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Effect of Inelasticity in Charge Symmetry Breaking Neutron-Proton Scattering

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We study the effect of the inelasticity in the charge symmetric amplitudes on calculations of the charge symmetry breaking spin observable $\Delta A = A_n - A_p$ in np scattering. The effect is significant ($\gtrsim 10\%$) above the Δ excitation threshold, but is vanishingly small below.

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Recent experiments on charge symmetry breaking (CSB) in neutron-proton scattering[1,2] have prompted a host of theoretical studies[3-7] interpreting the results in terms of meson exchanges. Specifically, the experiments have measured the CSB difference $\Delta A(\theta) \equiv A_n(\theta) - A_p(\theta)$ between the np scattering analyzing powers associated with the neutron and the proton spin orientations, concentrating (for experimental reasons) on scattering angles in the vicinity of θ_0, where $A(\theta_0) \equiv \frac{1}{2}[A_n(\theta_0) + A_p(\theta_0)] = 0$. The results obtained to date are $\Delta A(71°) = (47 \pm 22 \pm 8) \times 10^{-4}$ at $T_n^{\rm lab} = 477$ MeV (Ref. 1) and $\langle \Delta A \rangle_{82-116°} = (33.1 \pm 5.9 \pm 4.3) \times 10^{-4}$ at $T_n^{\rm lab} = 183$ MeV (Ref. 2), where in each case the first error specified is statistical and the second is systematic. These results are clearly in excess of the values expected from direct electromagnetic contributions alone (i.e., from the spin-orbit interaction between the neutron magnetic moment and the proton current). However, the measurements have been reproduced well[1,2] by meson-exchange calculations that incorporate short-range CSB contributions arising from the effect of the neutron-proton mass difference on one-pion and single ρ exchange and from $\rho\omega$ mixing. A new experiment in progress at $T_n^{\rm lab} = 350$ MeV[8] is intended to provide a further test for such calculations.

In the present note, we explore the implications of a shortcoming in many of the theoretical calculations that have been carried out at energies well above the pion production threshold. The calculations typically combine isospin-mixing parameters γ_J (mixing the ${}^1J_J$ and ${}^3J_J$ two-nucleon states) calculated within a meson-exchange model with charge symmetry conserving (CS) phase shift parameters determined from fits to NN scattering data. For the calculation of observables incorporating the γ_J, much of the recent theoretical work[4,6] has utilized the program SCORE developed by L.D. Knutson[9] for the analysis of CSB np scattering in the IUCF experiment[2] at 183 MeV. Since this energy is below the pion production threshold, the program uses only *elastic* NN amplitudes (phase shifts). The neglect of inelasticities extends as well to the calculations of Ref. 5, where the empirical phase shifts were replaced by a consistent use of the Bonn potential,[10] which is elastic by construction. Clearly, since the NN inelasticity could well play an important role, extension of the use of purely elastic amplitudes to energies far above pion threshold makes the accuracy of the results suspect, even if the CS phases are taken from an analysis of experimental data. The CS inelasticity *was* included previously in the CSB calculations of Ref. 7, which utilized an independently developed program. To facilitate a meaningful comparison of these earlier calculations, we investigate directly here the effect of the NN inelasticities on $\Delta A(\theta)$.

The CSB spin observable ΔA can be represented as the bilinear combination

$$\Delta A(\theta)\, \sigma = 2\,\mathrm{Re}\, b^* f$$

of spin amplitudes in the following standard barycentric parametrization of the scattering matrix[11]

$$M(\vec{k}_f, \vec{k}_i) = \frac{1}{2}\{(a+b) + (a-b)\,\vec{\sigma}_1\cdot\vec{n}\,\vec{\sigma}_2\cdot\vec{n} + (c+d)\,\vec{\sigma}_1\cdot\vec{m}\,\vec{\sigma}_2\cdot\vec{m} + (c-d)\;\vec{\sigma}_1\cdot\vec{\ell}\,\vec{\sigma}_2\cdot\vec{\ell} + e\,(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\vec{n} + f\,(\vec{\sigma}_1-\vec{\sigma}_2)\cdot\vec{n}\},$$

with

$$\vec{\ell} = \frac{\vec{k}_f + \vec{k}_i}{|\vec{k}_f + \vec{k}_i|}, \quad \vec{m} = \frac{\vec{k}_f - \vec{k}_i}{|\vec{k}_f - \vec{k}_i|}, \quad \vec{n} = \frac{\vec{k}_i \times \vec{k}_f}{|\vec{k}_i \times \vec{k}_f|}.$$

The five standard amplitudes $a - e$ are symmetric under isospin, parity and time reversal. The CSB amplitude f can be expressed in terms of the singlet-triplet mixing parameters γ_J and CS strong interaction phase shifts. For comparison, the charge symmetric analyzing power is given by

$$A(\theta)\,\sigma = 2\,\mathrm{Re}\; a^* e\,.$$

A complete calculation of $\Delta A(\theta)$ should strictly include possible imaginary parts of *both* the γ_J (which affect $f(\theta)$) *and* the CS phase shifts (affecting b and f). This was done in Ref. 12, where the emphasis was on the theoretical evaluation of $\mathrm{Im}(\gamma_J)$ within the framework of the coupled channels Δ isobar model of NN scattering. At and above the Δ production threshold the effect of the rather large $\mathrm{Im}(\gamma_J)$ on the angular distribution $\Delta A(\theta)$ was significant. However, just at the zero crossover angle (θ_0) of the analyzing power, the effect of the inelasticity on ΔA was small. This study of box diagram isobar contributions has recently been extended to include also crossed boxes with both nucleonic and $N\Delta$ intermediate states,[14] with the main conclusions remaining the same as earlier.

Ref. 12 did not specifically investigate the effect on $\Delta A(\theta)$ of turning off the inelasticities in the strong charge-symmetric amplitudes, i.e., of making the elastic approximation used in many of the earlier calculations[3–6] of CSB. Such an investigation is the purpose of the present note. In an attempt to be as consistent as possible with the philosophy of earlier work, in the present calculations we treat the mixing parameters γ_J as being purely real, but we incorporate the experimental inelasticity in the CS phase shifts from the analysis of Arndt *et al.*[13] Although these phases are somewhat old, newer data superseding them will not qualitatively alter our conclusions. For comparison, then, we also perform calculations in which the NN partial wave S-matrices are made elastic simply by dividing them by their absolute values (or, in the case of tensor-coupled states, by the proper combination of the matrix elements).

In calculating the CSB amplitudes, we use the Reid soft core potential[15] as the diagonal distorting potential. In CSB OPE each pion-nucleon-nucleon vertex is

assumed to have a monopole form factor with $\Lambda_\pi = 1000$ MeV. To extend the amplitudes to high partial waves, after calculating the pion exchange amplitudes exactly for low J, we subtract the plane wave (Born approximation) OPE contribution from each partial wave and then add back an analytical plane-wave expression covering all partial waves.[7] This speeds up the convergence of the partial wave expansion, so that the np phase shifts specified up to $L = 6$ given in Ref. 13 are sufficient for an accurate determination of the spin amplitudes. A similar procedure is compulsory for the magnetic interaction, where the partial wave expansion is *divergent* in the forward direction.[16] For the calculation of the ρ-exchange and the $\rho\omega$-mixing effects in this investigation, we have used the full Bonn potential[10] parameters, except that the ρ and ω monopole form factor parameters were both taken to be 1400 MeV. The $\rho\omega$ mixing matrix element is -4520 MeV^2 from Ref. 17. For the electromagnetic interaction we adopt the universal dipole form factor[18] $[0.72\text{GeV}^2/(0.72\text{GeV}^2 + q^2)]^2$ in the γNN vertices.

An illustration of the results is given in Figs. 1 and 2 for a neutron (lab frame) bombarding energy of 800 MeV. There it is seen (solid vs. dashed curves) that the two-nucleon inelasticity *increases* the value of ΔA at the zero crossover angle by about 0.0015, in other words, by 15% of its value. The crossover angle of $A(\theta)$ itself remains unchanged, although the angular distribution shape changes slightly. Also shown by the dotted curves in Figs. 1 and 2 is the effect of the high partial-wave OPE contributions. In these curves only the partial waves up to $L = 6$ are taken into account, without any OPE subtraction and plane wave replacement performed. The early truncation causes extra oscillations in both $A(\theta)$ and $\Delta A(\theta)$.

From Figs. 1 and 2 we conclude that at 800 MeV, i.e., slightly above the nominal Δ threshold, the effect on $\Delta A(\theta_0)$ of inelasticity in the CS phase shifts is not really large but is still significant. However, this significance decreases quickly with decreasing energy. At 650 MeV the difference is already reduced to 4-5% at the crossover angle, while at the energy of the TRIUMF measurement[1] (477 MeV) it is totally negligible. Therefore, one can safely conclude that, despite the possibility of formal objections, the results of earlier calculations employing only elastic NN interactions are reliable at the energies where data are available or expected soon. Inelasticity should, however, receive serious consideration in extending predictions above the Δ threshold.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1. The CSB observable $\Delta A(\theta)$ at 800 MeV as a function of the center of mass scattering angle. The solid curve represents the full calculation including the experimental inelastic NN amplitudes, while for the dashed curve the inelasticity has been removed in the partial wave S-matrices. The dotted curve illustrates the effect of neglecting $L > 6$ partial-wave contribution from OPE.

Figure 2. The charge symmetric average analyzing power $A(\theta)$ as a function of the center of mass scattering angle. Notation as in Fig. 1.

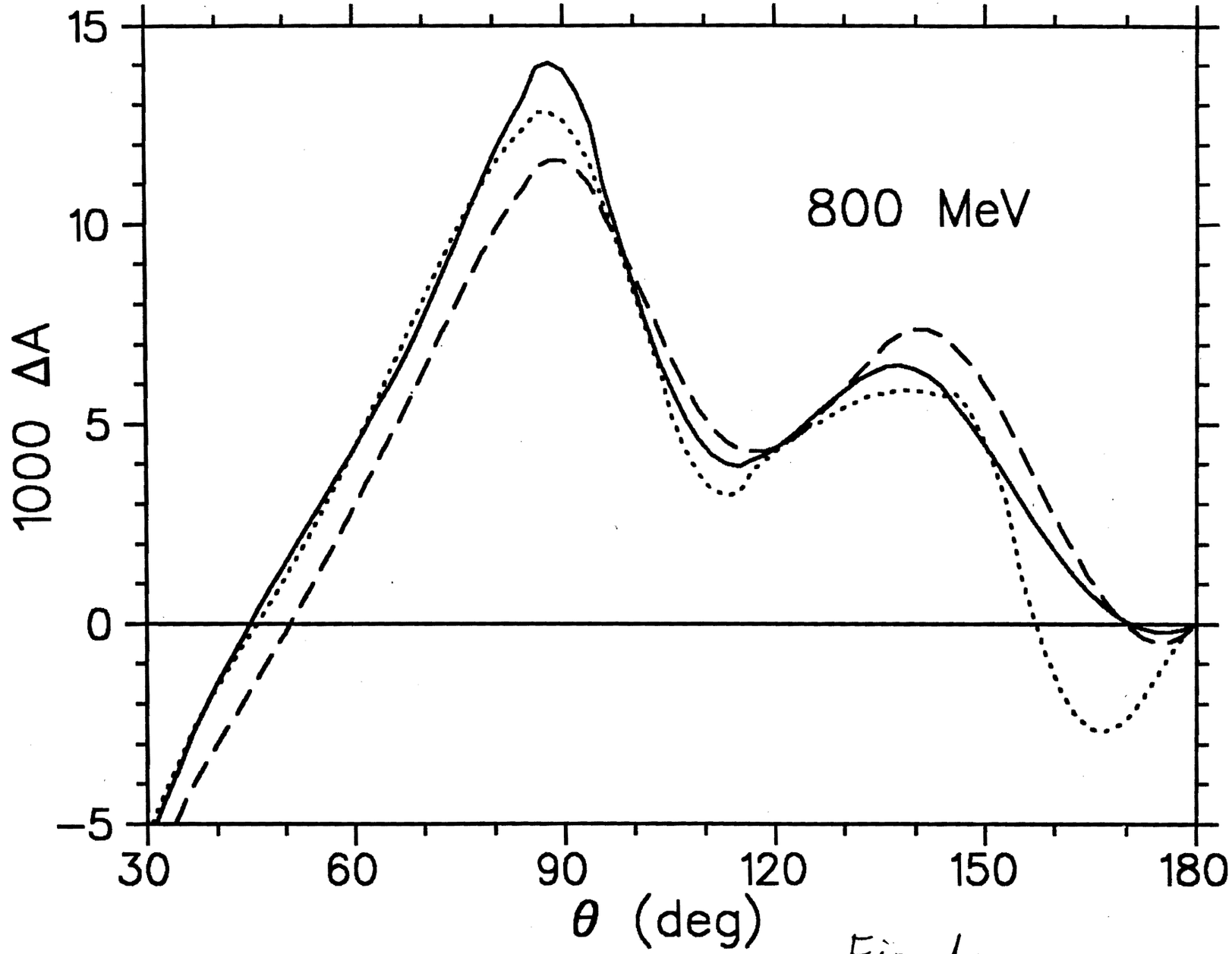

Fig. 1

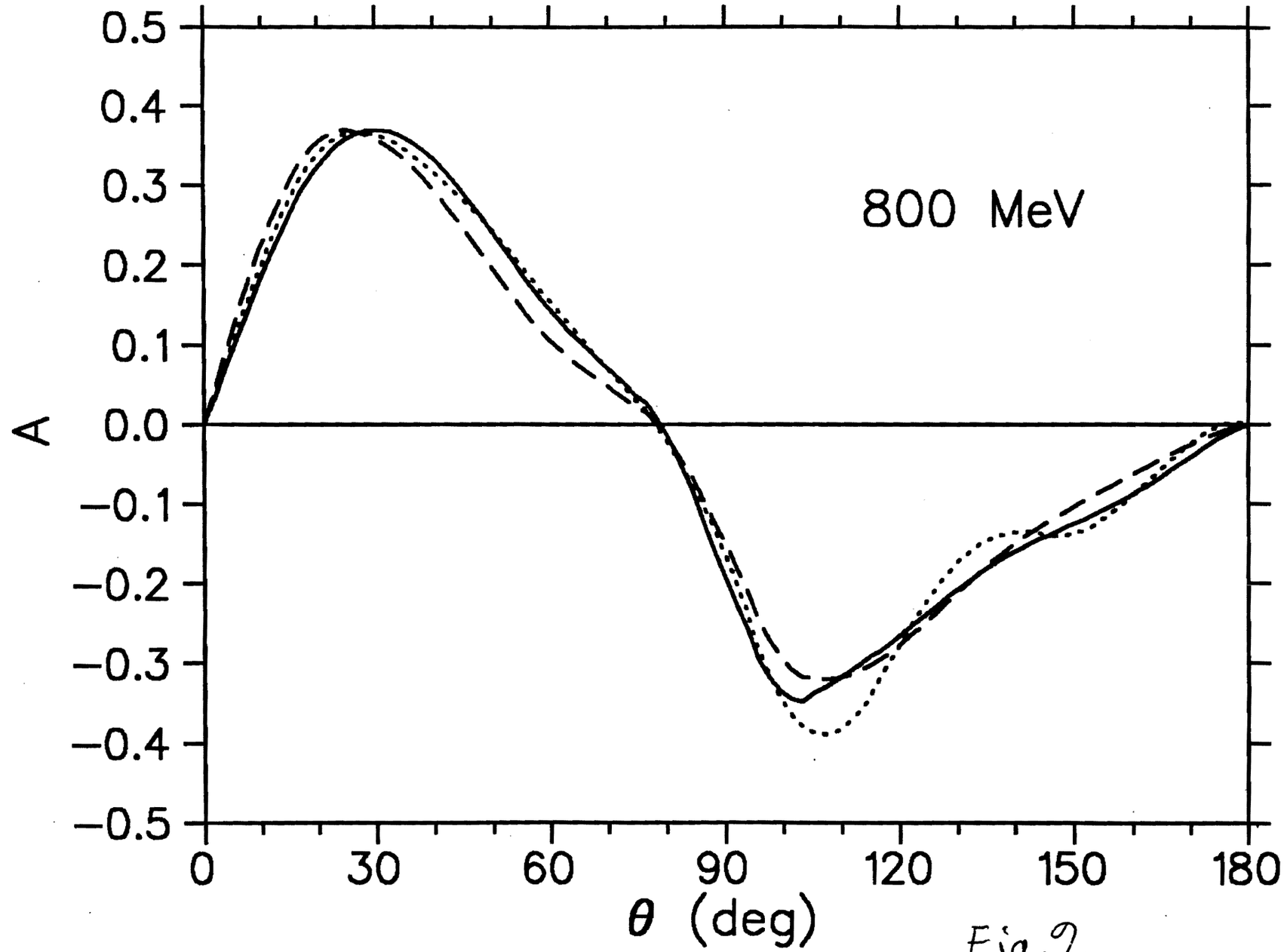

Fig. 2