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THE AXIAL ISOSCALAR NEUTRAL CURRENT FROM INELASTIC ELECTRON - NUCLEAR SCATTERING

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Parity violating effects due to neutral currents in isoscalar $0^+ \rightarrow 1^+$ nuclear transitions induced by electron scattering are enhanced owing to the small isoscalar magnetic dipole strength. A polarization asymmetry of the order 10^{-4} is expected at $q \sim 100$ MeV for the ^{12}C transition to the $1^+(T = 0)$ state at 12.71 MeV. It would allow to single out the (electron vector current) $\times$ (hadronic axial isoscalar current) quantum numbers and couplings of the neutral current interaction.

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One crucial question in physics is the structure of neutral currents. Determination of the empirical neutrino-hadron couplings without commitment to specific models has been discussed by several authors[1]. The information relevant for this purpose is extracted from high energy neutrino induced reactions, using inclusive, semi-inclusive and elastic scattering data. The couplings thus obtained are compatible with the neutral current structure as predicted by the standard W - S model[2] of weak and electromagnetic interactions. The absence of a parity violating signal in atomic Bi experiments carried out in Oxford[3] and Seattle[4] is a problem for the model. Recently, however, a positive result has been claimed from a Novosibirsk experiment[5], and the situation is confusing. To single out the different quantum numbers in a clear-cut way, making use of selection rules, inelastic neutrino scattering on nuclear targets[6] has been suggested in the literature.

The parity violating part of the semileptonic neutral current interaction interferes with the electromagnetic amplitude, inducing parity violating effects. These are generated by the product of vector and axial vector neutral currents to construct a pseudoscalar observable. One particular combination[7] of these quantum numbers is the one searched for in the atomic physics experiments in heavy elements. Complementary information[8] may be obtained from experiments in hydrogen and deuterium atoms[9]. Electron scattering provides a different tool to look for the parity violating part of the neutral current interaction. Very recently, a SLAC experiment in deep inelastic electron scattering from deuterium has reported[10] a positive signal of the polarization asymmetry, with sign and magnitude in agreement with the predictions[11] of the W - S model. Further work on the y dependence of the effect and results from protons would allow the extraction of separate quantum numbers and couplings. Again the possibility to choose the quantum numbers and hence the selection rules makes elastic and inelastic electron-nuclear experiments an important tool for this study. Explicit predictions for the incoming electron helicity dependence of the cross section have been made by Feinberg[12] for elastic scattering and Walecka[13] for isovector magnetic dipole transitions. The information content from elastic electron scattering is the product (electron axial coupling) $\times$ (hadronic vector coupling), i.e. the same as the one in the first generation atomic physics experiments. For magnetic dipole transitions, both hadronic axial vector and vector components of the neutral current are a priori relevant. Effects of the order 10^{-5} for the polarization asymmetry are predicted for momentum transfers typical of nuclear transitions.

In this paper we wish to point out that parity violating effects in inelastic electron scattering are enhanced for isoscalar magnetic dipole transitions. This originates from the small isoscalar magnetic moment of the nucleon which suppresses the contribution from vector currents. As a consequence, the piece of the weak interference contribution (electron vector current) × (hadronic axial isoscalar current) gets enhanced relatively to the electromagnetic strength. Even at low energies $(E_e \sim 50 - 100$ MeV), where the cross sections are large, the polarization asymmetry at backward angles is of the order 10^{-4}. In order to interpret asymmetry results in terms of neutral current theory, the nuclear physics part of the problem must rest under control. We prove that, in the impulse approximation framework, the parity violating effect becomes nuclear model independent to leading order in the momentum transfer. The reason is that for isoscalar transitions, contrary to the isovector ones, the relative contribution of convection and spin currents is fixed in the long wave length limit. This will allow us to present in a transparent fashion the physical basis for the expected enhancement. But we shall argue that, because of isospin admixtures, a realistic prediction of the polarization asymmetry needs a reliable experimental study of the isoscalar form factor.

The leading order argument goes as follows. In the long wave length limit, the matrix element of the current operator responsible of isoscalar magnetic dipole transitions is given by

$$\langle \vec{J}^{\,e.m.} \rangle (q) = \frac{|\vec{q}|}{2 M_p} \left\langle \sum_{i=1}^{A} \left[\frac{\mu_p + \mu_n}{2} \vec{\sigma}_i + \frac{1}{2} \vec{l}_i \right] \right\rangle \qquad (1)$$

where μ is the total magnetic moment of the nucleon and the matrix element has to be understood between the configurations of the two nuclear levels which are considered. For inelastic scattering, rotational invariance imposes the following restriction

$$\left\langle \sum_{i=1}^{A} \left[\frac{1}{2} \vec{\sigma}_i + \vec{l}_i \right] \right\rangle = 0 \qquad [\text{inelastic}] \qquad (2)$$

owing to the definite total angular momentum of the nuclear states. With the same normalization as Eq. (1), but for the fundamental weak neutral current couplings, the space components of the axial isoscalar nuclear current are given by

$$\langle \vec{J}^{A} \rangle (q) = - g_A^{\circ} \langle \sum_{i=1}^{A} \frac{1}{2} \vec{\sigma}_i \rangle \qquad (3)$$

where g_A° is the renormalization of the axial isoscalar coupling constant for the nucleon. Its value has been the origin of some controversy in the literature[14]. One expects a value of the order of unity, with 0.75 as the canonical prediction.

The interference which originates the parity violating observable is constructed from the contraction of (1) and (3) with the e.m. current and the vector neutral current, respectively, of the electron. Apart from the weak neutral current couplings and some q dependent kinematical factors (not varying drastically with the quantum numbers of the transition), the polarization asymmetry will be determined from the ratio

$$\zeta_0 (q^2) = - \frac{2 M_p \, g_A^{\circ}}{|\vec{q}| (\mu_p + \mu_n - \frac{1}{2})} \qquad (4)$$

This quantity gives an indication of the relative contribution expected with the choice of the transition quantum numbers for fixed small momentum-transfer $|\vec{q}|$. In fact, the corresponding quantity in elastic scattering[12] is unity, whereas in isovector magnetic dipole transitions[13] it is

$$\zeta_1 (q^2) = - \frac{2 M_p \, g_A^{1}}{|\vec{q}| (\mu_p - \mu_n - \frac{c}{2})} \qquad (5)$$

where $g_A^1 = 1.25$ is the renormalization of the axial isovector coupling constant for the nucleon and c is nuclear model-dependent [there is no relation similar to Eq. (2) for this case]. We see that there is a relative enhancement in going from (5) to (4) of a factor about 10. This simple observation shows the interest to explore further the possibilities open to isoscalar transitions.

To discuss the information content of the proposed experiment we follow the notations of Ref. 15). The electron-quark parity violating neutral current couplings $\tilde{\alpha}$, $\tilde{\beta}$, $\tilde{\gamma}$, $\tilde{\delta}$, appearing in the effective Lagrangian

$$\mathcal{L}_{PV} = -\frac{G}{\sqrt{2}}\Big\{\bar{e}\gamma^\mu\gamma_5 e\Big[\frac{\tilde{\alpha}}{2}(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d) + \frac{\tilde{\gamma}}{2}(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d)\Big] + \bar{e}\gamma^\mu e\Big[\frac{\tilde{\beta}}{2}(\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d) + \frac{\tilde{\delta}}{2}(\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d)\Big]\Big\} \quad (6)$$

are associated with vector isovector, axial isovector, vector isoscalar and axial isoscalar hadronic currents, respectively. Atomic physics experiments in heavy elements are sensitive to $\tilde{\gamma}$ and, to lesser extent, $\tilde{\alpha}$. All couplings are relevant for the interpretation of the SLAC experiment on inelastic electron-proton and deuteron scattering. Isovector magnetic dipole transitions in electron-nuclear scattering depend on $\tilde{\beta}$ and, to lesser extent, $\tilde{\alpha}$. Isoscalar magnetic dipole transitions give information on $\tilde{\delta}$ and, to a much lower level, $\tilde{\gamma}$. The enhancement factor (4) discussed above only applies to the axial piece of the neutral current. If the electron-hadron interaction were mediated by the same intermediate vector boson Z responsible of the sectors for neutrino physics one would have[16)]

$$\tilde{\gamma} = 2\,\frac{G_A\gamma}{\varkappa} \quad , \quad \tilde{\delta} = 2\,\frac{G_V\delta}{\varkappa} \quad (7)$$

where γ, δ (G_V, G_A) are the couplings as measured in neutrino-hadron (electron) scattering and $\varkappa$ is the neutrino-neutrino coupling. In any $SU(2)\otimes U(1)$ gauge theory these couplings can be expressed[16)] in terms of the assignments of all right-handed fermions to weak multiplets. The standard W - S model predicts $\delta = 0$, so it would be crucial to device a yes-no experiment to detect such an axial isoscalar component of the neutral current.

Now we proceed to the calculation of the expected polarization asymmetry for the ^{12}C transition to the $1^+(T = 0)$ level at $\Delta = 12.71$ MeV. The parity violating observable is the difference in cross section for the scattering of longitudinally polarized right $\sigma\uparrow$ and left $\sigma\downarrow$ handed incident electrons. Our transition is pure magnetic dipole and there is only one vector form factor. The hadronic axial neutral current matrix element is calculated in the impulse approximation. The relevant result for the polarization asymmetry is

$$\mathcal{R}(E,q^2) \equiv \frac{d\sigma\uparrow - d\sigma\downarrow}{d\sigma\uparrow + d\sigma\downarrow} = \frac{G(-q^2)}{2\pi\alpha\sqrt{2}}\left[\tilde{\gamma} - \tilde{\delta}\,\frac{2(E+E')|\vec{q}|}{(E+E')^2+|\vec{q}|^2}\,\zeta_o(q^2)\right] \tag{8}$$

where G and α are the Fermi coupling and fine structure constants, E $(E' = E - \Delta)$ is the incident (outgoing) electron energy in the lab. system and $q^2 = \Delta^2 - |\vec{q}|^2$ is the momentum transfer squared. The enhancement factor $\zeta_o(q^2)$ is calculated from

$$\zeta_o(q^2) = \frac{2M_p}{|\vec{q}|}\;\frac{-g_A^{\,o}}{(\mu_p+\mu_n) - \sqrt{6}\,\dfrac{[i\,\pi/q]^{11}}{[\sigma]^{10} - \frac{1}{\sqrt{2}}[\sigma]^{12}}} \tag{9}$$

where the notation $[\;.\;.\;.\;]^{L\ell}$ is the one of Mukhopadhyay[17] for nuclear matrix elements. The q^2 dependence of the nucleon form factors has not been explicitly written and it is quite irrelevant for the kinematical region in which we are interested. Eq. (9) reproduces the long wave length limit discussed above. Because of the strong cancellation between the two terms of the denominator some detailed control of the q^2 dependence of the nuclear transition matrix elements is necessary. Although the actual value of each matrix element is nuclear model dependent, the ratio present in $\zeta_o(q^2)$ is much less sensitive to nuclear physics. For comparison we use a simple $j - j$ coupling and an intermediate coupling scheme, such as Bojarkina's wave functions[18]. The ratio of matrix elements in Eq. (9) is given by

$$\sqrt{6}\,\frac{[i\,\pi/q]^{11}}{[\sigma]^{10} - \frac{1}{\sqrt{2}}[\sigma]^{12}} = \begin{cases} [2(1-\frac{1}{2}y)]^{-1}, & j\text{-}j \text{ model} \\ [2(1-.576\,y)]^{-1}, & \text{intermediate coupling} \end{cases} \tag{10}$$

where $y = (1/2\,|\vec{q}|\,b)^2$ and b is the oscillator parameter to describe the radial behaviour of the system. For ^{12}C we have $b = 1.70$ fm. As we see explicitly, there is no big uncertainty in the analysis coming from the evaluation of the nuclear matrix elements. The fundamental restriction (2) obtained for $y = 0$ is mainly responsible for this result.

One should be especially careful of possible isospin admixture effects contributing to the electromagnetic transition. They are taken into account in the following way. We write the state in the form

$$|1^+, 12.71\,\mathrm{MeV}\rangle = \sqrt{1-\epsilon^2}\,|1^+, T=0\rangle + \epsilon\,|1^+, T=1\rangle \quad (11)$$

where $|1^+, T = 1\rangle$ has the wave function of the isovector state at 15.11 MeV. The value of ϵ is expected to be very small (probability $\epsilon^2 \lesssim 1\%$), so that it does not affect the neutral current contribution, i.e. the numerator of $\zeta_o(q^2)$. However, the isovector magnetic dipole transition is so strong (compared with the isoscalar one) that the small admixture ϵ of wrong isospin can change appreciably the denominator of $\zeta_o(q^2)$. Therefore it must be replaced in Eq. (9) by

$$(\mu_p+\mu_n) - \sqrt{6}\,\frac{[i\,\Pi/q]^{11}}{[\sigma]^{10} - \frac{1}{\sqrt{2}}[\sigma]^{12}} + \epsilon\,\frac{(\mu_p-\mu_n)\left\{[\sigma\tau]^{10} - \frac{1}{\sqrt{2}}[\sigma\tau]^{12}\right\} - \sqrt{6}\left[i\frac{\Pi}{q}\tau\right]^{11}}{[\sigma]^{10} - \frac{1}{\sqrt{2}}[\sigma]^{12}} \quad (12)$$

The additional nuclear matrix elements introduced in the analysis are well known from detailed studies of the electromagnetic and weak transitions to the $T = 1$ 15.11 MeV level of ^{12}C and its analogue states of ^{12}B and ^{12}N. In particular, they have a comparable magnitude to the isoscalar matrix elements and it shows that the great difference in strength follows from the nucleon magnetic moments.

With all ingredients at our disposal, we can now compute the enhancement factor $\zeta_o(q^2)$ if we have a value of ϵ. This is extracted from the measured electromagnetic width of the level by comparing with the theoretical isoscalar value

$$\frac{\Gamma_\gamma(1^+, T=0 \rightarrow 0^+, T=0)}{\Gamma_\gamma(1^+, T=1 \rightarrow 0^+, T=0)} = 0.504 \times 10^{-2} \quad (13)$$

using the wave functions of Ref. 18). The experimental result[19)] for this ratio is $(0.95 \pm 0.15) \times 10^{-2}$. This implies a value $\epsilon = 0.05 \pm 0.01$, which is very similar[19)] to the result extracted from an analysis in which Cohen-Kurath's wave functions[20)] were used.

In the Figure we plot the results obtained for the asymmetry parameter $R(E, q^2)$, as function of the scattering angle θ, for incident electron energies of 50 MeV and 100 MeV. The values of R are given in units of $(\tilde{\delta}\, g_A^{\,0})$ and only the second term of Eq. (8) is relevant. The relative contribution of the hadronic axial component versus the vector one at these energies is a factor of about 50. As emphasized above, the proposed experiment is primarily a determination of the axial isoscalar neutral current coupling of hadrons with electrons. From the results shown in the Figure we see that the enhancement discussed for the isoscalar transitions is actually operating in a realistic case. Typical values for the polarization asymmetry are around 10^{-4} for $|\vec{q}|$ values of about 100 MeV, where the electromagnetic form factor is near its maximum. Unless a coincidence technique is used to detect the excitation of the isoscalar level [it decays by α emission], the electron scattering experiment must be planned in the backward region. The magnetic transitions become then observable from only electron kinematics. At $E = 100$ MeV, $\Theta = 180^{\circ}$, the predicted effect is $R = 2 \times 10^{-4}\, (g_A^{0}\ \tilde{\delta})$ for the relevant isospin admixture. The momentum transfer is at that point $|\vec{q}| = 187$ MeV, which is still far from the minimum (~ 330 MeV) in the form factor. As illustrated in the Figure, the effects of isospin admixture are very important, so we propose a preliminar study of the electromagnetic form factor in order to fix the parameter ϵ.

To conclude, we have discussed the interest of an experiment looking for parity violating effects in isoscalar magnetic dipole transitions induced by electrons. It would allow to single out the axial isoscalar neutral current coupling $\tilde{\delta}$ of hadrons with electrons. The effect is naturally enhanced over the typical weak-electromagnetic interferences. A realistic calculation for the ^{12}C transition to the 1^{+} level at 12.71 MeV gives a polarization asymmetry of the order 10^{-4} at momentum transfers $|\vec{q}| \sim 100$ MeV.

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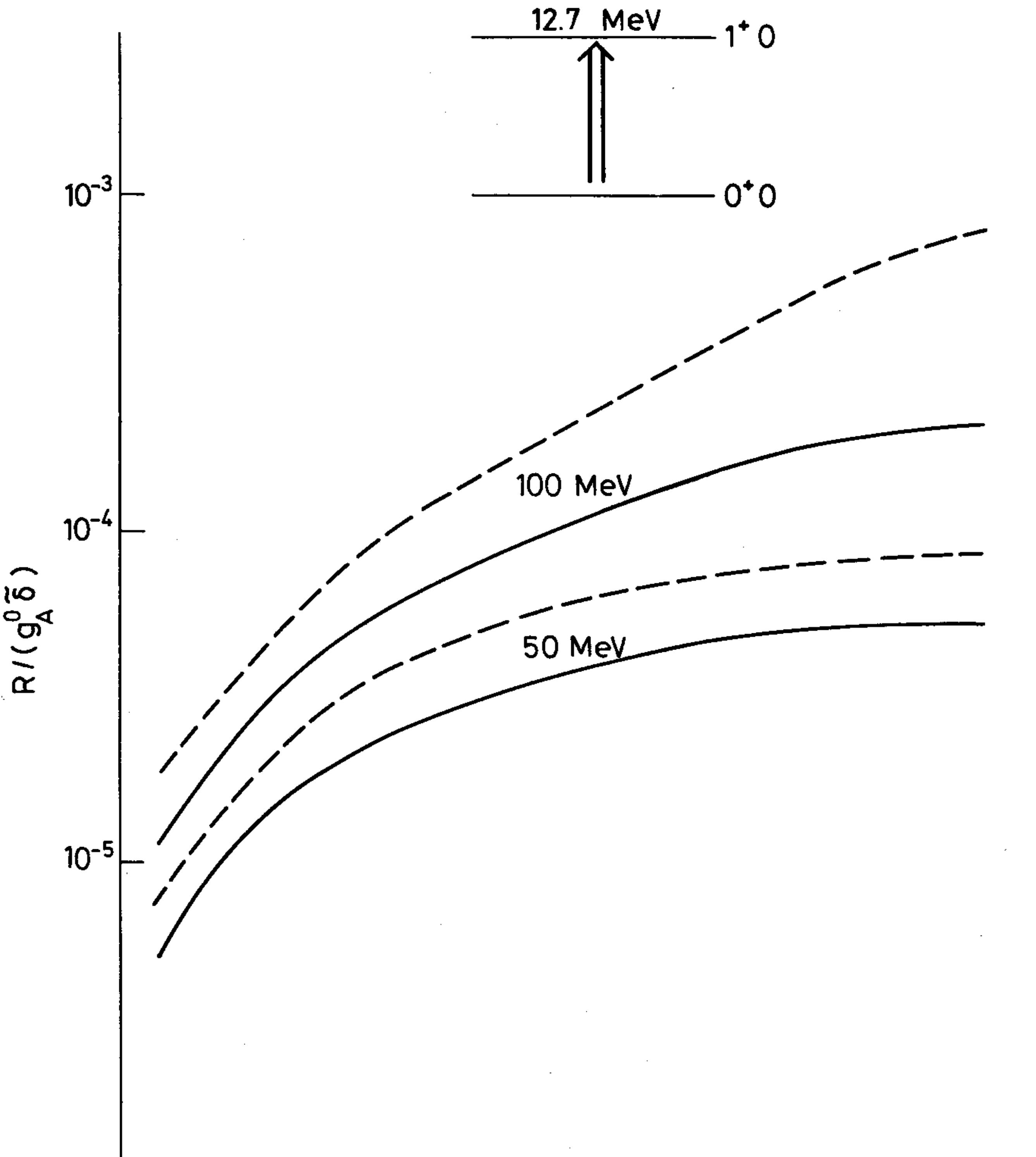
FIGURE CAPTION

Values of the polarization asymmetry R for the ^{12}C transition to the 12.7 MeV isoscalar level induced by longitudinally polarized electrons, as function of the scattering angle Θ. The results correspond to incident electron energies of 50 MeV and 100 MeV for a pure isoscalar state [broken lines] and for a realistic isospin admixture parameter $\epsilon = 0.05$ [continuous lines].



12.7 MeV
1⁺ 0
0⁺ 0
10⁻³
10⁻⁴
10⁻⁵
100 MeV
50 MeV
R / (g$_A^0$ $\tilde{\delta}$)
30°
60°
90°
120°
150°
180°
θ