Coulomb effects in three-nucleon scattering versus charge-symmetry breaking in the ^3P nucleon-nucleon interactions

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Comparison of data for neutron-deuteron and proton-deuteron analyzing power A_y for elastic scattering has become crucial for investigating charge-symmetry breaking in the ^3P nucleon-nucleon interactions. We extended this comparison down to 5 MeV and find that the relative difference between *n-d* and *p-d* scattering at the A_y maximum near 120° increases with decreasing energy. By applying a straightforward Coulomb "correction" to the *p-d* data, we account for most of the difference, suggesting that the Coulomb force, rather than charge-symmetry breaking, is responsible for most of the observed difference.

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Coulomb effects do not account completely for the mass difference between the three-nucleon (3*N*) bound states ^{3}H and ^{3}He. The Coulomb energy anomaly of about 80 keV (Refs. [1–3]) indicates class III (Ref. [4]) charge-symmetry breaking (CSB) of the nucleon-nucleon (*NN*) interaction: the neutron-neutron (*n-n*) interaction must be stronger than the proton-proton (*p-p*) interaction. Recommended values [5] for the *n-n* and *p-p* $^1S_0$ scattering lengths a_{nn} and a_{pp} are in agreement with this conclusion ($a_{nn}=-18.5\pm0.5$ fm, $a_{pp}=-17.3\pm0.3$ fm). The origin of CSB is related mainly to the ρ^0-ω mixing [6,7]. Recent calculations [1–3] of the ^{3}H and ^{3}He mass difference closely reproduce the measured mass difference. Except for the static Coulomb contribution, the CSB effects account for the largest contribution to the mass difference.

Since CSB effects are now well established in the $^1S_0$ *NN* interaction, the question arises whether CSB effects can also be found in *NN* interactions for partial waves higher than the $^1S_0$. CSB effects in $^3P_0$ and $^3P_1$ *NN* phase shifts were predicted by Langacker and Sparrow [8]. Due to the lack of a free neutron target, class III CSB studies have not been feasible in 2*N* systems. Therefore, 3*N* scattering systems are of special interest. In principle, besides *p-p* scattering, proton-deuteron (*p-d*) scattering gives information about the *p-p* force while neutron-deuteron (*n-d*) scattering gives information about the *n-n* force acting in the *n-d* system (as well as the *p-n* force in both the *p-d* and *n-d* systems).

Below the deuteron breakup threshold at 2.225 MeV in the c.m. system or $E_N=3.375$ MeV in the laboratory system, the exact inclusion of the Coulomb interaction in Faddeev calculations in both momentum and coordinate space is now feasible [9,10]. Unfortunately, the necessary *n-d* data to examine CSB do not exist at such a low energy. Recently, results of rigorous Faddeev calculations in momentum space became available [11] for the *n-d* scattering system in the 5 to 65 MeV range using realistic *NN* potentials based on meson exchange (for example, Paris [12] and Bonn [13]). However, similar rigorous calculations for the *p-d* system above breakup threshold are still unavailable because the Coulomb interaction, due to its infinite range, cannot be treated exactly in Faddeev calculations that use realistic *NN* potentials. Prescriptions [14] to include the Coulomb force exactly were used to obtain *p-d* phase shifts, but only for the case with simple *NN* *S*-wave interactions. Alt *et al.* [15] concluded that published procedures [16] for approximating the Coulomb interaction in *p-d* Faddeev calculations yield unsatisfactory results. As a consequence, details of the differences between *n-d* and *p-d* scattering above breakup threshold cannot be interpreted theoretically. On the other hand, present experimental techniques allow one to determine the magnitude of such differences.

Since the nucleon-deuteron (*N-d*) cross section $\sigma(\theta)$ is governed by *S*-wave *NN* interactions below 20 MeV, such measurements are not suited for CSB studies in ^3P interactions. However, below 20 MeV the magnitude of the analyzing power $A_y(\theta)$ is governed by triplet *P*-wave ($^3P_{0,1,2}$) *NN* interactions, and furthermore, small changes in the individual ^3P interactions have large influences [17] on the shape of $A_y(\theta)$. As a consequence, this observable should be an excellent testing ground for CSB effects in the ^3P interactions. Such effects cannot be determined for *P* waves from the 3*N* bound-state information. In addition, the vector and tensor analyzing powers for *d-n* as well as the vector-to-tensor polarization transfer coefficients for *n-d* scattering are also sensitive to variations of the ^3P *NN* interactions [18]. Although such types of measurements are possible now with protons, current techniques do not allow these experiments to be performed with neutrons to an adequate accuracy. In fact, such neutron data do not exist. This leaves the $A_y(\theta)$ in *N-d* scattering as the only presently practical probe of

CSB effects in the ^3P interactions. This realization is the underlying reason for our recent accurate measurements [19] of $A_y(\theta)$ for *n-d* scattering below 10 MeV.

In this Brief Report we focus on the comparison of $A_y(\theta)$ data for *n-d* [17,19–21] and *p-d* [22,23] in the 5 to 14 MeV range. Three sets of *n-d* data, obtained [19] at Triangle Universities Nuclear Laboratory below 10 MeV, are compared in Fig. 1 to *p-d* data; similar comparisons at higher energies appear in Refs. [20,24]. The curves through the *n-d* and *p-d* data were obtained by fitting the product of $\sigma(\theta)$ and $A_y(\theta)$ using associated Legendre polynomials. At forward angles, where Rutherford scattering dominates the *p-d* system, a difference between the data is clearly noticeable. More importantly, the distributions differ at $A_y(\max)$, the maximum of $A_y(\theta)$ near 120° c.m. Sensitivity studies [25] to the individual ^3P interactions clearly demonstrate that such observed differences at $A_y(\max)$ can be produced by introducing CSB in the $^3P_0$ *NN* interaction, i.e., by making the $^3P_0$ *n-n* interaction weaker than the $^3P_0$ *p-p* interaction. For this reason the present paper focuses on the angular range around 120° c.m.

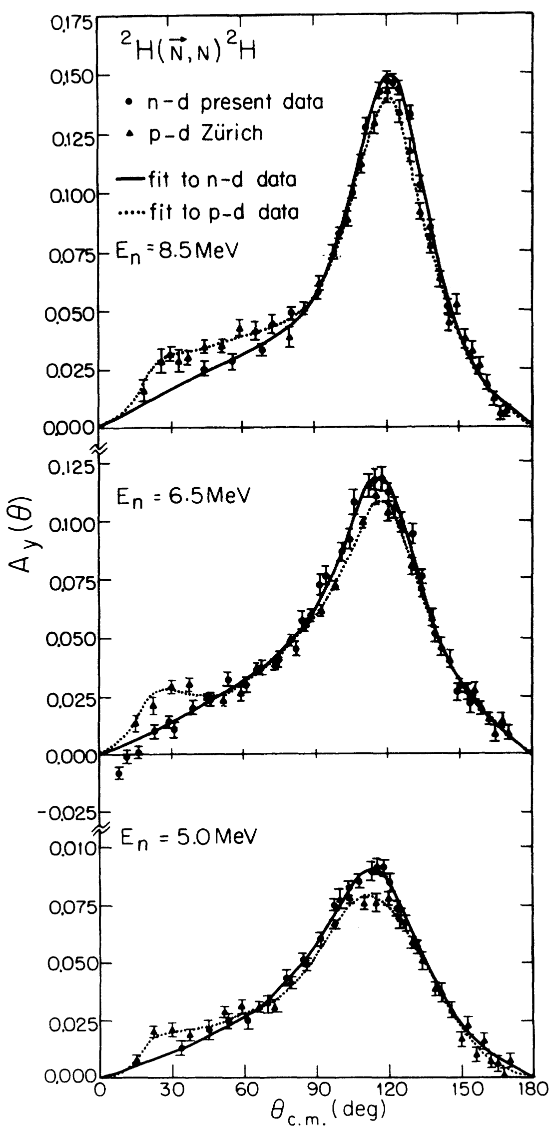

FIG. 1. Comparison of *n-d* [19] and *p-d* [22] analyzing power data. The curves are based on polynomial fits to the product $\sigma(\theta)A_y(\theta)$.

In Fig. 2 the energy dependence of $A_y(\max)$, for *n-d*, and *p-d*, is displayed from 2.5 to 14 MeV. The width of the bands represents the associated uncertainties, but does not include the "scale uncertainty" associated with the polarization of the neutron and proton beams that were used in the measurements. Except for a constant displacement, the *p-d* and *n-d* $A_y(\max)$ curves are nearly identical. The inclusion of the scale uncertainties for the beam polarization widens the bands so that they almost touch each other.

The approximate Coulomb correction method of Doleschall *et al.* [16] predicts only a very small difference in the $A_y(\max)$ values at 10 MeV. Thus, it has been assumed in later analyses that the difference in Fig. 2 is caused by CSB effects in the ^3P interactions [25,26]. However, we feel that one should subtract off the effect of the Coulomb interaction (as was done in the case of the 3*N* bound state ^{3}He) in order to delineate CSB effects. For the *p-d* scattering case, in first order this amounts to accounting for Coulomb repulsion; i.e., as is well known from nucleon-nucleus optical-model studies, the specific nuclear interaction takes place at lower energy than the beam energy because the proton is slowed down by the Coulomb field of the target nucleus.

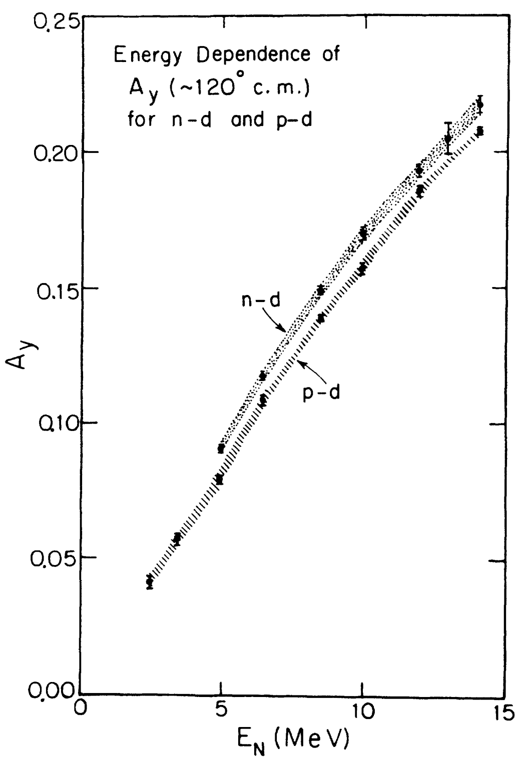

FIG. 2. Energy dependence of $A_y(\max)$ near $\theta_{c.m.} = 120°$ for *p-d* scattering from Refs. [22,23] and *n-d* scattering from Refs. [17,19–21].

Two simple approaches can be taken to calculate the so-called "Coulomb shift." Using $R=4.31$ fm (from $R=\hbar/\sqrt{MB}$ with $M=M_n=M_p$ and $B=2.225$ MeV) as the "radius" of a deuteron (uniformly charged), one obtains a Coulomb shift of $\Delta E_C=400$ keV. Consequently, one should compare *p-d* data at $E+\Delta E_C$ to *n-d* data at E. Another estimate obtained similarly by using the rms radius of the deuteron [27] (1.953 fm) yields $\Delta E_C=880$ keV. A shift of the *p-d* values shown in Fig. 2 by $\Delta E_C=640$ keV (the average of both ΔE_C values) brings the Coulomb "corrected" *p-d* values into excellent agreement with the corresponding *n-d* values. Assuming that this treatment of the Coulomb effect is correct to first order, the residual CSB effects in the ^3P *NN* interactions appear to be very small and probably will be difficult to observe in $A_y(\theta)$ data obtained with present techniques. Our conclusion is that the major part of the observed differences between *n-d* and *p-d* A_y(max) data are most likely caused by the Coulomb interaction.

To further illustrate the basis for this conclusion, in Fig. 3 we plot the *relative* difference between A_y(max) for *n-d* and *p-d*. (The dashed error bars display the effects of merely adding the contribution of the scale uncertainty in the neutron and proton beam polarizations.) The decrease of the *relative* difference with increasing nucleon energy is consistent with that anticipated from the Coulomb interaction. The point plotted at 2.5 MeV was obtained from the theoretical work of Berthold *et al.* [9]. Their calculation includes, for the first time, the Coulomb interaction below the deuteron breakup threshold in an "exact" way in *p-d* Faddeev calculations using a realistic *NN* interaction; no CSB effects were incorporated in the ^3P *NN* interactions. Figure 3 shows that this point is consistent with the trend of the measurements at higher energies. We put the word exact in quotation marks since the Coulomb *t*-matrix was replaced in the *p-d* calculation of Ref. [9] by the *p-d* Coulomb potential. Multiple

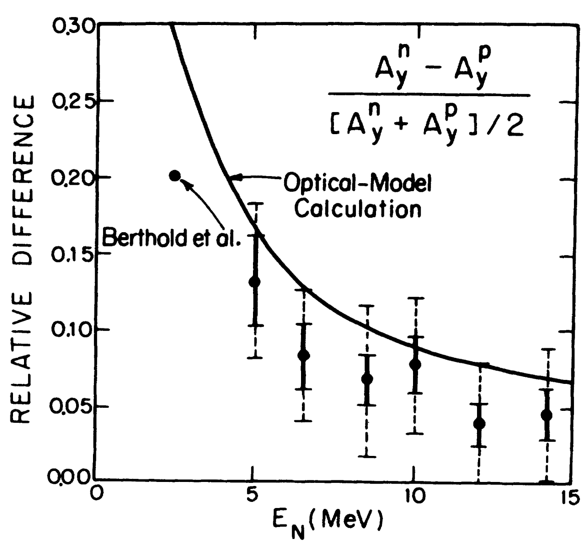

FIG. 3. Relative difference between *n-d* and *p-d* analyzing power A_y(max) near $\theta_{c.m.}=120°$. Error bars are described in the text. The point at 2.5 MeV was obtained from Ref. [9]. The solid curve is an optical-model calculation.

Coulomb interactions in the *t* matrix must also be included. Accurate *p-d* and *n-d* $A_y(\theta)$ data are needed to verify the accuracy of the theoretical approach of Ref. [9].

To investigate the effect of Coulomb repulsion using another approach, the *n-d* $\sigma(\theta)$ and $A_y(\theta)$ data at 10 MeV were "fitted" using an optical-model approach with Woods-Saxon form factors that is standard for heavier nuclei. The solid line in Fig. 4 was obtained by searching on the data, but restricting the potential parameters to values close to ones commonly accepted for heavier nuclei. For the real central potential we obtained $V_R=38.6$ MeV, $r_R=1.24$ fm, and $a_R=0.75$ fm. The spin-orbit potential parameters are $V_{\text{s.o.}}=2.24$ MeV, $r_{\text{s.o.}}=1.105$ fm, and $a_{\text{s.o.}}=0.65$ fm and the imaginary (surface absorptive) potential is characterized by $W_I=2.70$ MeV, $r_I=1.24$ fm, and $a_I=0.675$ fm. The shape of the measured $A_y(\theta)$ is qualitatively reproduced. The dotted curve was calculated for *p-d* scattering using exactly the same nuclear potential as for *n-d*. For the Coulomb potential we used that of a uniform charge distribution of radius parameter $r_c=1.24$ fm. Since our result does not depend strongly upon the value of r_c, for simplicity, we set $r_c=r_R$, i.e., we used for the Coulomb radius $R=1.24A^{1/3}=1.56$ fm. Of course, a folding model approach would give a value that is closer to the rms value of 1.953 fm. A polarization potential was not included since it was shown to be negligible [28]. Qualitatively, the curves exhibit the same difference at A_y(max) as observed experimentally (see Fig. 1). In addition, the forward-angle difference is also predicted. Carrying this optical-model approach farther, we used an energy dependence for the real potential that is common for heavier nuclei ($V_0-0.3E_N$, $V_0=41.6$ MeV) and calculated the solid curve in Fig. 3. This prediction compares favorably with the experimental trend, although it does overestimate the relative difference. Considering that the optical model has limited validity for such light nuclear systems, this overestimate should not be surprising. It also should be noted that $\sigma(\theta)$ is described quite well as scattering angles forward of 120° c.m. As expected, beyond 120° c.m. where nucleon pickup dominates, the optical-model calculation does not reproduce $\sigma(\theta)$. However, in agreement with experimental data [29], we find that the *n-d* backward angle $\sigma(\theta)$ is slightly larger than that for *p-d* scattering.

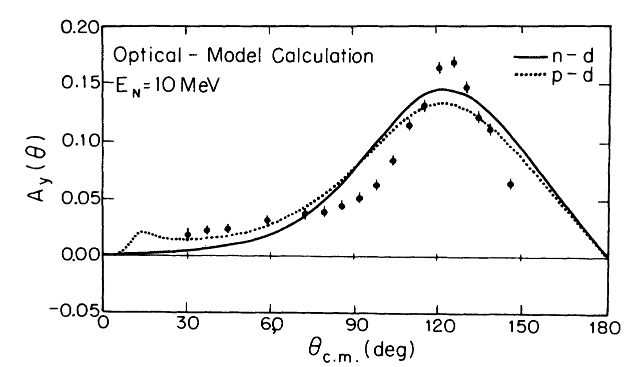

FIG. 4. Optical-model calculations for *n-d* (solid curve) and *p-d* (dotted curve) $A_y(\theta)$ at 10 MeV compared to *n-d* data.

In summary, the comparison of n-d and p-d $A_y(\theta)$ data has been extended down to 5 MeV, with a particular focus on differences at the maximum of $A_y(\theta)$. To first order, these differences can be reproduced by applying a simple correction to remove the effect of the Coulomb interaction in p-d scattering. [This approach to the Coulomb correction should also be applicable to other p-d and d-p observables, for example, $\sigma(\theta)$, but the quality of the available n-d $\sigma(\theta)$ data is insufficient for a meaningful comparison.] Reiterating our conclusion, we find that a straightforward treatment of the Coulomb correction has revealed that the major part of the observed differences between n-d and p-d $A_y(\theta)$ data is most likely an electromagnetic effect and not a charge-symmetry-breaking effect. It now appears likely that CSB effects in the ^3P *NN* interactions are too small to be observed in the *Nd* scattering systems at low energies with present techniques. It might well be that CSB effects account for only about 10% of the discussed differences, similar to what was found for the 3*N* bound-state binding energy difference [1–3]. However, rigorous Faddeev calculations that include the Coulomb interaction exactly are important for supporting the present conclusions.

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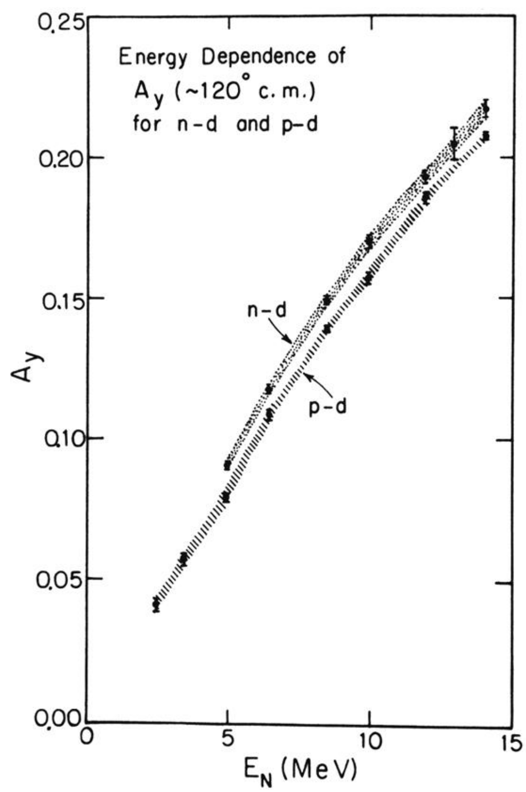
[1] R. A. Brandenburg, S. A. Coon, and P. U. Sauer, Nucl. Phys. **A294**, 305 (1978).
[2] J. L. Friar, B. F. Gibson, and G. L. Payne, Phys. Rev. C **35**, 1502 (1987).
[3] Y. Wu, S. Ishikawa, and T. Sasakawa, Phys. Rev. Lett. **64**, 1875 (1990), and references therein.
[4] E. M. Henley and G. A. Miller, in *Mesons in Nuclei*, edited by M. Rho and D. H. Wilkinson (North-Holland, Amsterdam, 1979), Vol. I, p. 405.
[5] I. Slaus, Y. Akaishi, and H. Tanaka, Phys. Rep. **173**, 257 (1989).
[6] G. A. Miller, Nucl. Phys. **A518**, 345 (1990).
[7] G. F. de Téramond, in Proceedings of Symposium on Spin and Symmetries, TRIUMF, Vancouver, edited by W. D. Ramsey and W. H. T. van Oers, Report No. TRI-89-5, (1989), p. 255.
[8] P. Langacker and D. A. Sparrow, Phys. Rev. C **25**, 1194 (1982).
[9] G. H. Berthold, A. Stadler, and H. Zankel, Phys. Rev. Lett. **61**, 1077 (1988); Phys. Rev. C **41**, 1365 (1990).
[10] G. Bencze, C. Chandler, J. L. Friar, A. G. Gibson, and G. L. Payne, Phys. Rev. C **35**, 1188 (1987).
[11] H. Witała, W. Glöckle, and T. Cornelius, Nucl. Phys. **A491**, 157 (1989).
[12] M. Lacombe, B. Loiseau, J. M. Richard, R. Vinh Mau, J. Cote, P. Pires, and R. de Tourreil, Phys. Rev. C **21**, 861 (1980).
[13] R. Machleidt, Adv. Nucl. Phys. **19**, 189 (1989).
[14] E. O. Alt, W. Sandhas, H. Zankel, and H. Ziegelmann, Phys. Rev. Lett. **37**, 1537 (1976); Y. A. Kuperin, S. P. Merkuriev, and A. A. Kvitsinski, Yad. Fiz. **37**, 1440 (1983) [Sov. J. Nucl. Phys. **37**, 857 (1983)].
[15] E. O. Alt, W. Sandhas, and H. Zieglemann, Nucl. Phys. **A445**, 429 (1985).
[16] J. V. Noble, Phys. Rev. **161**, 945 (1967); P. Doleschall, W. Grüebler, V. König, P. A. Schmelzbach, F. Sperisen, and B. Jenny, Nucl. Phys. **A380**, 72 (1982); H. Zankel and G. M. Hale, Phys. Rev. C **27**, 419 (1983).
[17] C. R. Howell *et al.*, Few-Body Syst. **2**, 19 (1987).
[18] W. Glöckle, H. Witała, and Th. Cornelius, Nucl. Phys. **A508**, 115c (1990).
[19] W. Tornow *et al.*, Phys. Lett. B **257**, 273 (1991).
[20] W. Tornow, C. R. Howell, R. C. Byrd, R. S. Pedroni, and R. L. Walter, Phys. Rev. Lett. **49**, 312 (1982); W. Tornow, R. C. Byrd, C. R. Howell, R. S. Pedroni, and R. L. Walter, Phys. Rev. C **27**, 2439 (1983).
[21] J. Cub, E. Finckh, H. Friess, G. Fuchs, K. Gebhardt, K. Geissdörfer, R. Lin, and J. Strate, Few-Body Syst. **6**, 151 (1989).
[22] W. Grüebler, V. König, P. A. Schmelzbach, F. Sperisen, B. Jenny, and R. E. White, Nucl. Phys. **A398**, 445 (1983).
[23] J. C. Duder, M. Sosnowski, and D. Melnick, Phys. Lett. **85B**, 206 (1979).
[24] W. Tornow, J. Herdtweck, W. Arnold, and G. Mertens, Phys. Lett. **203**, 341 (1988).
[25] H. Witała and W. Glöckle, Nucl. Phys. **A528**, 48 (1991).
[26] I. Slaus, Bull. Am. Phys. Soc. **II**, **35**, 1696 (1990); I. Slaus, R. Machleidt, W. Tornow, W. Glöckle, and W. Witała, Comments Nucl. Part. Phys. **20**, 85 (1991).
[27] S. Klarsfeld, J. Martorell, J. A. Oteo, M. Nishimura, and D. W. L. Sprung, Nucl. Phys. **A456**, 373 (1986).
[28] G. Bencze, Phys. Lett. B **202**, 289 (1987); S. K. Adhikari and T. K. Das, Phys. Rev. C **37**, 1376 (1988), and references therein.
[29] G. Rauprich, H. J. Hähn, M. Karus, P. Niessen, K. R. Nyga, H. Oswald, L. Sydow, H. Paetz gen. Schieck, and Y. Koike, Few-Body Syst. **5**, 67 (1988), and references therein.



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