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INVESTIGATION OF ε_1 AND THE ^3P_J PHASE SHIFTS IN THE n-p SYSTEM BY THE MEASUREMENT OF POLARIZATION TRANSFER COEFFICIENTS IN p-d ELASTIC SCATTERING

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The $^3S_1$-$^3D_1$ mixing parameter ε_1 and the ^3P_J phase shifts in the N-N system at low energy are investigated in the three nucleon system. The sensitivity of polarization transfer coefficients in p-d elastic scattering is determined by rigorous Faddeev calculations using Paris and Bonn potentials. The experimental results of $K_y^{y'}$ favours the tensor force component of the Bonn A potential.

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The fundamental problem in nuclear physics is the determination of the nucleon-nucleon (N-N) force. In spite of a large amount of data from different kinds of experiments the strength of the tensor force and the ^3P_J phase shifts at low energy could not yet be adequately determined. For this reason it is also unclear how much of the three nucleon force one needs to account for the difference between the experimental binding energies of nuclei, e.g. for ^3H and ^3He, and those obtained from model calculations using the N-N force.

Several realistic N-N potentials based on meson theory are now available; e.g. Paris[1], Bonn[2,3] and Nijmegen[4]. They provide a satisfactory agreement to the N-N scattering data, but the data are not sensitive enough to rule out differences in special force properties. An essential difference is the strength of the tensor force, which is measured by the $^3S_1$–$^3D_1$ mixing parameter ε_1. The Bonn potential of ref. 2 (Bonn A) has a significantly weaker tensor force than the Paris potential and the Bonn potential of ref. 3, called Bonn B. The weaker tensor force goes with a larger central force, which provides in the case of the Bonn A potential the larger triton binding energy[5]. This reduces the notorious discrepancy between the theoretical and experimental binding energy and leaves only a few hundred keV discrepancy to be filled by the contribution of three nucleon force effects. This raises the question, which of the established potentials is closer to reality and what is the strength of the tensor force. Unfortunately, the polarization effects of the neutron-proton scattering are very small and the data obtained so far miss the necessary precision in order to determine ε_1 to a sufficient accuracy.

Spin observables in the nucleon-deuteron (N-D) scattering are much larger than those in the N-N system and their measurements can give quantitative information on N-N force properties provided that a rigorous three body theory is employed. Such rigorous calculations using Paris and Bonn potentials and allowing for the charge dependence of the N-N force are now available[6].

The results for the N-D scattering have shown that:

1. at E_N=22.7 MeV the polarization transfer coefficients, notably $K_y^{y'}$, $K_z^{x'}$ and $K_z^{x'y'}$ are sensitive to the strength of the tensor force,
2. the vector analyzing powers A_y and iT_{11} at 10 and 22.7 MeV as well as the polarization transfer coefficients $K_z^{x'y'}$, $K_z^{y'z'}$, and $K_y^{x'z'}$ at 22.7 MeV are sensitive to a complex interplay of the ^3P_J phase parameters.

Although there are now extensive measurements of the vector analyzing power A_y of n-p and p-p scattering below 50 MeV, these data are not sufficient to determine uniquely all phase parameters. However, from the results of the above mentioned three body calculations and the many possible polarization transfer parameters in the p-d system, which involve different phase shift combinations, it is possible to disentangle the various phase parameters.

In comparing the results of the rigorous solution of the Faddeev equations with the Paris and Bonn potentials the nucleon to nucleon polarization transfer coefficients $K_y^{y'}$ and $K_z^{x'}$ at 10 MeV[7,8] show some sensitivity to the tensor force, as shown in Fig. 1. However, the comparison of the rigorous calculation and the $K_z^{x'}$ data is not conclusive[9], since the inclusion of the j = 3 force components puts the prediction from the Paris potential on the lower side of the experimental error bars, as can be seen in Fig. 1. The similar effect with the Bonn A potential decreases the result of this calculation to the upper side of the error bars. In case of $K_y^{y'}$, the situation is also unclear since angles $\theta_{cm} \leq 90^o$ favour Bonn A and two points at larger angles and with larger uncertainties favour the Paris

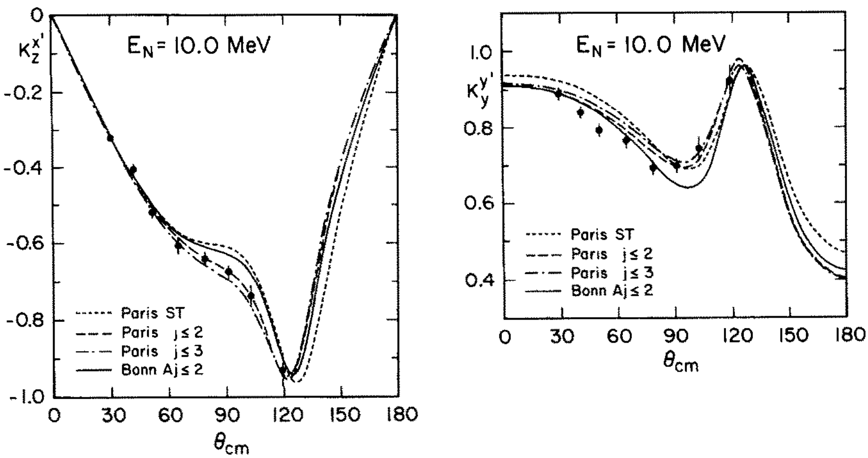

FIGURE 1

The polarization transfer coefficients $K_z^{x'}$ and $K_y^{y'}$ for an incident proton energy of 10 MeV. The dotted curves are calculations with the Paris potential including S-waves and the tensor force components $^3S_1$-$^3D_1$(ST). The dashed and dashed-dotted curves are calculations with j≤2 and j≤3 components, respectively. The solid curves are the results from the Bonn A potential with j≤2.

potential, which weakens a final conclusion[9]. In any case the sensitivities found made it promising to study these observables again at higher energies, where also possible Coulomb effects should be smaller. That expectation is borne out from the differential p-d cross section at 22.7 MeV. It agrees perfectly well with either potential prediction, except at angles $\theta_{cm} \leq 45^o$ where small Coulomb effects can be observed. In Fig. 2 the tensor analyzing power T_{22} at 22.7 MeV[10] is shown in comparison to the rigorous calculations with the Paris and Bonn A potentials. The two theoretical curves of Paris and Bonn A potentials with j≤2 nearly coincide. The addition of j = 3 components gives an excellent agreement with the data. Very much the same picture is also true for T_{20}. The very good agreement suggests that at this energy Coulomb force effects are not very important. The near coincidence of the Bonn A and Paris potential predictions also shows that the tensor analyzing powers at this energy are not sensitive observables to determine the details of the tensor force. In these calculations the 2/3-1/3 rule[11] for the ^1S_o state is applied. This rule takes care of the different strengths of the np and pp force. The np force is taken from the Bonn B and the pp force from the Paris potential.

Searching for observables sensitive to the tensor force it remains to look into the spin transfer coefficients. Among them $K_y^{y'}$ appeared promising and therefore a measurement of $K_y^{y'}(\theta)$ was performed at an incident proton energy of 22.7 MeV. This second order polarization observable is determined by a double scattering experiment. In the first scattering by an angle θ, with an analyzing power $A_y(\theta)$, the polarization p_1 of the beam is changed to p_2 according to

$$p_2(\theta) = \frac{A_y(\theta) + K_y^{y'}(\theta) \cdot p_1}{1 + A_y(\theta) \cdot p_1} \quad (1)$$

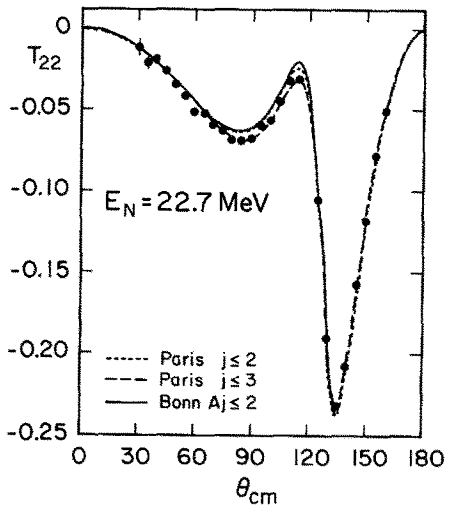

FIGURE 2
The tensor analyzing power T_{22} of p-d scattering for E_p=22.7 MeV.

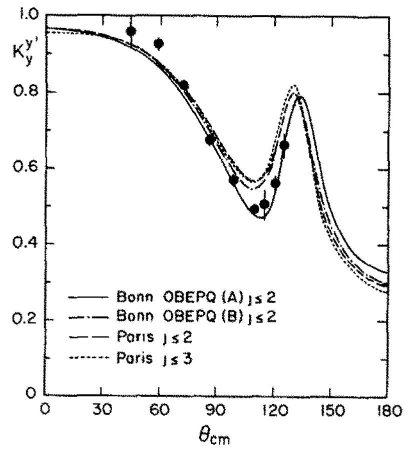

FIGURE 3
The polarization transfer coefficient $K_y^{y'}$ of p-d scattering for E_p=22.7 MeV. The experimental data are compared with calculations using Paris, Bonn A and Bonn B potentials. The Bonn A potential has a smaller strength of the tensor force (ε_1) than Paris and Bonn B. The calculations are charge independent.

The 22.7 MeV polarized proton beam from the PSI cyclotron was scattered from a deuterium target, pressurized to 16 bars and cooled to 77 K. The scattered protons were focussed by a magnetic quadrupole triplet lens into the polarimeter 2 m from the first scattering chamber. The beam polarization p_1 was continuously monitored by a ^{12}C polarimeter located upstream of the primary scattering deuterium target. The incident beam polarization was also calibrated by replacing the D_2 target with a ^4He target. The sign of the beam polarization was inverted every few seconds. This method allowed the determination of $K_y^{y'}$ from the ratios of the detector counting rates independently of solid angles. For the determination of $K_y^{y'}$ one also needs the values of the vector analyzing power $A_y(\theta)$, which are taken from ref. 10.

One of the main experimental problems is the measurement of the polarization p_2 of the scattered protons over a large angular range, since their energy decreases strongly with scattering angle. Two different polarimeters based on p-α and p-^{12}C scattering were used to cover the energies of the protons scattered from θ_{cm} = 45° to 125°. Details of these polarimeters and their calibrations are given in ref. 12. The polarization transfer coefficient $K_y^{y'}$ at θ_{cm} = 110° has been measured using both ^4He and ^{12}C polarimeters and the two values agree to within the error of the individual results of ± 0.02.

The results of the measurement are shown in Fig. 3 together with calculations. The new data clearly favour the Bonn A potential with the weaker tensor force. Bonn B and Paris potential predictions are close together in accordance with their similar ε_1 phase-shift parameter. From the investigation of the sensitivity of polarization data of N-D scattering at 10 and 22.7 MeV by rigorous calculations it is known that the ^3P_J wave forces do not lead to a noticeable shift of the theoretical curve of $K_y^{y'}$.

For the determination of the ^3P_J phase shifts second order polarization observables are required besides the already known sensitive first order polarization observables A_y and iT_{11}. From the Faddeev calculations the vector-to-tensor polarization transfer coefficients $K_z^{x'y'}$, $K_y^{x'z'}$ and $K_z^{y'z'}$ seem to be an interesting choice. The sensitivity of $K_z^{x'y'}$ is shown in Fig. 4. The dashed curve is the result of a calculation with the Paris potential including S-waves and the tensor force (ST). The solid curve is a full calculation and reflects mainly the effect of the ^3P_J phase shifts. Similar sensitivity is observed for the two other coefficients. The measurement of these observables will enable us to uniquely determine all three phase shifts $^3P_0$, $^3P_1$ and $^3P_2$.

In conclusion we have shown that polarization transfer coefficients in p-d scattering are necessary observables in order to determine the strength of the N-N tensor force and low energy ^3P_J phase shifts.

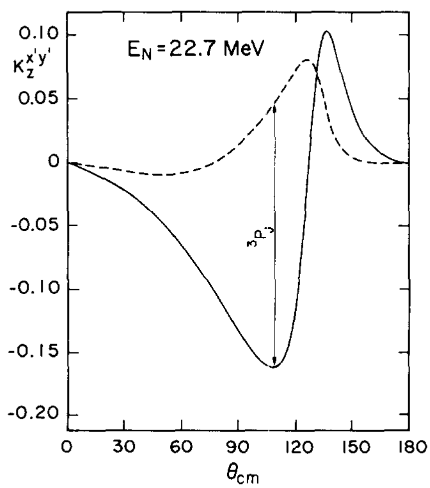

FIGURE 4

The sensitivity of the polarization transfer coefficient $K_z^{x'y'}$ to the ^3P_J phase shifts for E_N=22.7 MeV. Dashed curve: $^1S_0$, $^3S_1$-$^3D_1$. Solid curve: j$\leq$3. The difference is mainly due to the ^3P_J waves.

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