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FINE TUNE OF N-N FORCE, LOW ENERGY p – d AND n – d ELASTIC SCATTERING OBSERVABLES AND THE COULOMB SLOW-DOWN EFFECT

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We examine the differences between n-d and p-d analysing power in elastic scattering at energies below 25 MeV and investigate whether these differences can be understood as the result of charge-symmetry breaking in the $^3\mathrm{P}_J$ states.

We show that a correction of the data to account for the slowing down of the proton under the Coulomb force does not account for these differences. The differences can be explained by introducing 3 to 4 % charge symmetry breaking in the $^3\mathrm{P}_J$ states of the Bonn potential. We give the explicit values of the parameters setting the strength of the NN force in $^3\mathrm{P}_j$ states for n-n, n-p and p-p forces. Such modified Bonn potential gives simultaneously good agreement for both 2N scattering data and the 3N observables.

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1. *Introduction*

The analysis of low-energy two- and three-nucleon interactions involves the study of a number of effects: off-shell effects, the three-nucleon force, relativistic corrections, the Coulomb interaction and other electromagnetic interactions. These effects cannot be easily isolated. Their isolation and characterization depends on the model of the nuclear interactions and on the parameters in the calculations used to fit that model to the experimental data. One approach [1,2] to these difficulties is to use 2N scattering data to set limits for the parameters entering the nuclear force model and, in addition, to use observables measured for 3N systems, along with rigorous 3N calculations to fine tune those parameters. A concordance with a large body of data would increase confidence in the characterization of the different effects and the properties of the nuclear force.

Within this approach, an attempt has been advanced to characterize and isolate the effect of the Coulomb interaction [3]. According to this suggestion, the predominant, static, effect of the Coulomb force, in the incoming channel in p-d elastic scattering, is the repulsion between the proton and the deuteron which leads to a slow-down of the proton. Because of this slow-down, when the projectile is a proton, the nuclear interaction takes place at energies effectively lower than the nominal energy in the incoming channel. From the accepted size of the deuteron, Tornow et al. [3] estimate this energy shift to be $\delta E_c = 0.64$ MeV and, therefore, argue that we must compare p-d observables at energy E with n-d observables at energy E-δE_c. If, over a range of energies, one finds that the p-d data can be brought into concordance with the n-d data by this energy shift, one can then argue to have isolated the main effect of the Coulomb interaction.

We will argue that the discrepancy between the n-d and p-d observables can be explained in term of differences in the forces between nucleons, the relative strength of the Coulomb and nuclear force and their interference in different partial waves as the energy varies. There is evidence [4] that the n-p, n-n and p-p interactions in the same orbital and spin angular momentum state $^1S_0$ are different. The n-p interaction is stronger than either the n-n or p-p interactions, which in turn are different from each other. The recommended values, $a_{\rm np} = (-23.75 \pm 0.01)$ fm, $a_{\rm nn} = (-18.5 \pm 0.3)$ fm and $a_{\rm pp} = (-17.3 \pm 0.8)$ fm, indicate that charge independence (CI) and charge symmetry (CS) in $^1S_0$ are violated.

In the region of its maximum, $A_y(\theta)$ is very sensitive to small changes in the strength of the nn, pp, and np potentials for the ^3P_J partial waves [6]. By changing these strengths, one can reproduce the differences that are found in the experimentally observed n-d and p-d analysing powers [5]. Accordingly, it has been recommended [3,6] that the analysing power, $A_y(\theta)$, can be used as a probe to study charge-symmetry breaking (CSB) effects in the ^3P_J partial waves. However, if the slow-down effect applies, one must take it into account by including the energy shift in the p-d channel.

Lacking, at present, a suitable procedure for extracting the Coulomb effect, we follow a proposed approach [2] and attempt to account for the differences between n-d and p-d observable by adjusting the strength of the forces between nucleons in the ^3P_J states to fit the data with rigorous three-body calculations which, however, do not include the Coulomb interaction. Naturally, this can only lead to an estimate of any CSB effect. However, unlike in Refs. 5 and 7, we start from parameters that agree with the predictions of the one-pion exchange (OPE) and two-pion exchange (TPE) calculations. In searching for ^3P_J parameters, we put the constrain that the n-n and p-p phase shifts must be higher than the n-p phase shifts. We obtain ^3P_J parameters that equally well describe 3N and 2N data, and that introduce reasonable charge breaking of about 3 to 4 percent.

2. *Coulomb slow-down effect and differential cross section*

In our study, we compare the n-d and p-d measurements of the analysing power in the 2 to 14 MeV energy interval. In addition to the n-d data used by Tornow et al. [3], we include n-d and p-d data at 3.0 MeV [8] and for p-d, from 4 to 18 MeV, the more recent and more accurate data of Sagara [9,10]. Accurate A_y p-d data are also available at 19.0 and 22.7 MeV [11], however, the available A_y n-d data in that energy range [12–14] do not have comparable accuracy.

For energies between 3 and 14 MeV, the p-d analysing power, $A_y(\theta)$, in the region surrounding its peak, which occurs at about 120°, is always lower than the A_y for n-d elastic scattering, and both observables decrease with energy [11,15–19]. When comparing the peak of these two observables, Tornow et al. find that they can be brought into agreement by the shift along the energy axis, thereby suggesting that the Coulomb slow-down effect does indeed isolate the main contribution of the Coulomb force. This conclusion is physically very appealing. If correct, one can use it to employ rigorous 3N calculations that do not include the Coulomb force, to predict A_y and other p-d observables, by performing the calculations at shifted energies.

The difference between n-d and p-d data around the maximum for A_y and the minimum for the cross section (see, e.g., Figs. 1 and 2) cannot be accounted for by a simple energy shift as implied by the Coulomb slow-down effect. More specifically, over the angular range of the minimum of the cross section and the maximum of the analysing power, one cannot find an energy shift that brings the A_y n-d and p-d data into coincidence. At the same time, if such a shift is advocated to explain the differences in the A_y, it implies contradictions with the cross sections data.

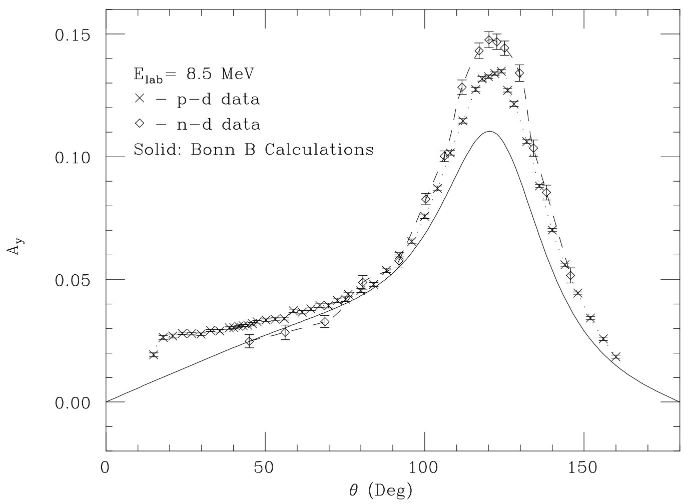

Fig. 1. Comparison of n-d *[24] and* p-d *[9] analysing power $A_y(\theta)$ data to rigorous calculations using the Bonn B potential (solid curve) at $E_N = 8.5$ MeV [5].*

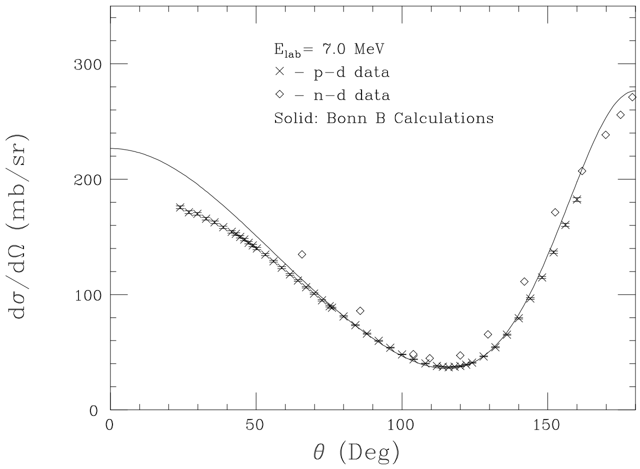

Fig. 2. Differential cross section of the p-d *(diamonds) [9] and* n-d *(crosses) [24] elastic scattering data and the predictions of the rigorous three-body calculations using the Bonn B* N-N *potential [5] at 6.5* MeV.

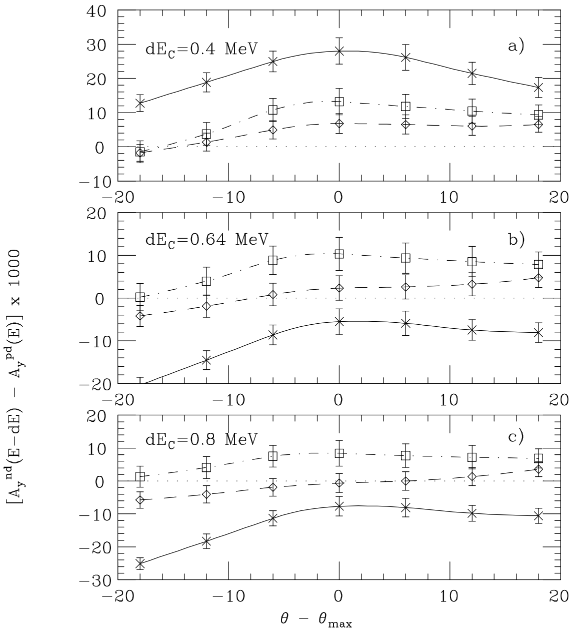

Fig. 3. Differences between A_y^{nd} and A_y^{pd} data: $(A_y^{nd} - A_y^{pd}) \times 1000$ in the region -20° to 20° around the maximum A_y for Coulomb slow-down δE_c shifts of (a) $\delta E_c = 0.40$ MeV, (b) $\delta E_c = 0.64$ MeV and (c) $\delta E_c = 0.8$ MeV, at incident nucleon energies of 3.5 MeV *(———) with crosses, 6.5* MeV *(− − −−) with diamonds, and 14.0* MeV*(− · − · −) with squares. The curves are fits through the data.*

Using the $\delta E_c = 0.64$ MeV shift, we have compared the p-d A_y at E with that for n-d at $E - \delta E_c$ as obtained by interpolation from the experimental data. Figure 3 displays the differences in A_y, i.e., $\delta A_y = A_y^{nd} - A_y^{pd}$, for E equal 3.5 MeV, 6.5 MeV, and 14 MeV. Displayed are δA_y for $\delta E_c = 0.4$ MeV, $\delta E_c = 0.64$ MeV, and $\delta E_c = 0.8$ MeV, which bracket the range of acceptable shifts. The error bars in this figure are obtained by adding the errors for p-d and n-d data. We see that δA_y is very dependent on the estimate for δE_c. However, regardless of which estimate we use, we see that, by following the slow-down hypothesis, we cannot extract an energy shift that will reduce all differences to fluctuations within the range of the experimental errors.

If the slow-down hypothesis is valid it must be valid not just for A_y, but also for other observables. For instance, according to the slow-down effect, the p-d elastic cross section data at energy E must be compared with the n-d data at energy $E - \delta E_c$, since in the p-d system the nuclear interaction occurs at the lower energy. However, we can see that the n-d data at energy E are already higher than the p-d data at the same energy, and since a shift of n-d data to lower energy would further increase the n-d differential cross section, it is clear that the disagreement between p-d and n-d cross sections will be increased and not reduced by an energy shift.

We have compared n-d and p-d cross sections at 3.5 and 4.0 MeV, at 6.5 and 7.0 MeV, at 8.5 and 9.0 MeV and at 16.75 and 18.0 MeV. The last comparison, though outside the range of the acceptable Coulomb shift, is the only one available at the higher energy end. In all instances, except for 8.5 MeV, the n-d cross sections at the lower energies are clearly higher than the p-d cross section, as shown for instance in Fig. 4 for the 6.5 and 7.0 MeV comparison. It appears reasonable to conclude that the Coulomb slow-down correction, if applied, cannot describe simultaneously the A_y and the cross section data.

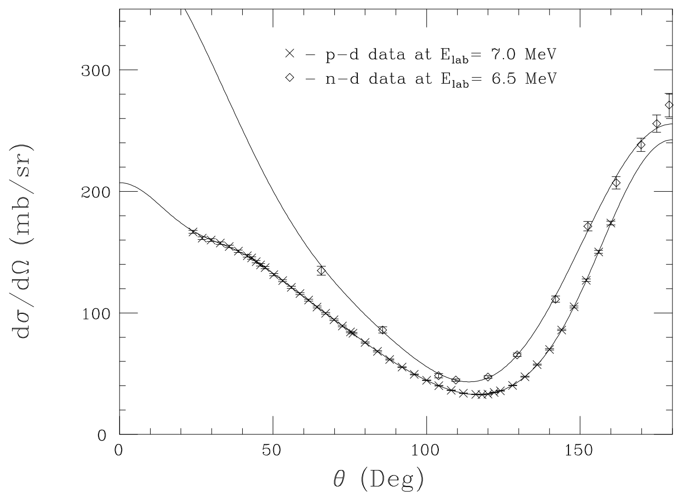

Fig. 4. Comparison between differential cross section of the p-d (diamond) cross section data at 7.0 MeV *[9] and n-d data (crosses) at 6.5* MeV *[24].*

An alternative explanation of the difference between vector analysing powers could be the presence of CSB in those partial waves which do not influence other observables significantly. It has been shown [6] that the region of the vector analysing power, where there are significant differences between neutron-deuteron and proton-deuteron data, i.e. around 120°, is dominated by $^3\mathrm{P}_J$ waves. This is also confirmed by work in Refs. 20 and 21, showing that a few percent of charge breaking in $^3\mathrm{P}_J$ waves can change A_y by about 30%. So, this might be the signal for charge symmetry breaking in the $^3\mathrm{P}_J$ waves. At higher energies, other partial waves also contribute, and the effect of $^3\mathrm{P}_J$ is relatively much smaller, and, consequently, there is a good agreement between n-d and p-d A_y data.

It has been shown [5] that the N-N low-energy nucleon data do not determine the $^3\mathrm{P}_J$ phase shift unambiguously. Hence, the greater sensitivity of the n-d and p-d data to the $^3\mathrm{P}_J$ state has been exploited to fit the p-p, n-p, n-d and p-d elastic scattering data by adjusting the $^3\mathrm{P}_J$ phase shifts. It was also shown that each partial wave, $^3\mathrm{P}_0$, $^3\mathrm{P}_1$ and $^3\mathrm{P}_2$ contributes independently to the magnitude of the analysing power. These contribution can be extracted from the published calculations [5,7,22]. Figs. 5 a, b and c show extracted contributions of these partial waves when the strength of one of them is changed by 5 percent. One can see that partial wave $^3\mathrm{P}_0$ reduces A_y, while $^3\mathrm{P}_1$ and $^3\mathrm{P}_2$ partial waves increase its value. Thus, it is possible to find many different values of $^3\mathrm{P}_J$ parameters that will lead to agreement with the data.

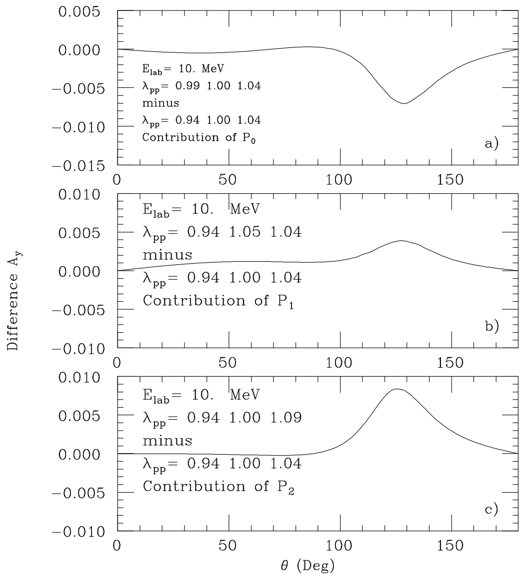

Fig. 5. Contributions of $^3\mathrm{P}_0$ (Fig. 5a), $^3\mathrm{P}_1$ (Fig. 5b) and $^3\mathrm{P}_2$ (Fig. 5c) partial waves to analysing power A_y, when a value of one of the $^3\mathrm{P}_J$ partial waves is increased by 5 %. The curves were obtained by subtracting A_y calculated in Refs. 5, 7 and 22 using lower values of $^3\mathrm{P}_J$, from A_y calculated with higher value and normalizing the differences to 5 % increase in one of the $^3\mathrm{P}_J$.

To have confidence in the set of values, we must impose additional conditions on $^3\mathrm{P}_J$ phase shifts. A number of observables are sensitive to the $^3\mathrm{P}_J$ strengths. They have a different dependence on the $^3\mathrm{P}_J$ parameters. By requiring that the $^3\mathrm{P}_J$ parameters must satisfy not just A_y observables, but also all other observables sensitive to $^3\mathrm{P}_J$ waves, we will avoid ambiguities and obtain unique solutions for $^3\mathrm{P}_J$ strengths. This is where this analysis differs from previous attempts in which only one spin observable, A_y, was considered.

We did not perform 3N rigorous calculation, but we used already published results [5,7,22] in which the contribution of each partial wave was already determined for various observables. For energies where no published results were available, we interpolated. This was appropriate, since for the small energy intervals, where the interpolations are done, the dependence on $^3\mathrm{P}_J$ strengths appears to be a linear function of energy.

Whenever for one spin observable the calculations are performed with various $^3\mathrm{P}_J$ strengths parameters, we extracted from the published results the contributions of each partial wave for that observable. Figures 5a, b and c show the extracted difference for A_y. Similar figures were obtained for iT_{11}, T_{20}, T_{21}, T_{22} and mixing parameter $\epsilon_{1/2-}$ observables. The contributions for all these observables, once normalized, are used as input in a fitting code. The code performs all possible variations of the coefficients that should multiply differences from figures such as Fig. 5 for each $^3\mathrm{P}_J$, for each of the above listed spin observables. We searched for the amount of change in each $^3\mathrm{P}_J$ that would bring our fitting for each of the quoted spin observables simultaneously into the best agreement with the data.

Table 1 displays the outcome. It presents $^3\mathrm{P}_J$ that gives good agreement with experimental values for all quoted spin observables for p-d data. Table 2 gives the $^3\mathrm{P}_J$ strengths for the n-d data. We obtained $^3\mathrm{P}_J$ values that are close to those recommended by Machleidt [23] and that are listed in new potentials that include charge breaking (see Table 3). Thus, we are able to find parameters that simultaneously give good agreement with all 3N spin observables and that also satisfy 2N data. The comparison between the spin observables obtained through our

TABLE 1. λ factors obtained by analysis of the p − d *analysing-power data.*

Interaction	Energy (MeV)	$^3\mathrm{P}_0$	$^3\mathrm{P}_1$	$^3\mathrm{P}_2$
λ_{pp}	5.	0.94	0.99	1.04
λ_{np}	5.	0.85	0.93	1.00
λ_{pp}	6.5	0.94	1.00	1.04
λ_{np}	6.5	0.85	0.93	1.00
λ_{pp}	10.	0.93	1.01	1.05
λ_{np}	10.	0.84	0.94	1.01
λ_{pp}	22.7	0.94	1.00	1.04
λ_{np}	22.7	0.85	0.93	1.00

TABLE 2. λ for the best fit to the n − d *data starting from the λ factors for the* p − d *parameters.*

Interaction	Energy (MeV)	$^3P_0$	$^3P_1$	$^3P_2$
λ_{nn}	5	0.92	1.04	1.07
λ_{np}		0.85	0.93	1.00
λ_{nn}	10	0.90	1.00	1.13
λ_{np}		0.85	0.93	1.00

TABLE 3. λ factors obtained by the phase shift analysis of the p − p *and* n − p *data data, recommended by Machleidt.*

Interaction	$^3P_0$	$^3P_1$	$^3P_2$
λ_{pp}	0.95	0.97	1.025
λ_{np}	0.86	0.915	0.985

interpolation process and the experimental data is shown in Figs. 6 to 17. We see that agreement is more than anticipated for both n-d and p-d data. Figures 6 to 10 show the A_y obtained with our fitting procedure at 5, 10 and 22.7 MeV. Data for n-d are not available at 22.7 MeV.

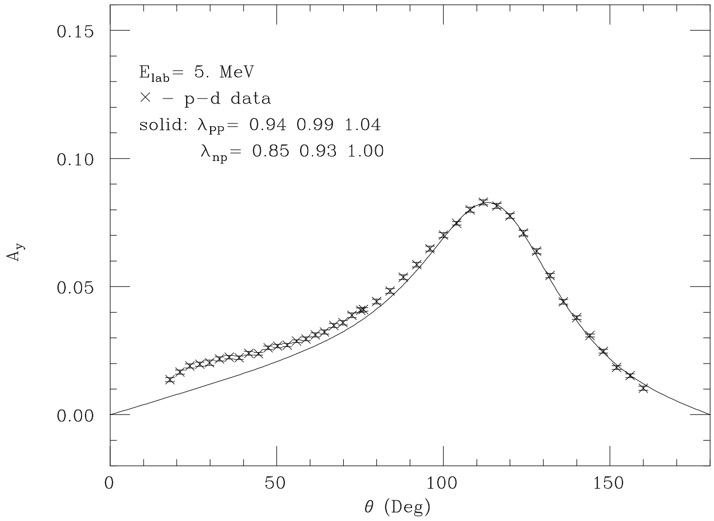

Fig. 6. A_y p-d at 5 MeV, *obtained by adding optimal combinations of ^3P_J partial waves contributions to initial Bonn B A_y calculations. The solid curve is equivalent to rigorous* 3N *calculations with Bonn B potential and ^3P_J partial waves modified in* p-p *interaction by the so called λ factor of $^3P_0$ for 0.94, $^3P_1$ for 0.99 and $^3P_2$ for 1.04. In* n-p *interactions λ factors, which are multiplying $^3P_0$, $^3P_1$ and $^3P_2$ waves, are 0.85, 0.93 and 1.00 respectively. A_y* p-d *data are from Ref. 9.*

Our analysis uses published calculations that do not include Coulomb interaction, hence they are appropriate for n-d data. As we stated at the outset, this implies

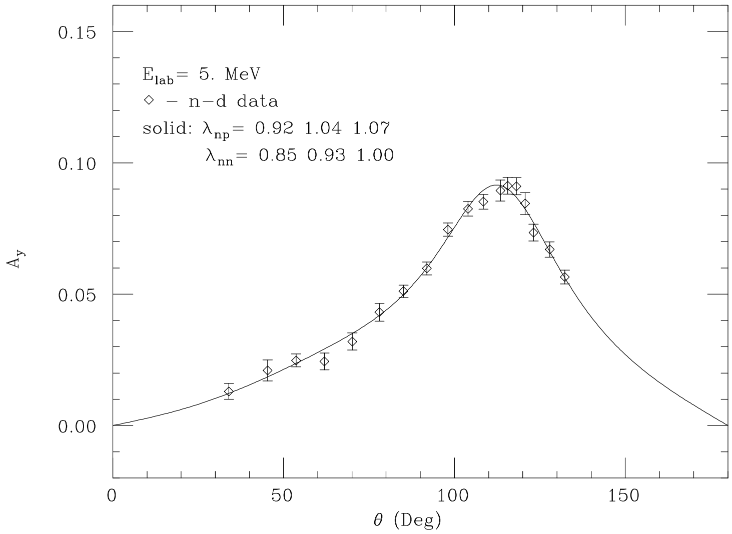

Fig. 7. A_y n-d *at 5* MeV, *obtained as in Fig. 6 Solid curve is equivalent to Bonn B calculations with λ Factors, which are multiplying* $^3\mathrm{P}_J$ *waves in* n-p *interactions equals 0.85, 0.93 and 1.00 and in* n-n *interaction λ factors are equal 0.92, 1.04, 1.07. A_y* n-d *data are from Ref. 24.*

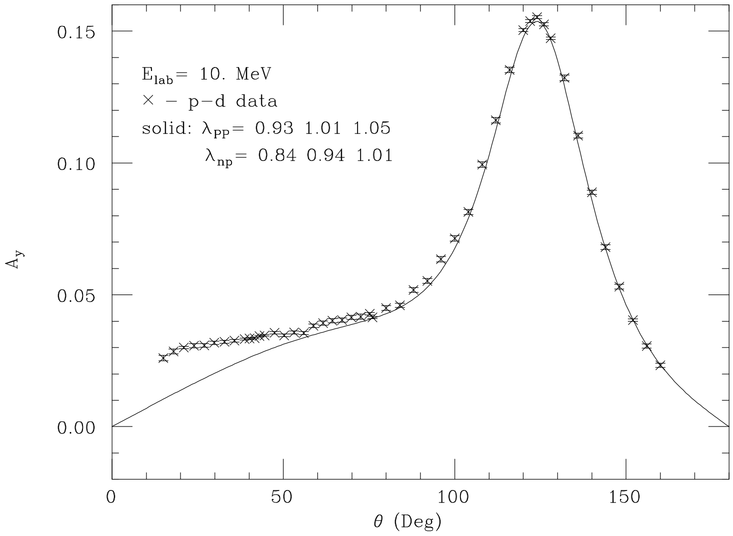

Fig. 8. A_y p-d *at 10* MeV, *obtained as in Fig. 6, with* p-p *λ factors equal 0.93, 1.01 and 1.05, and* n-p *λ factors equal 0.84, 0.94 and 1.01. Data are from Ref. 9.*

either that we assume that any difference between the n-d and p-d data is entirely due to differences in the n-n and p-p interaction (CSB) or we accept

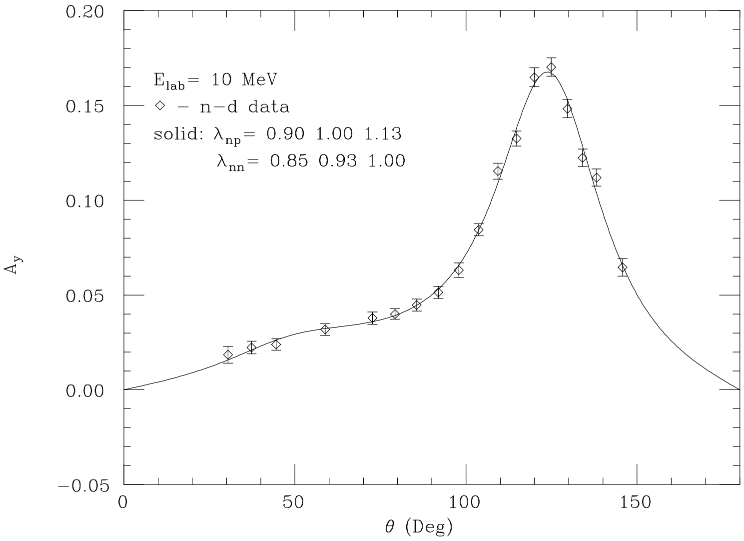

Fig. 9. A_y n-d *at 10* MeV, *obtained as in Fig. 6, with* n-n *λ factors equal 0.90, 1.00 and 1.13, and* n-p *λ factors equal 0.85, 0.93 and 1.00. Data are from Ref. 24.*

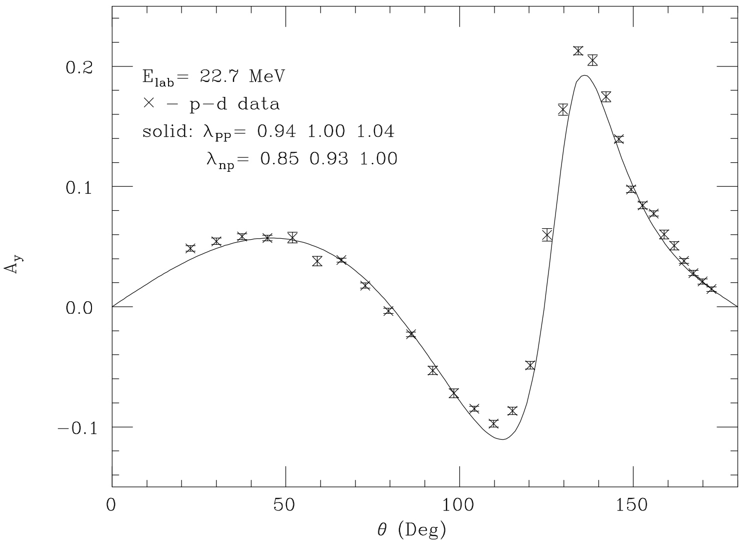

Fig. 10. A_y p-d *at 22.7* MeV, *obtained as in Fig. 6, with* p-p *λ factors equal 0.94, 1.00 and 1.04, and* n-p *λ factors equal 0.85, 0.93 and 1.00. Data are from Ref. 11.*

such difference as an upper bound to the size of CSB, implying that part of the difference is to be accounted by the Coulomb interaction. With this understanding,

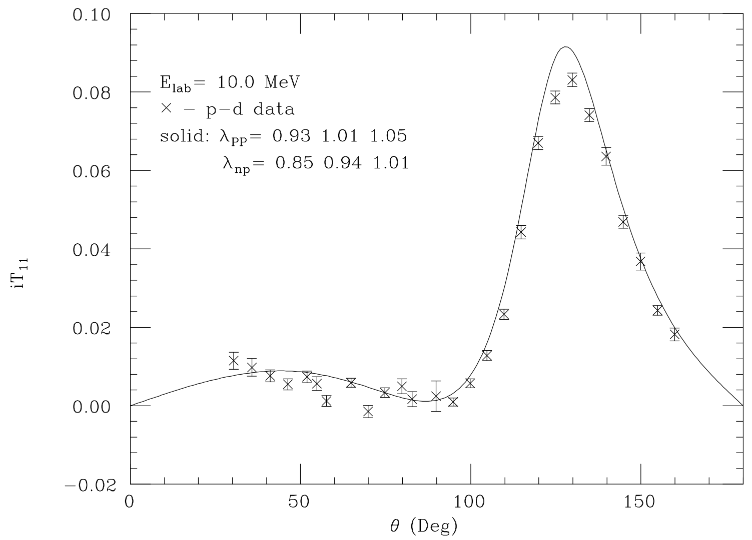

Fig. 11. iT_{11} p-d *at 10.0* MeV *obtained by adding optimal combination of* $^3\mathrm{P}_J$ *partial waves contributions to initial Bonn B* iT_{11} *calculations. The* λ *factors in* p-p *interactions are equal 0.93, 1.01 and 1.05, and* n-p λ *factors are equal 0.84, 0.94 and 1.01.* iT_{11} p-d *data are from Ref. 11.*

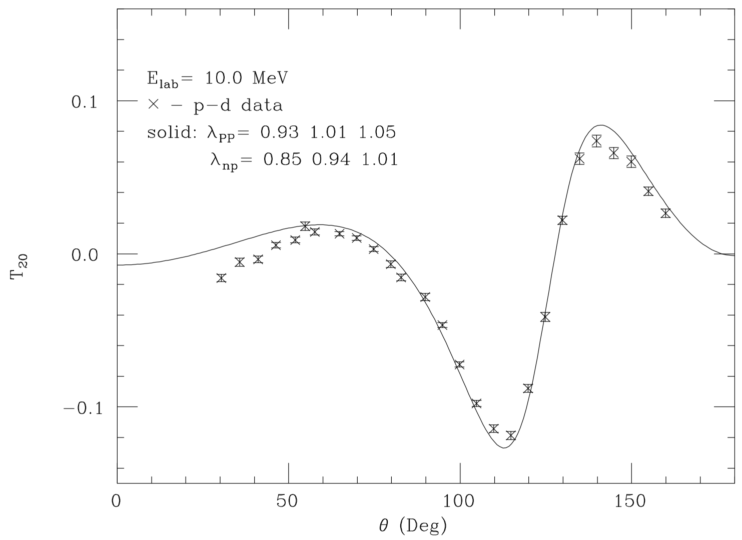

Fig. 12. T_{20} p-d *at 10* MeV, *with* λ *factors in* p-p *interactions equal 0.93, 1.01 and 1.05, and* n-p λ *factors 0.85, 0.94 and 1.01.* T_{20} p-d *data are from Ref. 11.*

we estimate the n-n ^3P_J strengths, that produce the best fit to the n-d data for A_y and other spin observables. From a comparison of Table 1 and Table 2 data, we

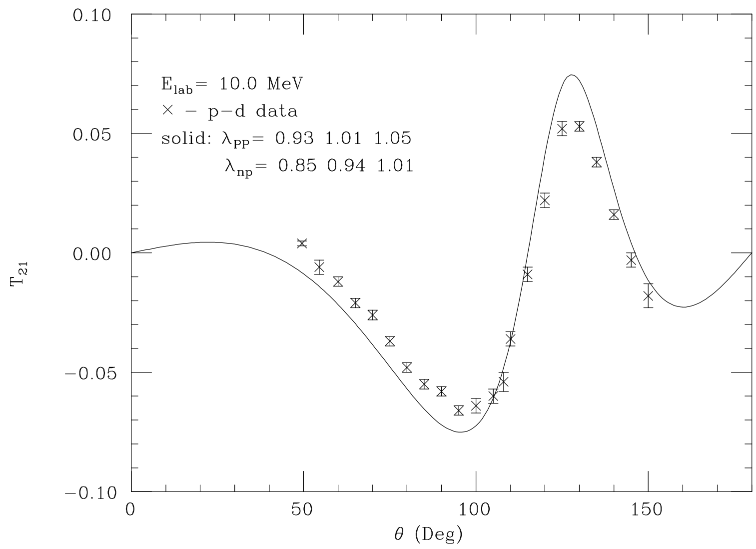

Fig. 13. T_{21} p-d *at 10* MeV*, with* λ *factors in* p-p *interactions equal 0.93, 1.01 and 1.05, and* n-p λ *factors 0.85, 0.94 and 1.01.* T_{21} p-d *data are from Ref. 11.*

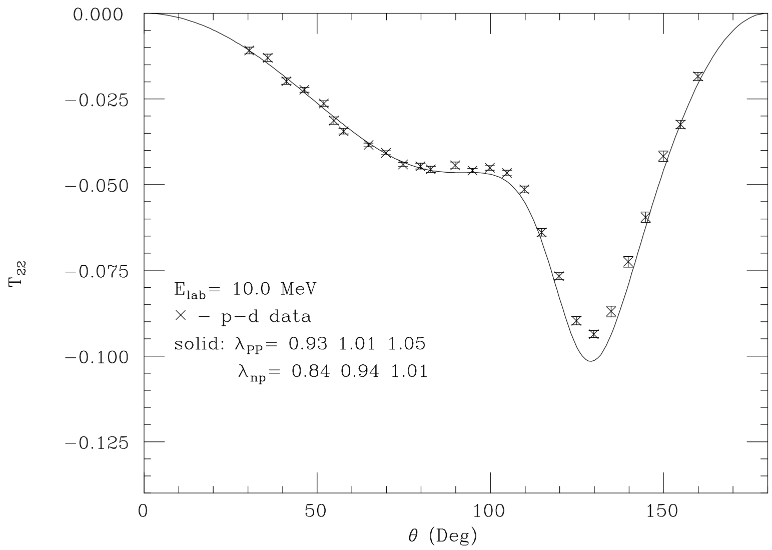

Fig. 14. T_{22} p-d *at 10* MeV*, with* λ *factors in* p-p *interactions equal 0.93, 1.01 and 1.05, and* n-p λ *factors 0.85, 0.94 and 1.01.* T_{22} p-d *data are from Ref. 11.*

conclude that the upper limit for CSB at 5 MeV is 3.4% and it is 4.0% at 10 MeV. At the same time, the upper limits for CI breaking are around 8.4% and 8.5% at 5 and 10 MeV, respectively, from n-d scattering and 6.6% and 7.2% at 5 and 10 MeV, respectively, for p-d scattering.

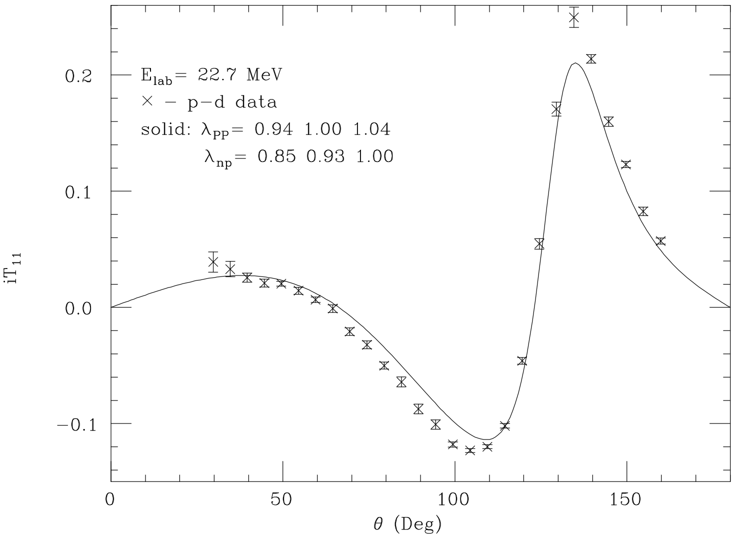

Fig. 15. iT_{11} p-d *at 22.7* MeV*, with* p-p λ *factors equal 0.94, 1.00 and 1.04, and* n-p λ *factors equal 0.85, 0.93 and 1.00. Data are from Ref. 11.*

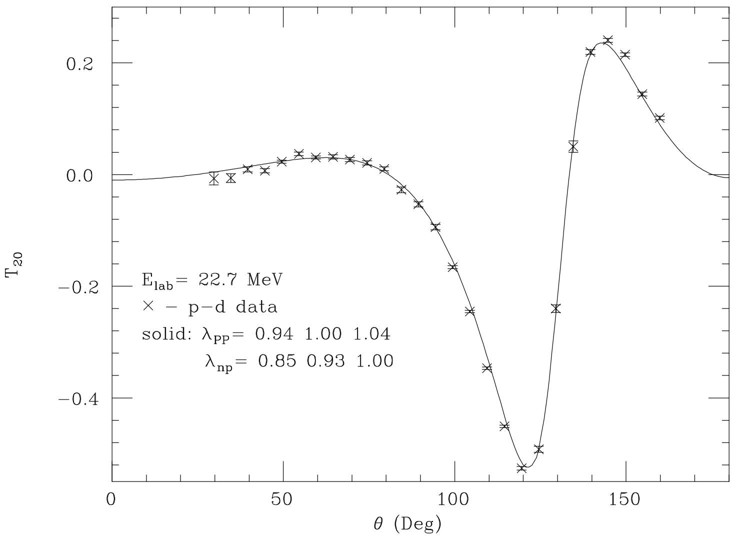

Fig. 16. T_{20} p-d *at 22.7* MeV*, with* p-p λ *factors equal 0.94, 1.00 and 1.04, and* n-p λ *factors equal 0.85, 0.93 and 1.00. Data are from Ref. 11.*

One can argue that the parameters obtained by fitting the data will not reproduce the data if used in 3N rigorous calculations. However, since we did just small adjustment of few percent of parameter used in rigorous 3N calculations, it will be

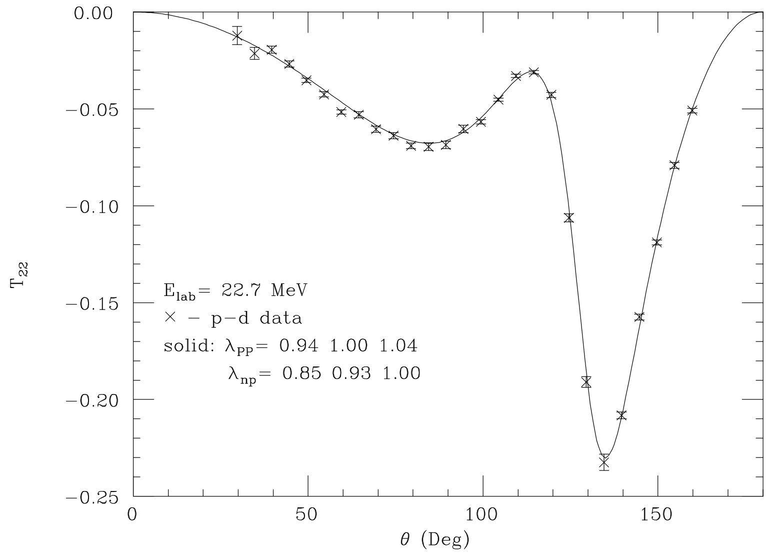

Fig. 17. T_{22} p-d *at 22.7* MeV, *with* p-p λ *factors equal 0.94, 1.00 and 1.04, and* n-p λ *factors equal 0.85, 0.93 and 1.00. Data are from Ref. 11.*

surprising if our assumption of linearity is wrong. Also, with our fitting program we are able to exactly reproduce published results [7] by forcing the fitting code to use the parameters used in published papers.

3. *Conclusion*

The detailed analysis of the A_y data at incoming channel energies in the range from 3.5 MeV to 18 MeV leads, at best, to the identification of an energy shift between 0.4 MeV and 0.8 MeV. However, such a shift cannot account for all the differences between the p-d and n-d data. Also, an interpretation of the difference in the A_y data as due exclusively to the slow-down effect is in conflict with the energy dependence of the differential cross sections.

It is perhaps surprising that such a physically intuitive effect as the slow-down of the proton projectile by the deuteron should not contribute to a complete explanation of the differences in the A_y and the differential cross section for p-d and n-d elastic scattering in the region of their maximum and minimum. The relative strength of the nuclear and Coulomb interactions, the difference in the contributions that each makes to higher angular momentum partial wave and the interference of these contributions cooperate in masking its presence.

Analysing all available spin observables, sensitive to $^3\mathrm{P}_J$ waves, we have found $^3\mathrm{P}_J$ parameters that simultaneously satisfy both 2N and 3N data. The amount of CSB is reasonable and similar values were suggested by other groups [20]. The explicit values of those parameters that should multiply $^3\mathrm{P}_J$ waves are listed for n-n, n-p and p-p forces. This result, addresses a long standing problem, the A_y puzzle, and it suggests that the same Bonn potential can be applied to 2N and 3N data. If confirmed by rigorous calculations, there will be many important implications of this result. For instance, there would be no need to include a strong 3N force to explain the A_y data.

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FINO PODEŠAVANJE NN SILE, p-d i n-d OPSERVABLE NISKOENERGIJSKOG ELSATIČNOG RASPRŠENJA I UČINAK COULOMBOVOG USPORAVANJA

Ispitujemo razlike moći analiziranja u elastičnom n-d i p-d raspršenju na energijama ispod 25 MeV i istražujemo mogu li se te razlike tumačiti kao posljedica kršenja nabojne simetrije u $^3\mathrm{P}_J$ stanjima. Pokazujemo da popravka podataka zbog usporenja protona pod djelovanjem Coulombove sile ne može objasniti te razlike. Te se razlike mogu objasniti uvođenjem kršenja nabojne simetrije od 3 do 4% u stanjima $^3\mathrm{P}_J$ Bonnskog potencijala. Dajemo izričite vrijednosti parametara koji određuju NN silu u stanjima $^3\mathrm{P}_J$ za n-n, n-p i p-p sile. Tako izmijenjen Bonnski potencijal daje dobro slaganje za 2N raspršenje i opservable 3N procesa.