{-1}$ the temperature gradient scale along the magnetic field and $\varkappa_T$ a dimensionless heat conductivity which depends on the ion charge Z as electron-electron collisions with collision time $\tau_{ee} = Z\tau_{ei}$ try to restore a Maxwellian distribution. For protons, Z=1, $\varkappa_T$ = 3.16 in the normalization of Braginskii (1967) for τ_{ei}. The classical (first) relation holds for $(\lambda_{ei}/L_T) \ll 1$ and $\alpha_q = 0(1)$ corresponds to free streaming. Variations of $\hat{q}_e$ and λ_{ei}/L_T between 0.1 and 1 are typical for the interplanetary solar wind. The shape of the electron distribution is strongly non-Maxwellian in this case, consisting of a nearly isotropic core and a hotter low density halo which may be considered collisionless and may be strongly anisotropic (e.g. Feldman et al., 1975, 1979; Ogilvie and Scudder, 1978; Pilipp et al., 1981).

The normalized heat flux $\hat{q}_e$ depends only on the shape of the electron distribution, or more precisely the isotropic part f_0 and the $l=1$ anisotropy f_1/f_0

$$\hat{q}_e = \int_0^\infty dx \frac{8\pi}{3} f_0 \frac{f_1}{f_0} x^2 \qquad (3)$$

where $x = mv^2/2T_e$, $f_1(x) = (3/2) \int_{-1}^{+1} d\cos\theta\, f(x,\theta)\cos\theta$. The replacement $x^2 \rightarrow x$ in (3) gives $\langle v_\| /v_e \rangle$. For the electron rest frame to be used here, $\langle v_\| /v_e \rangle \equiv 0$ thus implies $f_1 < 0$ at lower energies.

Classical transport theory assumes the dominance of Coulomb collisions, leading to a nearly Maxwellian, $f_0 = f_M = (2\pi)^{-3/2} e^{-x}$, and weakly anisotropic distribution, with f_1/f_M proportional to λ_{ei}/L_T or the parameter $(B_T/Z) = (8/3)(2/\pi)^{1/2} \lambda_{ei}/L_T$ of Spitzer and Härm (1953). As the collision frequency for large speeds de-

creases as v^{-3} these assumptions must break down at some speed v_c. This is signaled by an ever increasing anisotropy (see Fig. 1).
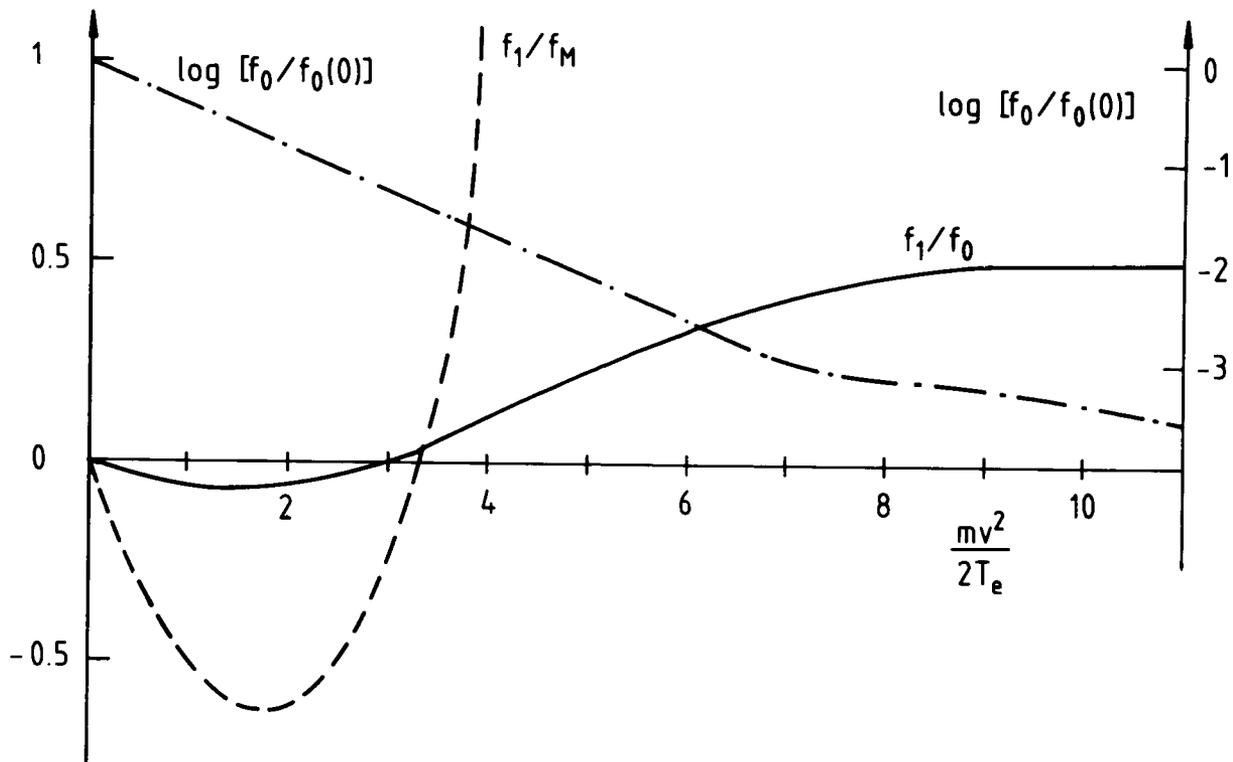

Figure 1. Heat flux limitation for weakly collisional electrons. Shown are (schematically): (a) the isotropic part $(-.-.-)$ f_0 of the distribution $f(\underline{v})$ exhibiting core and halo, (b) the $1 = 1$ component $(-)$ $f_1(v)$, which determines the return current of low energy electrons $(f_1 \lesssim 0)$ and the heat flux, due mostly to strongly anisotropic high energy electrons. Also shown is $f_1/f_M \propto \lambda_{ee}/L_T$ $(---,\ f_M$ Maxwellian) predicted by classical transport theory e.g. for $\lambda_{ee}/L_T = 0.32$ $(\lambda_{ee} = \lambda_{ei}$ mean free path for thermal electrons, L_T temperature gradient scale), demonstrating total breakdown of this local theory.

A generous condition for the applicability of the classical transport relation in (2) may be found from the requirement that 90% of the predicted heat flux (3) should arise from the population $v < v_c$. This gives $x_c = 9$ for the Spitzer-Härm distribution. Assuming that the validity of the theory can be streched to $|f_1/f_M| < 1$ gives then the remarkable small values, $\lambda_{ei}/L_T < 10^{-2}$, $\hat{q}_e < 0.03$. Because breakdown is rapid $(f_1/f_M) = 0(x^3)$, even more generous criteria give similar results, see Gray and Kilkenny (1980). For the commonly assumed limit of validity, $\lambda_{ei}/L_T = 1$ we obtain $x_c = 1/2$ for $|f_1/f_M| < 1$, corresponding to a population $x < x_c$ which carries a negligible portion of the heat flux.

In contrast to the predictions of classical transport theory, $|f_1/f_0| < 3$ by definition of the $1 = 0,1$ components for any $f(\underline{v})$. For other physical situations, e.g. neutron transport and laser heated plasmas where one has the same problem of scale lengths comparable to the mean free path, ad hoc microscopic flux limits $|f_1/f_0| < \alpha_f$ have long been introduced in order to salvage diffusive transport theory. The usual limitation, $\alpha_f \le 1$ simply comes from the requirement $f = f_0 + f_1 \cos\theta > 0$ and ignores the fact that $\lambda_{ei}/L_T = 0$ (1) also implies significant terms

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$l \geq 2$ in a Legendre expansion of $f(v, \cos\theta)$. The level at which f_1/f_0 saturates is not a universal constant but determined by the nearly scatter free motion of energetic electrons in the global electric and magnetic fields. Collisionless expansion from some exospheric base with magnetic field B_0 suggests an approximate distribution $f(v, \theta) = f(v)$, $\theta < \theta_m$, where $\cos\theta_m = (1-B/B_0)^{1/2}$ is the asymptote resulting from conservation of magnetic moment, $mv_\perp^2/2B = const$. This model yields $f_1/f_0 = (3/2)(1+\cos\theta_m)$, independent of energy for $x > x_c$. Observed high energy electron distributions are similarly restricted in pitch angle (Strahl) with a half width that varies but may become as small as $10°$ in the interior of a magnetic sector. Near isotropy in the vicinity of sector boundaries, however, suggests strongly enhanced scattering (Pilipp et al., 1981).

Instabilities and Anomalous Transport

Breakdown of classical transport theory relatively close to the solar corona results in observable strongly non-Maxwellian distribution functions at greater distances. Exospheric theory, or more correctly a theory that accounts for the rapid increase in Coulomb mean free path with speed, $\lambda_{ei}(v) \propto v^4$ (Scudder and Olbert, 1979) can in principle account for this non-local transport. However, model distribution functions related to these theories or actual observations not only allow for essentially the same heat flux instabilities as the weakly non-Maxwellian electron distribution for classical heat flux (Schulz and Eviatar, 1972; Gary et al., 1975), but open up a wealth of new free energy sources such as anisotropies and ion beams (see e.g. a recent review by Schwartz, 1980). To be sure, instability depends on the assumed range of plasma parameters, but as is well known small scale turbulence of varying nature and intensity has now been observed throughout the interplanetary solar wind (e.g. Gurnett, 1981).

Associated anomalous transport in the solar wind as for many other plasmas is most frequently discussed by determining plasma parameters corresponding to marginal stability, or more generally by estimating anomalous relaxation rates for these parameters. Such a simplified description is suitable for inclusion in global solar wind models (Hollweg, 1978). A simple model for heat flux that includes rates for core electron deceleration by the global electric and magnetic fields against acceleration to the proton frame by Coulomb collisions and the phase speed of waves by wave-electron interactions, for example, on comparison with observations indicates the importance of all three effects in regulating heat flux (Feldman et al., 1979).

If phenomenological models indicate the potential importance of anomalous transport then evidently the need for deriving new transport relations from a first principle theory is even greater. This difficult task not only involves the calculation of particle distribution functions from a kinetic equation with given collision terms, as in classical transport theory, but also another kinetic equation for the evolution of the wave spectrum. Diffusion coefficients with a velocity dependence that usually is quite different from that of corresponding terms for Coulomb collisions, and wave growth rates for the self-consistent highly non-Maxwellian distribution function are basic new elements in these equations. The important questions if and how the detailed microscopic description can be reduced systematically to a fluid type dynamical description that is at least tractable for numerical codes have been examined previously and were answered in the affirmative for the interaction of electrons with ion acoustic like fluctuations (Dum, 1978a,b). The key role anomalous transport connected with these fluctuations undoubtely can play e.g. in collisionless shocks and laser heated plasmas (e.g. Gray and Kilkenny, 1980) motivated this research. Because very similar electrostatic fluctuation spectra are frequently observed in the solar wind (Gurnett, 1981) their origin and

their effect on electron heat flux, electron-ion energy exchange and the global electric field should be studied, also with the aim of finding extensions of anomalous transport theory. Such a program in no way prejudices the role electromagnetic instabilities can possibly play for these transport processes and certainly not the role of e.g. anisotropy driven electromagnetic instabilities in shaping solar wind ion distributions.

To see the effect on electrons, ion acoustic like fluctuations may be considered an extension of the stable fluctuation spectrum responsible for electron-ion collisions with wave number range $1 < k\lambda_{De} < \Lambda = \lambda_{De}/b_0 \gg 1$ to the range $\lambda_{De}/\rho_e < k\lambda_{De} < 1$ and phase velocities $\omega/k > v_i$ (λ_{De} Debye length, ρ_e electron gyroradius, b_0 minimum impact parameter, v_i ion thermal velocity). For most electrons $v > \omega/k$, thus scattering is predominantly elastic with diffusion coefficient $D^t = \nu v^2/2$ and frequency (Dum, 1978a)

$$\nu(v) = \nu_{ei} + \nu_{ew} = 3 \, \omega_e (v_e/v)^3 \left[Z \frac{\ln\Lambda}{\Lambda} + \frac{\pi}{3} \frac{W}{nT_e} \left\langle \frac{1}{k\lambda_{De}} \right\rangle \right] , \tag{4}$$

where ω_e is the electron plasma frequency, and the average in the second term is over the wave spectrum with energy density $W = \langle \delta E^2/8\pi \rangle$. Wave activity in the interplanetary solar wind (Gurnett, 1981) with $W/nT_e = 10^{-7} - 10^{-5}$ (peak) completely dominates elastic scattering, as $\Lambda = 1.24.10^4 (T_e^3/n)^{1/2} = 10^{11} - 10^{12} (T_e \, ^\circ K, n \, cm^{-3})$. Inelastic scattering with diffusion coefficient $D^1 = \nu_{ei} v^2 + \nu_{ew} \langle (\omega/k)^2 \rangle$ although comparatively slow, still dominates electron-electron scattering, at least for thermal electrons, and tends to flatten the electron distribution. Because of the v^{-3} dependence of D^1, this process is most rapid for low energy electrons, taking a time that may be estimated from (Dum, 1978a, Fig. 1)

$$\int_0^{T_0} dt \, \pi \, \omega_e \frac{W(t)}{nT_{eo}} \left\langle \frac{1}{k\lambda_{Deo}} \left(\frac{\omega}{k v_{eo}} \right)^2 \right\rangle \gtrsim \frac{1}{5} \tag{5}$$

for an initially Maxwellian distribution with temperature T_{eo}.

An anomalous transport theory that includes classical transport may be constructed under the assumption that elastic scattering is sufficiently frequent to maintain a nearly isotropic electron distribution function against the perturbing forces such as gradients, the electric field etc. (Dum, 1978b). The anisotropic part $\tilde{f}$ of the distribution function becomes a functional of the isotropic part f_0, with $|\tilde{f}/f_0| \ll 1$. In contrast to classical transport theory, f_0 is generally non-Maxwellian and is to be determined from a kinetic equation which includes the much slower inelastic scattering and nonlocal propagation effects in time or distance. If local relaxation by ion acoustic like fluctuation dominates, then f_0 takes the shape $f_0 \propto \exp -(v/v_0)^5$. The structure of the transport relations depends strongly on the shape of f_0. For example, in addition to a heat flux proportional to the temperature gradient, there is for non-Maxwellian f_0 also a heat flux, usually in the opposite direction, that is proportional to the density gradient. The effective collision frequency, in contrast to the Coulomb collision frequency, is not simply a number that depends on a few plasma parameters but is proportional to the fluctuation level and thus is a dynamic quantity connected with wave growth. Also (4) was written for simplicity assuming an isotropic wave spectrum. Actual spectra are usually strongly anisotropic and the collision frequency depends thus on the pitch angle (Dum, 1978b).

The anomalous transport theory provides the framework for estimating the effects

of the observed short wavelength turbulence in the interplanetary solar wind. Taking e.g. $W/nT_e = 10^{-7}$, $k\lambda_{De} = 1/2$, $n = 17$ cm^{-3} gives $\tau_{ew} \equiv (\pi/8)^{1/2} \, 3/\gamma_{ew}(v_e) = 25$ sec from (4) and $\tau_0 \approx 100 \, \tau_{ew}$ from (5). The time τ_0 for flattening may be still longer as the average fluctuation level required by (5) is reduced from the peak values by the fact that wave activity occurs in form of many bursts that individually may be as short as a fraction of a second (Gurnett, 1981). The observed shape of f_0 (Fig. 1) also indicates that the effect of the turbulence on f_0 is nonlocal, except perhaps at very low energies where f_0 cannot be measured due to contamination with photoelectrons and distortions by the spacecraft potential. Effective collision times during wave activity are much shorter than the Coulomb collision time $\tau_{ee} = \tau_{ei}$ (Z=1) $= 1.3 \times 10^5$ sec for $T_e = 3.6 \times 10^5$ °K (parameters correspond to Fig. 3-5 of Dum et al., 1980). Coulomb collisions may still play a role in regions of velocity space where the resonance condition $\omega - \underline{k} \cdot \underline{v} = 0$ is satisfied only for a small part of the wave spectrum and obviously during periods of no wave activity.

An estimate for the applicability of the anomalous transport theory may be obtained in a similar manner as described above for classical transport. The anomalous theory obviously has a much wider range of applicability because it does not demand that f_0 is Maxwellian and the effective mean free path $\lambda_{ew} = v_e/\tau_{ew}$ for scattering from waves is generally much shorter than for Coulomb collisions ($\lambda_{ee} = 2$ AU for the example given above). Still, the theory assumes dominance of elastic scattering and for the v^{-3} dependence in (4) also must break down at some speed, v_c, which, however, is larger than in the case of scattering solely by Coulomb collisions.

The detailed measurements of distribution functions available for the solar wind are of particular value for an investigation of the physical mechanism of heat flux limitation. In order to test the anomalous transport theory, the ratios of effective mean free path to the gradient scales of temperature and density as well as the ratio of interplanetary electric field to effective runaway field were determined from fits of measured and predicted distributions for $v < v_c$, because these values are not known sufficiently well. They come out to be quite reasonable, however, also in relation to the prevailing fluctuation levels. For the highest measured fluctuation levels among the cases studied so far, using Helios measurements (Dum et al., to be published), the $l = 1$ component of the distribution function predicted by anomalous transport theory for measured f_0 can be fitted with observations in a large velocity range $v < v_c$, thus describes almost the entire heat flux. For more quiet conditions and large heat fluxes, a substantial fraction of the heat flux is carried by energetic electrons $v > v_c$, which are strongly anisotropic. Enhancement of the ambipolar electric field by anomalous momentum transfer to bulk electrons still affects these electrons, however.

An instability analysis for waves in the solar wind which directly uses the measured distribution functions rather than model distributions has been described previously (Dum et al., 1980a, 1981). We now find that most of the observed electrostatic short wavelength fluctuation may definitely be identified as ion acoustic waves. Wave growth and wave characteristics such as ω, $\underline{k}$, depend very strongly on the actual detailed distribution functions. This is also demonstrated by the fact that we found both weak electron (heat flux) and more recently also ion (beam) driven modes, whereas previous calculations with model distribution functions never established instability when parameters in these models were not simply assumed but determined from fits to actual measurements (Lemons et al., 1979). The instabilities we find are very weak, highly variable and limited to relatively narrow ranges

f phase velocity and angles of the wave vector, all consistent with observations (Dum et al., 1980b). The short duration of individual wave bursts can be understood if we close the loop by estimating the time in which e.g. minute changes in the electron distribution by isotropization change the sign of the growth rate $\gamma_k = \gamma_{ke} + \gamma_{ki}$, cf. also Lemons et al. (1979). Relaxation oscillation around marginal stability $\gamma_k \approx 0$ are to be expected if these relaxation effects are combined with the perturbing forces that provide the free energy for wave growth. They are a common feature of other turbulent collisionless plasmas (Dum, 1981) and imply an exchange of energy between electrons and ions, with energy extracted from the electrons for $\gamma_{ke} > 0$, i.e. electron (heat flux) driven modes. Rates for energy and momentum transfer may be computed from a given wave spectrum once the dielectric properties are known from the stability analysis with the actual distribution functions (e.g. Dum, 1978a, 1981). The rate of momentum transfer (mostly to core electrons) is

$$\underline{R}_e = \int d\underline{k}\ W(\underline{k})\ 2\ \mathrm{Im}\ \epsilon_e(\underline{k}, \omega_{\underline{k}})\ \underline{k} \tag{6}$$

where $\mathrm{Im}\,\epsilon_e$ is the electron contribution to the imaginary part of the dielectric constant. In the energy transfer rate K_e, $\underline{k}$ is replaced by $\omega_{\underline{k}}$. Using the parameters given before, $T_e/T_i = 7.5$, and wave information from Fig. 4 of Dum et al. (1980a) gives an acceleration rate $du/dt = R_e/nm \approx 32$ km/sec^2 as compared to $\omega/k \approx 64$ km/sec and $u = 392$ km/sec. The cooling time is $-(3/2)nT_e/K_e \approx 3900$ sec as compared to 1.34×10^8 sec for energy exchange by Coulomb collisions. It is emphasized again that integral effects over many individual wave bursts must be considered, but these numbers certainly indicate the potential importance of scattering by ion acoustic turbulence.

In conclusion, we have tried to demonstrate that the recent in situ measurements of fluctuations and particle distribution functions offer an excellent opportunity for a test of theories of wave particle interaction and for finding necessary extensions.

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