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Introduction: We will describe here some results from a MRS scattering model designed to be appropriate for 'slow' resonant scattering. This temporal model is based squarely in induced currents in individual nuclei; a natural consequence is that reradiation into 4π is natural, and does not involve special mechanisms like spin-flips or imperfections of the lattice. Driven by these ideas, we have been able to do experiments where the '4π-shine' decay rate around the scattering (FS) slabs is measured simultaneously with the FS rate.

Our SS scattering slabs are simple as possible - no hyperfine fields , no crystal structure, and quite static in time.. Get mainly the one important set of currents jp, an associated FS field Ep, and finally an associated beamlike intensity $R_{fs}(t)$. But in addition, each current, even jp, contributes to the '4π-shine' intensity. This gives quantitative agreement with $R_{4\pi}(t)$, which is rather more complicated than the simple e^{-t} one might first expect.

MRS predicts another set of currents ju, with an associated 4π intensity $R_{4\pi}(t)$. The modifiers refer to unphased and phased. With static SS slabs, this branch is weak, and can be neglected. Driven by these ideas, we have prepared scattering samples where the atoms holding the currents are being stirred about (by diffusion) rather rapidly. This provides a method for dephasing the jp, but also provides a generation rate for ju.

The experimental data is not of great quality at this early stage. But the present rough MRS calculations fit easily.

Experimental Arrangements:

Begin with a plane wave source tuned to the 14.4 Kev resonance, and monochromatized down to some 5 or 10 mev. Basically, we see events originating in the individual electrons of each bunch, and 5 million bunches/sec. The result is that while most bunches irradiate our enriched stainless steel slabs with no effect, maybe a few hundred times per second a single quantum is absorbed in some one of our Fe57 nuclei. Knowing the arrival time t0 of the bunch, we need merely note the t-t0 when, if ever, one of our detectors receives a delayed count from an absorption @t0.. One set of samples is 90% enriched SS of different thicknesses. Second set of samples for diffusion has the iron atoms contained in Dowex50 ion-exchange resin of three degrees of wetness.

These experiments were made with up to three Fe-enriched slabs in the beam before the FS detector. The detectors are called Avalanche Photo Diodes, and are beautifuly adapted to measuring time, although they do well in energy too. We always place one detector in the forward beam, after all the slabs, to measure the FS R(t). In addition we frequently place another APD just above a FS slab. Here it is well suited to measure 4π shine, which we call by such names as $R_{4\pi}(t)$, or sumjsq(t). With our present beams, there is an unimportant prompt background of only some 10^5 cps at t=0. And the delayed rates of maybe 5 cps can be readily measured with discriminators and TACs.

Treatment of FS:

Begin with the phased currents in a slab L(cm) thick or μ_0L s absorb-thick at position s=z/l @t. But instead of summing wavelets from each atom, pass to a description involving Ndv where one can use integrals. The resulting current is the amplitude for an excited nuclear state in a particular atom; one needs to specify its position in space, its frequency and phase,all at a given t. Also the generation number m is important. Each calculation begins with a single absorption somewhere in the slab, and can 'hop ' from atom to atom as well as decay by IC, or radiation to 4π, or radiate forward. m defines how many generations have precceded this current.

$$\mathbf{jm(m,t,z)} = \xi^{\mathbf{m-1}}\,\mathbf{(1/(m-1)!)2}\quad \mathbf{e^{-t/2}}\quad \text{with}\quad \xi = -\beta o L\ s\ t/4$$

□□(1)

These currents have been found three ways:

a) ***SoP methods.*** Here one uses only conventional microscopic amplitudes and builds it all up from there. Strictly space-time. It follows the Feynmann aphorism to 'sum-over-all -the-paths'. The path is a series of separate steps, and its amplitude is merely the product of the elementary amplitudes of each step. Each path has numerous invisible times and places; one stage in performing the SoAllP, is to collect huge numbers of such paths, and add them all up by integrating over the invisible times and places. The result for the mth current is given above.

A major feature revealed by this approach is that amplitudes for getting to the detector with 1, or 2, or 3 scatterings are sufficiently different to require separate names. A given measurement will have simultaneously amplitudes arising from 1,or 2 or 3 or more scatterings in the slab before reaching the detector. These all have different time dependencies one from another. Can call them **Generations**. And I index them below with a subscript m. No time for more here.

b) a ***Currents/Fields approach*** uses the same elementary amplitudes, but creates from them by direct summing a pair of coupled differential eq'ns. One eq'n shows how all the j(m) currents @ time t make the macroscopic fields E(m) everywhere. 2nd eq'n shows how the E(m) fields create the new currents j(m+1). One works with a pair of coupled DE's describing how j(m) -> E(m) ->j(m+1). Easy to see that a sharp initial condition allows a recursive integration that gives the currents and fields at all future times. Specializing to the phased fields and currents now, these are:

$$\mathbf{Ep(m,t,z) = -2\pi N \int dz'\ jp(m,t,z)}$$

$$\mathbf{d/dt\ jp(m+1,t,z) = -\Gamma_0/2\ jp(m+1,t,z)\ + \Gamma_r/2\ \sigma/4\pi\ Ep(m,t,z)} \qquad \mathbf{(2)}$$

d/dt jusq(m,t,z) = $-\Gamma_0$ jusq(m,t,z)

The unphased currents ju of 2c will be explained at greater length below. It is characteristic of the C/F approach that there are more than one kind of currents in the slab at once, and they can make more than one kind of field. Written here without a generator term, they will never be different from zero.

Starting with an initial condition, one recursively finds all the currents and fields. The advantage of the C/F method appears when one begins to do more complicated problems than single freq FS. It helps one greatly in deciding which partial sums are most important. Again, one distinguishes the currents corresponding to their scattering generation - m.

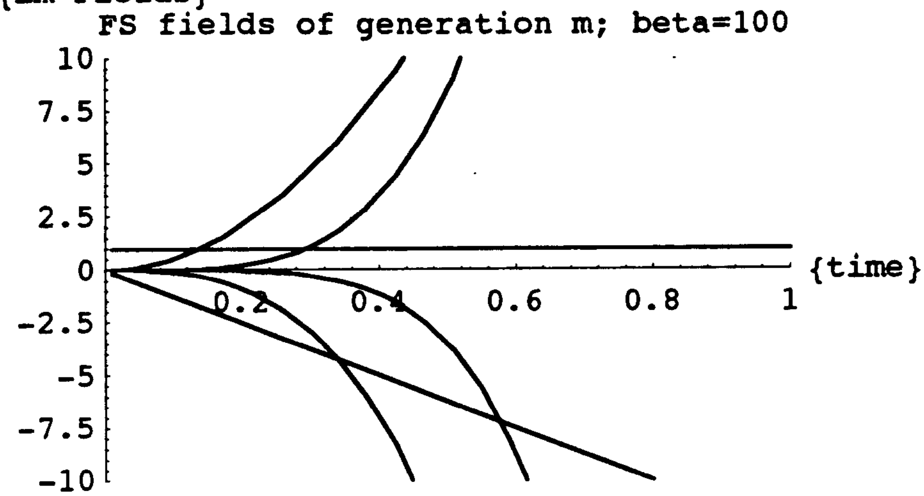
c) ***FT[E(ω)] method.*** A famous expression (Kagan) has been given for the FS field Efs from a simple slab. Was derived from a normal frequency description, built on the scattering amplitude for single atoms, where the reflectivity for a macroscopic slab is given as $E_{fs}(w)$. This results was Fourier Transformed to give $E_p(t)$ for time domain experiments. The J0 expression from Kagan corresponds to summing all the FS amplitudes over m.

One insight learned from the C/F model was that the coherent phased currents in a slab, and the strong field they generate , are related as Ep(t,z) $= \int dz'\, j\,(t,z')$. So, take the E_{fs} given by Kagan,and differentiate to find the current at z. When the single current found this way is expanded as a Taylor series in time, it
reproduces all the jm currents displayed above in (1).

To compare with experiments, start by finding all the fields E(m,t,z) coming from the j(m) currents by integrating (2a) over z'. And since we observe only the total FS field, also sum all the E(m) to get Ep. Here the simple e^{-t} time dependance of single atoms has been temporarily factored out of the time dependance.

Fig.1 shows the fields Ep(m,t,z) for fixed z generated by the first 6 generations of currents for a thick sample. The f(t)-like Es produces a spatially uniform j(1) through out the slab; the j(1) currrents produce a field increasing in the downstream direction with z but constant in time, the j(2) produce a field of opposite phase increasing linearly with time, the E(3) field from the j(3) currents increases quadratically with t, and so on.

{Em Fields}



Since our detector does not distinguish between different m, the next step is to sum over all m. Adding the separate amplitudes in the above figure, one gets the single FS amplitude E_{fs} below(Fig 2) that leaves the slab. Merely square this for $R_{fs(t)}$.

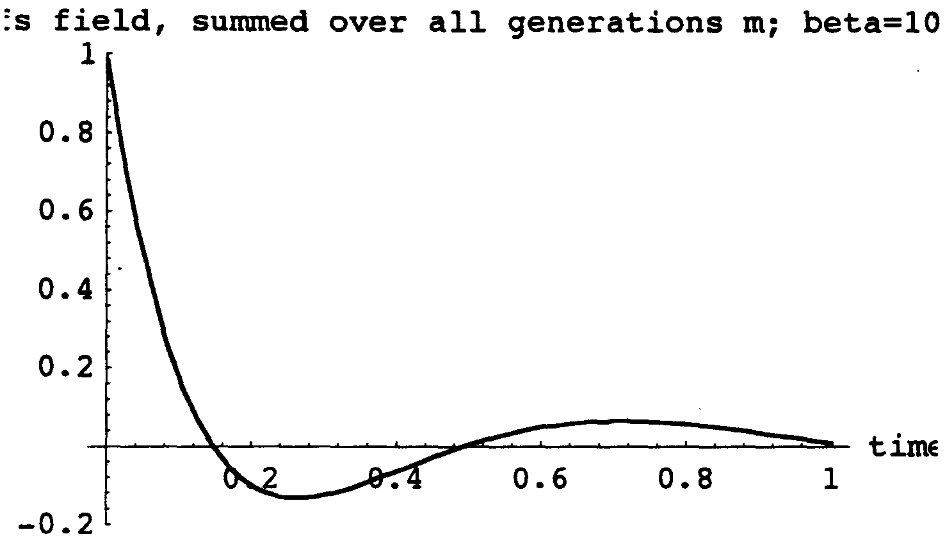
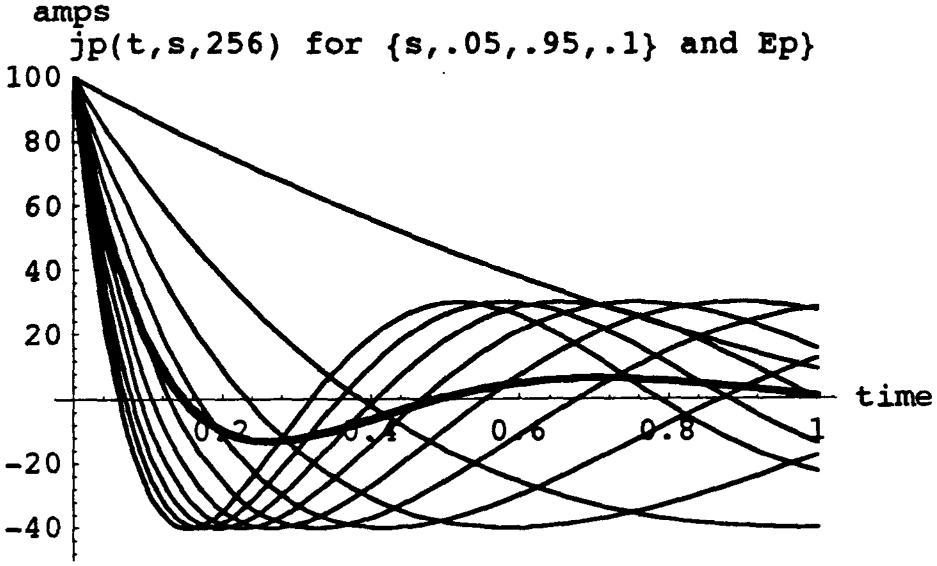


Fig 3 below really displays **Where and When are the induced currents?** Show here the j(t,z) amplitudes vs time. The z position in the slab has been defined by a grid ûs = {5,15,25,...95}
through the thick û=100 slab. This is roughly like {.5, 1.5, 2.5,... ,9.5} microns inside a 10 μ enriched SS slab. Right after the flash, all depths in the slab are uniformly excited. The upper curve for û=.05 shows a slowish decay. If had taken û->0, would have seen no decay at all! (Remember we have factored out the normal Fe decays, and what we see here refers only to the forward radiative emission from our slab).

As you move deeper in the slab, their induced currents decay more and more rapidly. But also they go negative and then more or less oscillate in time. What is happening is explained by the behaviour of the numerous j_m(m,t,z) whose sum is displayed here. No time now to explicate more details of this. A major point is that one can sum the currents to get the bold amplitude shown. Another main point is that E_{fs}(t,z) is a poor measure of the amount of induced current. The figure clearly demonstrates that these currents, born with the same phase, soon get dephased, and add nearly to zero. The magnitude of these currents is about 1/4 of their initial value after dephasing;

this suggests that perhaps a few percent of the original j*j(t,z) currents may remain after the dephasing is fairly complete at about .2 meanlives.



It is quite clear that the zeros of the FS arise each time the sign of the Es changes, and these occur partly because each E(m) is of opposite sign to that for E(m-1), and partly because the magnitudes of successive Em can be larger than the preceeding one. As t increases, field magnitudes for m increase more rapidly with t than those of m-1. Quite roughly, you get another 'zero' each time an Em field exceeds the sum of all the fields of lower m.

Worth mentioning that Fig 3 strongly suggests multiple slab scattering. With one thick slab, hard to tell details of 'where are the currents?' By cutting a slab in to 10 slices,
and separating them along the beam line, one can use their individual Inco rates as a pretty clear answer to this question.

Need a name to distinguish these beats from the better known time beats. They have been called 'Bessel' beats, merely because a J1 function appeared as part of the Kagan FS equation. We prefer 'multiple scattering' beats, which carries some understanding of their origin.

How do you get counts into 4π?

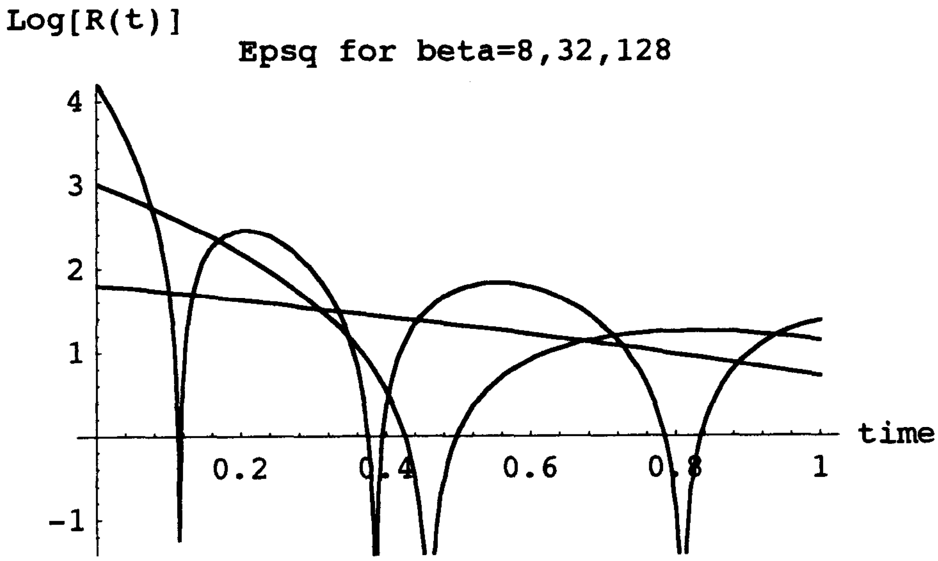
Easily. We nuclear MB people have always known that excited nuclei,*ie currents*, radiate amplitudes (fields) into 4π. Merely need to square to get the intensity. Only slightly more complicated when many currents are excited at once . (I know there is never more than one 14 Kev quantum in our slabs, but since we don't know where it is, have to sum over all the places where it might be, and the result from SoP, as well as more ordinary QM, is close to the idea that it is everywhere at once.) In this C/F model, where we take the microscopic currents seriously, we merely need to add up all the fields from all individual nuclei, their phases as seen in the Inco detector have been randomized both by the multitude of source pts as well as the numerous locations of the detector atoms, and squared. A little thought will convince you that the random phases allows 'squaring before adding' with enormous simplification of the calculation. Our computations for FS and for Inco both use the same phased currents jp(t,z). Contrast $R_{fs}(t) = [\int_0^L dz' \, jp(t,z')]^2$ where the phases are maintained in the calc, while $Rinco(t) = \int_0^L dz' \, jp(t,z')^2$.

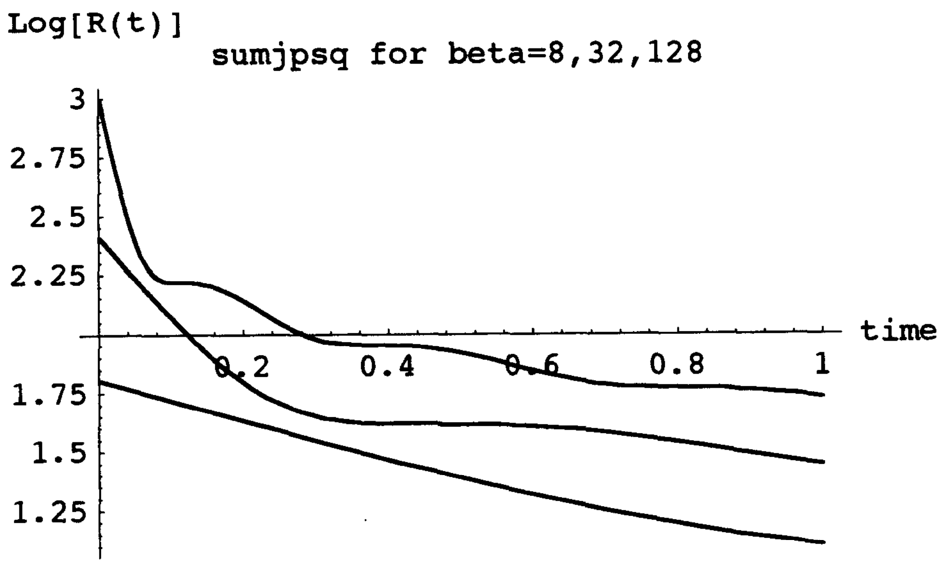
This is not so easy for people who have lived with DTXS all their life. They have understood scattering in terms of one frequency at a time, and they need major use of ideas like 'elastic' and coherent'. In their mental images, it is difficult for a ray to scatter into 4π - it must be made 'incoherent' by some special process like a spin flip. They also think of the traditional calculation of the Bragg intensity far from a perfect crystal, which essentially claims that the intensity -> 0. MRS predicts 4π-shine will be weak, but that summed over all angles, that intensity becomes comparable to the integrated FS beam intensity. And which gets more or less of N depends on the thickness of the sample. Many DTXS people, because of this problem, reject the Multiple Resonant Scattering model completely.

Does this theory work? Are these currents real?

How to test the MRS algorithm? A major point is that their time behaviour, as well as their directions, distinguish the 4π and FS exit channels. Display below two MRS graphs showing $R_{fs}(t)$ and $R_{4\pi}(t)$ for

$\hat{u}_0 z=\{8,32,128\}$. Here the effects due to electronic absorption and to IC have been suppressed. See that $R_{fs}(t=0)$ increases with L^2, while $R_{4\pi}(t=0)$ ->L.





Recent SS measurements:

In July we were able to complete a series of measurements using SS slabs where we used one 4μ slab ($\beta \approx 35$) with its associated APD 4π detector, and the FS detector too. We made measurements with 0, 4 and 10 μ of additional SS upstream of the rear foil. We wished to demonstrate how currents in different parts of the slab behave differently. 'Where and When are the Currents' has been an unanswered question for us for several years. This is finally a method to see that. $R_{4\pi}$ = sumjsq can be considered simply a measure of how much current is in the slab at a given time. So by comparing 0 - 4 with 4 - 4 we get a pretty direct look comparing currents in 1st and 2nd halfs of an 8μ slab.

The next three graphs show this series. The $R_{fs}(t)$ is quite well measured, and is quite secure. We understand these foils well in forward emission. The $R_{4\pi}$ data is considerable weaker, largely because there are less counts. The results support the MRS statement that the the initial currents in the foils are independent of depth (except for μ), and that the currents decrease more rapidly in the rear. The fields from the front are so phased to 'stimulate' the emission of the rear slabs. Despite the single quantum nature of our experiment, it seems a strain not to use the old-fashioned language. But both the experimental situation and the theoretical treatment are yet far from mature. I find the results pretty convincing that MRS knows how to handle both coherent and incoherent decay channels.

Unphased Currents and recent Diffusion measurements.

The logic of MRS strongly urges the existence of unphased currents. A physical case easy to visualize is an enriched Fe blanket spiked with Co^{57}. The initial current is distincly localized, even though we do not know where in the slab it is. It is a far cry from a plane wave excitation! 'Hopping', which is a translation of 'bent paths', pictures the multiple scattering of an unphased system. This leads to an old subject called 'resonant trapping'; usually observed in the time domain. Suggests the experimental lifetime measured with an Fe-blanket source would be longer than when measured with a single atom Co^{57}-in-Cu source.

Analysis difficult for me, and that has taken months, has convinced me that unphased currents from static slabs is a weak phenomena, and does not lead to easily observed effects. That is why the generator term has been omitted from (1c). Now consider a slab where the atomic positions are being churned about by diffusion.

Use $r(t)^2 = Dt$, with units such that D=1 correspondes to average movements of $\lambda/2\pi$ after a nuclear meanlife. Too quick analysis lead to (*which I now consider incorrect*) a new triplet of DEs which include diffusion. Main changes are that the coherent field will be dephased by the diffusion 1a, and that there is now a generation term for jusq (1c). *I think there is also a correction needed in 2b, but am too short of time now.*

$$\mathbf{Ep(m,t,z) = -2\pi N\, Exp[-Dt/2]\ \int dz'\ jp(m,t,z')}$$
$$\mathbf{d/dt\ jp(m+1,t,z) = -\Gamma_0/2\ jp(m+1,t,z)\ + \Gamma_r/2\ \sigma/4\pi\ Ep(m,t,z)} \qquad (2)$$
$$\mathbf{d/dt\ jusq(t,z) = -\Gamma_0\ jusq(t,z) + D\ Exp[-D\ t]\ jpsq(t,z)}$$

Was able to get MMA to solve this set, and show a figure below here of calculated results for D =1,4,10. Have plotted jpsq, jusq, and their sum which is what one would see in $R_{4\pi}$. Despite obvious errors (jpsq should not survive nearly so long after initial drop), a major effect is still to be seen - jusq dominates for D>5 or so. And similar plots show this that you recover the static results as D->0.

We also show a graph of the results of diffusion measurements on the 'dry' sample. The results of the 3 diffusion measurements are:

a) FS is nearly normal near t=0, but decreases in funny ways. The most wet sample shows almost no FS, dry is plotted here, and fry is even slightly higher at 80 nsecs.

b) $R_{4\pi}$ gives lot of counts and they follow e^{-t} as nicely as you could hope.
Look just like
the calculations for D>5.

I am delighted that the weak unphased effect in static samples can be made dominant with a motion like diffusion. It is also quite pretty to see the FS signal disappear, and to see those currents appear on the other detector. It is also another confirmation of the idea that you can count currents of either parentage with the 4π detector.

Need, among other things, to do these experiments better.

MRS vs DTXS:

DTXS assumes a field for each exit channel in a precise direction. Each field can be operated on (in QM sense) to produce power only in its direction. DTXS is virtually mute on what happens in other directions between the exit beams.

A standard guess for the state vector for our multiparticle system would be the product of all the j_i. Does not MRS supply all the same 'coarse-grained' information when you know j(t,z) throughout the system?

With a state vector, different operators can find amplitudes for different final states. The single matrix element of DTXS is too confining for a system which contains a wide variety of outcomes. But indeed, **MRS is repulsive** in the sense that all who have come near it turn away quickly. Why?

Some are so brainwashed about time that they are uncomfortable using before, during, while etc in discussions about short time intervals. Poorly taught stories about Heisenberg inhibit us a lot.

Some are so wedded to the 'field' that they begin to confuse a matrix element with events. And the field that they want complicated experiments to conform to is highly (over)simplified.

Most important, anyone who changes successful ways of thinking glibly is quite rare. DTXS has performed nobly and correctly for 70 years, and will continue to do so far into the future for coherent static scattering. Don't expect anyone to be much interested in the generalized scattering theory like MRS till there are experiments that DTXS can not explain.

For me, in July'93 we have begun to report experiments beyond the range of applicability of DTXS. Need something that predicts all the outcomes - FS and Inco. Are SoP and C/F and MRS the only way to do this?

I doubt it.