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A SPIN-FILTER FOR LOCATING CRITICAL OPALESCENCE IN NUCLEI

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ABSTRACT

Wolfenstein parameters D , R and A' are sensitive to the meson exchange mechanism of inelastic scattering of protons by nuclei, $A(p, p')A^*$. Measurement of these parameters at momentum transfer $q = (1.5 - 3)m_\pi$ would be a sensitive test of critical opalescence (ie the proximity of a pion condensate) in nuclei. At centre of mass scattering angle θ , the signature of π exchange is $D = -1$, $R = \cos^2\theta$, $A' = -\cos^2\theta$, while the signature of the principle background, ρ exchange, is $D = A' = 0$, $R = -\cos^2\theta$.

Migdal (1971) has suggested that at 2-3 times normal nuclear density, nuclear matter may undergo a transition to a new phase, called a pion condensate, having the symmetry of the pion field. Attempts to calculate this phase transition are inconclusive, because of sensitivity to unknown short-range forces; Brown and Weise (1976) and Weise (1980) have reviewed the state of these calculations. Ericson and Delorme (1978) have pointed out that the proximity of this phase transition should be signalled by a degree of spin-isospin order persisting in nuclei at normal density, just as short-range order persists in ferromagnetic and anti-ferromagnetic solids above the transition temperatures. To locate this order, one needs a probe with the quantum numbers of the pion. The signature is then an enhancement in the scattering amplitude at $q = (2-2.5)m_\pi$, characteristic both of the spacing of nucleons in nuclei and of the momentum at which the πN interaction is strongly attractive. This enhancement is given the name critical opalescence, by analogy with the enhanced scattering of light from a gas near its critical point.

The most significant evidence for critical opalescence in nuclei presently comes from a detailed study by Delorme et al (1980 a, b, c) of electron scattering data on the M1 form factors of ^{12}C (15.11 MeV) and ^{13}C (ground state), which show significant departures from shell-model calculations in the right range of q . They adopt a nucleon-nucleon interaction (for isospin 1)

$$V(q) = \frac{1}{4M^2} \left[\frac{1}{2} \left(g_\pi^2 (g' \sigma_1 \cdot \sigma_2 - \frac{q_1 \cdot q_2}{q^2 + m_\pi^2}) v_\pi^2(q) - f_\rho^2 (\sigma_1 \times q) \cdot (\sigma_2 \times q) \frac{v_\rho^2(q)}{q^2 + m_\rho^2} \right) \right] \quad (1)$$

To fit the data, they require a surprisingly low value of g' , namely 0.39; Futami, Toki and Weise (1978) calculate that pion condensation should occur in nuclear matter at normal density for $g' < 0.4$. However, the problem with present data is that they average over nucleon spins, making it hard to separate the effects of the three terms in (1); results are sensitive to assumptions about f_ρ^2 , also the q dependence of the form factors

$v_\pi^2(q)$ and $v_\rho^2(q)$ and about nuclear wave functions. Toki and Weise (1980) show that an improved treatment of 2π exchange increases g^* to 0.5.

An alternative experimental approach (Fayans, Saperstein and Tolokonnikov, 1979, Toki and Weise, 1979) is to study inelastic proton scattering from nuclei with excitation of $I = 1$ unnatural parity states, eg the 1^+ level at 15.11 MeV in ^{12}C . It is experimentally straightforward to measure Wolfenstein parameters, ie the transfer of polarisation from the incident beam to the scattered proton. For protons between 120 and 500 MeV, a carbon polarimeter has an analysing power, averaged over scattering angle and azimuth, of 0.35, and a scattering efficiency of 5-7% (Waters et al, 1978). Wolfenstein parameters separate cleanly the various spin dependent terms in the interaction (1).

Let momenta and energies of incident and scattered protons (mass M) be $\vec{p}_i, \vec{p}_f, E_i$ and E_f . In order to find expressions for Wolfenstein parameters, it is convenient to use orthogonal axes $\hat{p}_i, \hat{p}_f$ parallel to $\vec{p}_f + \vec{p}_i$ and $\hat{n}$ parallel to $\vec{p}_i \times \vec{p}_f$.

The matrix element for π exchange is proportional to

$$\frac{g_\pi^2 v_\pi^2(q)}{q^2 + m_\pi^2} \left\{ \frac{\vec{\sigma}_1 \cdot \vec{p}_i}{E_i + M} - \frac{\vec{\sigma}_1 \cdot \vec{p}_f}{E_f + M} \right\} \left\langle \psi_f | q \sigma_{Q2} | \psi_i \right\rangle,$$

where wave functions refer to initial and final nuclear states. Writing

$$\frac{|p_f|}{E_f + M} = \frac{|p_i|}{E_i + M} (1 - \alpha),$$

where α is of order 0.03, the matrix element for π exchange takes the form $B(q)(\sigma_{Q1} + \alpha \sigma_{P1})\sigma_{Q2}$, where it is implied that the operator σ_{Q2} acts between nuclear initial and final states. The matrix element for the full interaction (1) is

$$\mathcal{M} = A(q)(\sigma_{N1}\sigma_{N2} + \sigma_{Q1}\sigma_{Q2} + \sigma_{P1}\sigma_{P2}) + B(q)(\sigma_{Q1} + \alpha \sigma_{P1})\sigma_{Q2} + D(q)\{(\sigma_{P1} - \alpha \sigma_{Q1})\sigma_{P2} + \sigma_{N1}\sigma_{N2}\}. \quad (2)$$

To this one should in principle add a spin-orbit term $C(q)(\sigma_{N1} + \sigma_{N2})$. Apart from the small term proportional to α , (2) is of the same form as for nucleon-nucleon elastic scattering:

$$\mathcal{M} = a + c(\sigma_{N1} + \sigma_{N2}) + m\sigma_{N1}\sigma_{N2} + (g+h)\sigma_{P1}\sigma_{P2} + (g-h)\sigma_{Q1}\sigma_{Q2}. \quad (3)$$

In the inelastic case, the spin independent term a is absent because the nuclear matrix element is zero. One can now read off expressions for Wolfenstein parameters from the well-known expressions for NN elastic scattering (Hoshizaki, 1968). The important point is that π exchange contributes only to $B(q)$ and $(g-h)$. In order to identify an incipient pion condensate, the task of experiment is to isolate this amplitude and determine its q dependence. This requires measurement of at least four of the observables $d\sigma/d\Omega$, P , D , R and A' . Of these, P depends directly on $C(q)$, while D , R and A' have characteristic dependence on $A(q)$, $B(q)$ and $D(q)$; parameters A and R' are proportional to $\sin \frac{1}{2}\theta$ and $\alpha \cos \frac{1}{2}\theta$, and are much less helpful. If π exchange dominates, and if one neglects α ,

$$D \rightarrow -1, R \rightarrow \cos \frac{1}{2}\theta, A' \rightarrow -\cos \frac{1}{2}\theta$$

This is a very distinctive signature. In contrast, if ρ exchange dominates,

$$D \rightarrow 0, R \rightarrow -\cos \frac{1}{2}\theta, A' \rightarrow 0.$$

If the contact term $A(q) \vec{\sigma}_1 \cdot \vec{\sigma}_2$ dominates,

$$D \rightarrow -\frac{1}{3}, R \rightarrow -\frac{1}{3} \cos \frac{1}{2}\theta, A' \rightarrow -\frac{1}{3} \cos \frac{1}{2}\theta.$$

Measurement of these parameters would therefore give a direct, unambiguous determination of $B(q)$. At small q , measurement of D and/or A' would also help locate the M1 strength in nuclei, since π exchange excites unnatural parity states; the background of natural parity states will generally give $D=R=A'=1$.

Fig. 1 illustrates the sensitivity with which Wolfenstein parameters can isolate the spin dependent terms. Figs. 1(a) and (b) shows amplitudes for $n\bar{p}$ charge exchange at 425 MeV from the phase shift analysis of Bugg et al (1980); (amplitudes vary only slowly with energy from 140 to 500 MeV). The t-channel singularities arise from $I = 1$ mesons, so the amplitudes of Fig. 1(a) are a direct determination of what should go in (2).

The conspicuous peak at $q^2 = 0$ in $(g-h)$ is quantitatively well described by π exchange with $g_{\pi}^2/4\pi = 14.25$. Note that the imaginary parts of the amplitudes are quite small. Fig. 1(c) shows Wolfenstein parameters evaluated with and without the amplitude $(g-h)$, to which π exchange contributes. The strong peaks in D and R clearly arise from the zero in this amplitude.

It is interesting that the magnitude of the amplitude $(g-h)$ at $q^2 = 0$ indicates $g' = 0.51$, very close to the value of Toki and Weise (1980); at other energies from 210 to 515 MeV it fluctuates only within the range 0.492 to 0.542. This is a direct reflection of (i) the dominance of the π exchange amplitude, (ii) the experimental fact (Axen et al, 1980) that the peak in R, hence the zero in $(g-h)$, remains at fixed q^2 over this energy range. Of course, the value appropriate to the NN interaction in nuclei and nuclear matter may be renormalised. Indeed, the origin of pion condensation (if it occurs) is that the propagator of the virtual pion of frequency ω is modified to the form $[q^2 - \omega^2 + m_\pi^2 + q^2 \alpha_0(q, \omega)]^{-1}$ by the nuclear axial polarizability α_0 .

It is also perhaps worth pointing out that the form given in (1) for ρ exchange by Delorme et al is a non-relativistic approximation. The full expression for ρ exchange is

$$\frac{(g_{\rho 1} + g_{\rho 1})^2 (\sigma_1 x q)^+ \cdot (\sigma_2 x q)^+ + E \sigma_{N1} \sigma_{N2} + i \text{Esin}(\sigma_{N1} + \sigma_{N2})}{q^2 + m_\rho^2},$$

$$\text{where } E = \frac{p^2}{M^2} \frac{q^2(1+z)}{q^2 + m_\rho^2} \left(\frac{1}{2} g_{\rho 1}^2 + g_{\rho 1} g_{\rho 2} + g_{\rho 2}^2 \right) + O(p^4/M^2)$$

$$\text{and } F = p^2 \left\{ 3g_{\rho 1}^2 + 4g_{\rho 1} g_{\rho 2} + 2(1-z)g_{\rho 2}^2 \right\} + O(p^4/M^2),$$

and p is centre of mass momentum, $z = \cos\theta$. The terms E and F are by no means negligible if one is trying to account quantitatively for delicate features of data. For example, the value of E is such that the ρ exchange contribution to the $\eta\rho$ charge exchange amplitude m is a factor ~ 1.36 larger (at 425 MeV) than to the $(g+h)$ amplitude; Fig. 1(a) indicates a ratio 1.48 in reasonable agreement.

From an experimental point of view, the 15.11 MeV level in ^{12}C may not be an ideal candidate (Comfort and Love, 1980). Maji-Saeid et al (1980) find that at 800 MeV this state is superimposed on a large background of broad natural parity states; furthermore, it shows no enhancement in the range $q = (1-3.3) m_\pi$ attributable to critical opalescence. Other candidates should be sought, preferably well away from closed shells. At a closed shell, the Pauli principle guarantees pairing of spins and inhibits spin-isospin correlations of the type of pion condensates. By analogy with magnetism in solids, where strong cooperative effects occur in transition metals, it would be sensible to choose nuclei with incomplete valence shells closely spaced in energy, to allow maximum play to spin correlations.

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Figure Caption

Fig. 1. (a) real (b) imaginary parts of np charge exchange amplitudes at 425 MeV: full line (g-h), dashed m, dash-dot a, circles (g+h), crosses ic; (c) Wolfenstein parameters: full line D, circles R, dashed D without the (g-h) amplitude, dash-dot R without the (g-h) amplitude.