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Abstract

An experiment is described to investigate the isospin-mixing, charge-symmetry breaking component in the n-p interaction. The experiment measures the difference ΔA between the neutron and proton analyzing powers A_n and A_p in n-p elastic scattering at 500 MeV. The experiment consists of two interleaved phases in which polarised (unpolarised) neutrons are scattered from an unpolarised (polarised) proton target of the frozen spin type. Designed as a null-measurement requiring no accurately known polarisation standards, the experiment determines the difference in angle at which A_n and A_p cross through zero. It is intended to provide an unambiguous test of a class IV charge-symmetry breaking effect to the level of $\Delta A \simeq 0.001$, corresponding to a laboratory angle difference at zero crossing of $\sim 0.05°$.

1. Introduction

Charge symmetry is a consequence of isotopic spin invariance, the first "internal symmetry" that was postulated in elementary particle physics. Isotopic spin invariance is broken by the electromagnetic interaction and consequently one expects effects of order the fine structure constant $\alpha = 1/137$. Charge symmetry is a lesser symmetry because it only involves a rotation in isospin space through π. In the case of nucleons charge symmetry has as a consequence that observables are unaffected by changing neutrons into protons and protons into neutrons. Thus, the neutron-neutron scattering length and effective range are equal to the proton-proton scattering length and effective range after correcting for electromagnetic effects, e.g., the Coulomb interaction. But also, charge symmetry has as a consequence various equalities among neutron-proton scattering spin-dependent observables, for instance the polarisation of the neutron resulting from the scattering of unpolarised neutrons from unpolarised protons equals the polarisation of the recoil proton.

Henley and Miller[1] have classified the nucleon-nucleon interaction within the framework of isospin. According to this scheme one can distinguish two charge-asymmetric charge-dependent interactions. The first (also called class III) interaction preserves symmetry under the interchange of nucleons i and j in isospin space; it is denoted by

$$V_{ij} = D\left(\tau_3(i) + \tau_3(j)\right) .$$

The quantities $\vec{\tau}(i)$ and $\tau_3(i)$ denote the isospin operator and the third component of the isospin operator of nucleon i, respectively. The analogous quantities for the total isospin are $\vec{T}$ and T_3. The above interaction only affects the n-n and p-p systems; there is no isospin mixing since $[T^2,T_3] = 0$. The second (also called class IV) interaction is antisymmetric under the interchange of nucleons i and j in isospin space; it is denoted by

$$V_{ij} = E\left(\tau_3(i)- \tau_3(j)\right) + F\left(\vec{\tau}(i) \times \vec{\tau}(j)\right)_3.$$

The quantities D, E, and F are functions of space and spin coordinates. The latter interaction only affects the n-p system, causing mixing of T=0 and T=1 isospin states.

2. Presence of charge-symmetry breaking interactions.

Studies of the low energy nucleon-nucleon scattering parameters[2] have shown that charge-independence breaking interactions exist. The neutron-neutron scattering length is greater than the T=1 $^1S_0$ neutron-proton scattering length or $|a_{nn}|<|a_{np}|$. Such studies do not allow the unequivocal determination of whether charge-symmetry breaking interactions are also present. The main problem is the complicated influence of the electromagnetic interaction in p-p scattering which forbids an unambiguous determination of the purely hadronic parameters. Theoretical considerations based upon standard ρ^0-ω mixing models of charge-symmetry breaking,[3] or more fundamentally, mass differences between the up and down quarks[4] predict $|a_{nn}|$ to be slightly larger than $|a_{pp}|$ making the n-n interaction slightly more attractive than the p-p interaction.

A comparison of neutron-neutron scattering with proton-proton scattering differential cross sections at intermediate energies is intrinsically difficult: experimentally due to normalization problems and theoretically due to shadow corrections connected with the use of a deuteron target. The accuracies that may be obtained at present are no better than a few percent.[5]

A great deal of circumstantial evidence for the presence of charge-symmetry breaking interactions has been accumulated over the years. The best known and most convincing example is the "Nolen-Schiffer" Coulomb energy anomaly.[6] A study of many mirror nuclei and in particular of the pairs ^{3}H-^{3}He, ^{17}O-^{17}F, ^{39}K-^{39}Ca and ^{41}Ca-^{41}Sc has shown that in every case the calculated direct electromagnetic effects (not including charge-symmetry breaking interactions) give too small a value for the binding energy difference. Thus the existence of charge-symmetry breaking interactions is implied as discussed, for instance, by Negele.[7] The ^{3}He-^{3}H binding energy difference after removal of direct electromagnetic contributions yields $\Delta E = 81 \pm 29$ keV.[8] Since for the two like nucleons the $^{1}S_{0}$ state makes up for more than 90% in the ground state wave function, the binding energy difference directly reflects charge asymmetry in the T=1 $^{1}S_{0}$ N-N system, or the presence of class III charge-symmetry breaking interactions. The ^{3}He-^{3}H binding energy difference is consistent with the strong interaction part of the n-n interaction being slightly more attractive than the p-p interaction. For heavier nuclei because of the complications of the nuclear many-body problem it is very difficult to interpret the Nolen-Schiffer anomaly quantitatively in terms of specific charge-symmetry breaking components of the N-N interaction.

Charge symmetry of the n-p interaction leads to the complete separation of the isovector and isoscalar parts of the scattering matrix for n-p elastic scattering. In the even (odd) partial waves the isovector part contains spin singlet (triplet) and the isoscalar part spin triplet (singlet) contributions only. The concept of charge symmetry forbids transitions between the two parts of the scattering matrix and thus between the spin triplet and singlet states. The triplet-singlet transition amplitude f_{TS} is thus forced to vanish. This restriction in turn leads to exactly equal polarizations of neutrons and protons in the scattering of initially unpolarised particles. Thus, for a given (neutron) scattering angle θ in n-p scattering, the concept of charge symmetry implies:

$$\Delta P(\theta) \equiv P_n(\theta) - P_p(\pi-\theta) \equiv 0 \ ,$$

i.e. the equality of scattered and recoil nucleon polarization. Exactly the same considerations hold for the analyzing powers $A_n(\theta)$ and $A_p(\pi-\theta)$ and their difference ΔA in the scattering of polarised nucleons.

If, on the other hand, charge symmetry is given up, isospin mixing via spin triplet-singlet transitions becomes possible and a non-zero difference ΔA will in general be observed. Such a difference is directly proportional to the amplitude f_{TS} and thus to the existence of isospin-mixing charge-symmetry breaking interactions (class IV charge-symmetry breaking interactions). From the detection of a non-vanishing analyzing power difference ΔA the amplitude f_{TS} can be determined to the extent that the other interfering amplitude is known, since

$$\Delta A = \frac{2}{\sigma_o} \mathrm{Re}\left[b^* f_{TS}\right] \ .$$

The centre-of-mass n-p scattering amplitude is written as

$$M = \frac{1}{2}\left[a + b + (a-b)(\vec{\sigma}_1\cdot\hat{n})(\vec{\sigma}_2\cdot\hat{n}) + (c+d)(\vec{\sigma}_1\cdot\hat{m})(\vec{\sigma}_2\cdot\hat{m}) + (c-d)(\vec{\sigma}_1\cdot\hat{\ell})(\vec{\sigma}_2\cdot\hat{\ell}) + e(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\hat{n} + f_{TS}(\vec{\sigma}_1-\vec{\sigma}_2)\cdot\hat{n}\right] \ .$$

Here $\hat{\ell}$, $\hat{m}$ and $\hat{n}$ are unit vectors defined as

$$\hat{\ell} = \frac{\vec{k}_i+\vec{k}_f}{|\vec{k}_i+\vec{k}_f|} \ ; \ \hat{m} = \frac{\vec{k}_f-\vec{k}_i}{|\vec{k}_f-\vec{k}_i|} \ ; \ \hat{n} = \frac{\vec{k}_i\times\vec{k}_f}{|\vec{k}_i\times\vec{k}_f|} \ ;$$

with $\vec{k}_i$ and $\vec{k}_f$ the initial and final state centre-of-mass nucleon momenta. The quantities a, b, c, d, e, and f_{TS} are functions of centre-of-mass energy E and scattering angle θ, while σ_0 is the differential cross section for the scattering of unpolarised particles. La France et al.[9] have listed all the spin-dependent observables in the centre-of-mass which involve the spin triplet-singlet transition amplitude. Experimental considerations show that the next simplest quantity to be measured in n-p elastic scattering is the difference in the spin-correlation parameters $C_{xz}(\theta)$ and $C_{zx}(\theta)$. The correlation parameter C_{xz} has the projectile spin transverse to the beam direction in the scattering plane and the target spin longitudinal with the incident beam direction, while for C_{zx} the reverse holds. Again charge symmetry leads to the equality of $C_{xz}(\theta)$ and $C_{zx}(\theta)$, but if charge symmetry is broken then one will be able to measure a difference:

$$\Delta C(\theta) \equiv C_{xz}(\theta) - C_{zx}(\theta) .$$

This difference in the spin correlation parameters $C_{xz}(\theta)$ and $C_{zx}(\theta)$ is, like the difference in the analyzing powers, directly proportional to the spin triplet-singlet transition amplitude:

$$\Delta C = \frac{2}{\sigma_o} \mathrm{Im}\left[c^* f_{TS}\right] .$$

All other spin-dependent observables which involve the spin triplet-singlet transition amplitude require the measurement of the polarization of either one or both of the scattered nucleons.

From theory[1] several kinds of charge-symmetry breaking interactions are predicted, caused by a variety of mesonic "indirect" electromagnetic effects such as mixing of mesons of different isospin, in particular π^0-η and ρ^0-ω mixing, π^0-γ exchange, and "electromagnetic renormalization" (radiative corrections) of meson-nucleon coupling constants and of the baryon masses.

Calculations of the charge-symmetry breaking effects on the analyzing powers at energies up to 460 MeV have been made by Cheung, Henley and Miller[10] and for energies up to 750 MeV by Gersten.[11] The differences in the analyzing powers were calculated as functions of angle and energy taking into account the direct electromagnetic effect (one photon exchange), ρ^{o}–ω mixing, and the neutron–proton mass difference effect in charged one pion exchange. Gersten[11] also included the neutron-proton mass difference effect in charged ρ-exchange. The latter approach is in terms of the bar phase shifts with values obtained in N-N phase shift analyses which assume isospin conservation. The triplet-singlet mixing angles were calculated in the first Born approximation. In general the absolute values of the triplet-singlet mixing angles are slowly increasing functions of energy. The 500 MeV predictions by these authors are shown in Fig. 1.

3. Experiment

The experiment currently in progress at TRIUMF will measure the difference ΔA between the neutron and proton analyzing powers A_n–A_p

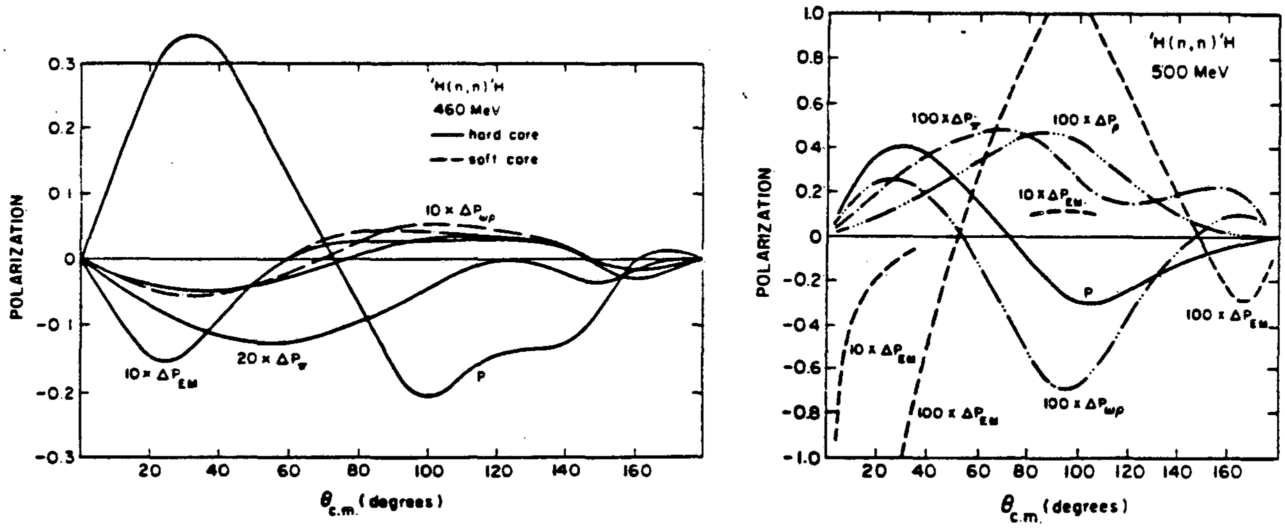

Fig. 1. Theoretical predictions for the difference in polarisations of scattered neutron and recoil proton in elastic scattering of unpolarised neutrons from unpolarised protons due to direct electromagnetic effects (ΔP_{EM}), due to ρ^{o}–ω mixing ($\Delta P_{\omega\rho}$), due to the n-p mass difference effect in charged one pion exchange (ΔP_{π}) and in ρ-exchange (ΔP_{ρ}), a) by Cheung, Henley and Miller, ref.[10]; b) by Gersten, ref.[11].

in n-p elastic scattering at 500 MeV. Designed as a null-measurement, requiring no accurately known polarization standards, the experiment will determine the difference in angle at which A_n and A_p cross through zero (~71° cm). The two interleaved phases of the experiment consist of scattering polarised (unpolarised) neutrons from an unpolarised (polarised) proton target of the frozen spin type. The experiment is intended to provide an unambiguous test of class IV charge-symmetry breaking effects to the level of $\Delta A = 0.001$, corresponding to a laboratory angle difference at the zero crossing of ~0.05°. Theoretical predictions for this angular difference by Cheung, Henley and Miller[10] and by Gersten[11] are a factor 2.5 and 10, respectively, larger than the experimental accuracy aimed for in the experiment (see Fig. 1).

In the experiment a neutron beam is obtained via the $^2H(p,n)2p$ reaction using a 20 cm long LD_2 target. A schematic layout of the experiment is presented in Fig. 2. Before impinging on the LD_2 target, the proton beam passes a polarimeter (observing p-p scattering at 17° lab from a thin CH_2 foil) which is used for diagnostic purposes and an energy monitor which is sensitive to mean energy shifts as small as 30 keV. The proton beam then passes two sets of split-plate secondary electron emission monitors (s.e.m.'s) coupled via a feedback system to two sets of steering magnets located upstream in

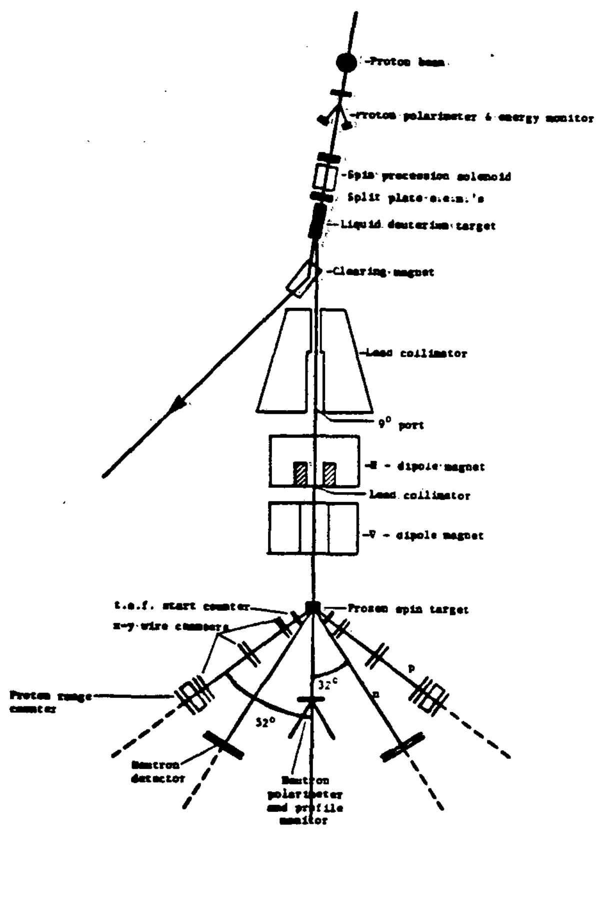

Fig. 2. Experimental layout of the test of charge symmetry in n-p elastic scattering at 500 MeV.

the beam line. This system allows the centroid of the proton beam at the LD_2 target to be locked into position to within 0.25 mm. The two sets of s.e.m.'s are separated by a superconducting solenoid which rotates (in the phase of the experiment requiring polarised neutrons) the transverse polarisation direction of the incident proton beam by 90° clockwise into the horizontal scattering plane. To reduce differences in beam emittance both polarised and unpolarised proton beams are extracted from the polarised ion source. After traversing the LD_2 target the proton beam is deflected away from the neutron beam and transported to a beam dump. The neutrons produced at an angle of 9° pass a 3.3 m long steel collimator with a tapered square aperture. With an incident proton beam polarisation of 0.80-0.85 and a polarisation transfer coefficient R_t = - 0.664 for $^2H(\vec{p},\vec{n})2p$ [12] a neutron polarisation of ~0.55 is obtained. The neutron beam passes two spin-precession dipole magnets with, respectively, vertical and horizontal magnetic fields. It is to be noted that all magnets of the neutron beam facility will be left on at all times during the experiment. A 0.60 m long anti-scattering baffle has been placed in the first spin precession dipole magnet. Polarisation direction reversals for the polarised neutron phase of the experiment are implemented at the polarised ion source. After termination of the preliminary experiments currently in progress, the collimated neutron beam will be incident on a frozen spin target containing a sample cell 4 cm in height and 4 cm in diameter holding pentanol beads. The frozen spin target is positioned at 12.5 m from the LD_2 target; the neutron beam intensity is of the order of $10^2 sec^{-1} cm^{-2} nA^{-1}$. Polarisation direction reversals for the polarized proton phase is effectuated through a shift in the micro-wave frequency when polarizing the target.

The strength of the holding field will be less than 3 kG. After traversing the frozen spin target the neutron beam passes a polarimeter determining left-right and up-down asymmetries and a profile monitor consisting of a converter and two sets of delay line chambers. The latter two systems are being used for diagnostic purposes.

Scattered neutrons and recoil protons originating in the frozen spin target are detected in coincidence in two left-right symmetric detection systems allowing cancellation of many of the systematic errors to first order. Each detection system consists of a neutron array placed at an angle of 32° and at 5 m from the frozen spin target and a proton range telescope placed at an angle of 51.5° on the opposite side of the incident beam. Each proton range telescope contains a time-of-flight (t.o.f.) start scintillator placed close to the target, three sets of delay line chambers measuring x and y coordinates, and a range counter consisting of a ΔE scintillator, a wedge-shaped brass absorber at 3 m from the frozen spin target, an E scintillator, and a veto scintillator. Each neutron array consists of two consecutive planes of 7 scintillator bars, each 1.05 m wide, 0.15 m high an 0.15 m thick with the bars placed one on top of the other. With this detection system one measures the neutron t.o.f. and position and the proton t.o.f., trajectory, and selects a range of proton energies. Measurements of the opening angle and coplanarity of the coincident neutron-proton pair will be used to discriminate against quasi-free n-p scattering from heavier nuclei, e.g. ^{4}He and ^{12}C, present in the frozen spin target. Each detection system covers an angular rang of 5° lab on either side of the crossover angle. Extensive Monte Carlo simulations to investigate effects of background and systematic errors have been made. Data taking is to commence in the summer of 1983.

A very similar experiment measuring the difference ΔA between the neutron and proton analyzing powers in n-p elastic scattering at 200 MeV is currently in progress at IUCF.[13] The latter experiment measures the ratio of the analyzing powers at two different angles: $A_n(\theta_1)A_p(\theta_2)/A_n(\theta_2)A_p(\theta_1)$. This ratio is again independent of beam and target polarisations and differs from one as a consequence of charge-symmetry breaking interactions.

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