Physics Letters B 302 (1993) 533–539
North-Holland

PHYSICS LETTERS B

Measurement of the spin-dependent structure function $g_1(x)$ of the deuteron

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Received 1 March 1993

We report on the first measurement of the spin-dependent structure function g_1^d of the deuteron in the deep inelastic scattering of polarised muons off polarised deuterons, in the kinematical range $0.006 < x < 0.6$, $1\ \mathrm{GeV}^2 < Q^2 < 30\ \mathrm{GeV}^2$. The first moment, $\Gamma_1^d = \int_0^1 g_1^d\, dx = 0.023 \pm 0.020$ (stat.) ± 0.015 (syst.), is smaller than the prediction of the Ellis–Jaffe sum rules. Using earlier measurements of g_1^p, we infer the first moment of the spin-dependent neutron structure function g_1^n. The difference $\Gamma_1^p - \Gamma_1^n = 0.20 \pm 0.05$ (stat.) ± 0.04 (syst.) agrees with the prediction of the Bjorken sum rule, $\Gamma_1^p - \Gamma_1^n = 0.191 \pm 0.002$.

In the past 15 years, two experimental determinations of the spin-dependent structure function $g_1^p(x)$ of the proton were made from measurements of cross section asymmetries in deep inelastic scattering of longitudinally polarised leptons by longitudinally polarised protons. The first was an experiment at SLAC [1] in which polarised electrons with energies between 6 and 21 GeV were used and which covered the kinematic range $0.1 < x < 0.7$, where x is the Bjorken scaling variable. The second was an experiment at CERN [2] in which polarised muons of 100, 120 and 200 GeV energy were used, and which covered the x range $0.01 < x < 0.7$. The result of these experiments disagrees with the prediction of the Ellis–Jaffe sum rule [3] for the proton and indicates that in the quark–parton model, the spins of quarks and antiquarks contribute little to the spin of the proton. In a large number of papers, a variety of theoretical ideas were proposed to explain this unexpected result [4]. Several experiments are presently being carried out or prepared at CERN [5], SLAC [6], and DESY [7] to measure the spin structure function of the neutron

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[13] Supported by Comision Interministerial de Ciencia y Tecnologia.
[14] Supported by the Department of Energy.
[15] Supported by KBN.
[16] Supported by the National Science Foundation of the Netherlands.
[17] Supported by Bundesministerium für Forschung und Technologie.
[18] Supported by the National Science Foundation.
[19] Supported by Monbusho International Science Research Program.
[20] Supported by the US–Israel Binational Science Foundation, Jerusalem, Israel.

and to repeat the proton measurement with improved accuracy.

In this paper, we present first results from a measurement of the cross section asymmetry for the deuteron,

$$A^{\mathrm{d}} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}. \quad (1)$$

In this expression, $\sigma^{\uparrow\downarrow}$ ($\sigma^{\uparrow\uparrow}$) are the cross sections for inclusive deep inelastic scattering of longitudinally polarised muons off longitudinally polarised deuterons, for antiparallel (parallel) orientation of beam and target polarisations. From this asymmetry, we evaluate the spin-dependent structure function $g_1^{\mathrm{d}}(x)$, which we then use to test the prediction of the Ellis–Jaffe sum rules [3]. In combination with the earlier results from measurements with proton targets, our data allow us to evaluate the first moment of the structure function $g_1^{\mathrm{n}}(x)$ of the neutron and to test the Bjorken sum rule [8].

The experiment uses a polarised muon beam, a polarised deuteron target, a spectrometer to measure the scattered muon, and a beam polarimeter. The target and the spectrometer are based on the apparatus built by the EMC Collaboration [2,9], but have been upgraded to reduce systematic uncertainties [5,10]. The polarimeter is new and will be described in a forthcoming publication [11].

For this experiment, we have used a beam of positive muons with an average energy of 100 GeV [12], a spill time of 2.4 s and a period of 14.4 s. The beam intensity was 4×10^7 muons per spill. The incident muon momentum is measured on an event-by-event basis.

The polarised target in the present experiment uses the same cryogenic components as the EMC target [2,13,14]. A superconducting solenoid provides a magnetic field of 2.5 T parallel to the beam direction. A dilution refrigerator cools the target to a temperature of about 500 mK during polarisation, and to 50 mK during frozen spin operation. The target is divided in two halves, each 40 cm long and 5 cm in diameter, separated by 20 cm. The longitudinal polarisations in the two halves are opposite in sign so that data can be recorded for both polarisation directions simultaneously.

The target material is deuterated butanol with an admixture of paramagnetic molecules. Dynamic Nuclear Polarisation (DNP) is obtained by applying microwaves at a frequency close to the resonance of the paramagnetic electrons. The typical deuteron polarisation was about 0.25 until it was discovered that a substantial increase in the polarisation can be obtained by modulating rapidly the microwave frequency over a range of 30 MHz [15]. In this way, deuteron polarisations larger than 0.40 have been routinely obtained. The polarisation is measured using 10 NMR coils embedded in the target material. The integrated NMR absorption signals were calibrated in thermal equilibrium at 1.1 K. This allows us to measure the polarisation to an accuracy of about 0.02.

In order to minimise systematic errors, we reversed the polarisation directions in the two target halves at regular time intervals. For most of our data the spins were reversed every 8 hours by rotating the field direction using the 0.2 T transverse field of a new superconducting dipole coil wound on the microwave cavity. In addition, the relative orientation of the solenoid field and the target polarisation was changed at least once per week with DNP.

In the first stage of the muon spectrometer, charged particles are momentum analysed with a conventional large-aperture dipole magnet and several sets of proportional and drift chambers. Hadrons are absorbed in an iron wall. Downstream of this wall streamer tubes, drift tubes, proportional chambers and scintillator hodoscopes are used for muon identification and triggering.

The beam polarisation is determined from the shape of the energy spectrum of the positrons from the decay $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$. Downstream of the muon spectrometer, a 30 m long muon decay path is defined between a shower veto hodoscope which identifies the μ^+ and a dipole magnet where the momentum of the e^+ is measured using multiwire proportional chambers. Identification of the decay positrons is done using the energy deposited in a lead glass calorimeter. Radiative corrections are taken into account. For 100 GeV positive muons, the beam polarisation is found to be $P_\mu = -0.82 \pm 0.06$, in good agreement with Monte Carlo simulations of the beam transport [12].

Off-line event reconstruction programs determine the kinematics of the incident and scattered muon and the vertex position. Starting from the scattered muon identified downstream of the absorber wall in the muon spectrometer, the upstream trajectory is reconstructed up to the interaction point. The average vertex resolution is 3 cm in the direction of the beam and 0.3 mm in the transverse plane. This permits a good identification of the events originating from the upstream and downstream target cells.

A Monte Carlo simulation was developed for our experimental set-up using the GEANT program [16]. The detailed description of the apparatus includes the resolutions and efficiencies of all detectors. The simulation uses the distribution of incident muons recorded during the data taking. The Monte Carlo program has been used to test the event reconstruction, to determine smearing due to finite resolution and to estimate systematic errors.

We report here on data taken in 1992, covering the kinematic range $1\ \mathrm{GeV}^2 < Q^2 < 30\ \mathrm{GeV}^2$ and $0.006 < x < 0.6$. Cuts were applied on kinematic variables in order to minimise smearing effects, to limit the size of radiative corrections, and to reject muons originating from the decay of pions produced in the target. After cuts, the data sample amounts to 3.2×10^6 events with an average deuteron polarisation $P_T = 0.35$.

The measured event yields from the two target cells can be expressed in terms of the cross section asymmetry A^d:

$$N_u = n_u \Phi a_u \sigma_0 (1 - f P_\mu P_u A^d), \qquad (2)$$

$$N_d = n_d \Phi a_d \sigma_0 (1 - f P_\mu P_d A^d), \qquad (3)$$

where the subscripts u and d refer to the upstream and downstream target cells, n is the number of target nucleons, Φ the beam flux, a the apparatus acceptance, σ_0 the unpolarised cross section, f the fraction of the event yield from the deuterons in the target material (dilution factor), and P_μ and $P_{u,d}$ are the beam and target polarisations. The sign of the polarisation of both the target and the incident muon is defined to be positive when parallel to the beam direction. With this definition, P_μ is negative for the μ^+ beam, and P_u and P_d are of opposite sign. Cuts are applied to ensure that the beam flux Φ is the same for both target cells. The dilution factor is $f \simeq 0.19$, and the raw asymmetry $f P_\mu P_T A^d$ is of order 10^{-3}.

The longitudinal virtual photon asymmetry A_1^d is related to the muon-deuteron asymmetry A^d by [17]

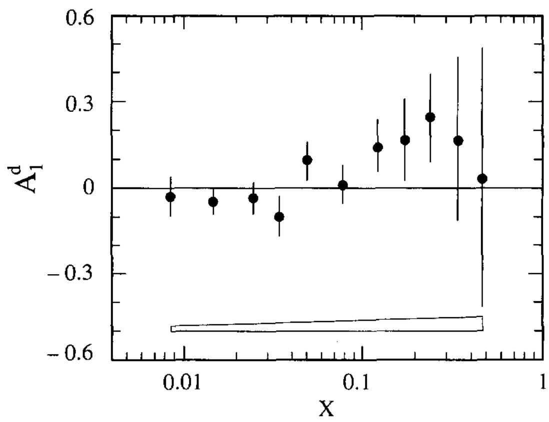

Fig. 1. The virtual photon-deuteron cross section asymmetry A_1^d as a function of the Bjorken scaling variable x. Only statistical errors are shown with the data points. The size of the systematic errors is indicated by the shaded area.

$$A_1^d = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{A^d}{D} - \eta A_2^d, \qquad (4)$$

where 1/2 and 3/2 are the total spin projections in the direction of the virtual photon. The depolarisation factor D and η depend on the event kinematics. The possible contribution from the transverse asymmetry A_2^d has been neglected; it is constrained by a positivity limit which is included in the systematic error. The contribution from the quadrupole structure function $b_1(x)$ of the deuteron is expected to be small in the kinematic range of our data [18], and has been neglected.

The combination of two data sets taken before and after a polarisation reversal provides four equations for the yields, from which A_1^d can be extracted under the assumption that the acceptance ratio $r = a_u/a_d$ is the same for the two data sets. The radiative corrections to A_1^d have been evaluated from a detailed calculation of higher order effects on spin-dependent cross sections [19]. Within the systematic uncertainty, they are in agreement with the corrections obtained from the method described in ref. [2], and are small with respect to the statistical errors. A_1^d is evaluated in bins of x and Q^2; however, no Q^2 dependence of A_1^d is observed within the statistical errors. We therefore present the average A_1^d in each bin of x (table 1 and fig. 1).

The dominant systematic error is a possible time variation of the acceptance ratio r. To estimate this

Table 1
Results on the virtual photon asymmetry A_1^d and on the spin structure function g_1^d of the deuteron. The first error is statistical, the second one is systematic.

x range	$\langle x \rangle$	$\langle Q^2 \rangle$ (GeV^2)	A_1^d	g_1^d
0.006–0.010	0.009	1.2	$-0.029 \pm 0.071 \pm 0.013$	$-0.554 \pm 1.347 \pm 0.251$
0.010–0.020	0.015	1.7	$-0.046 \pm 0.046 \pm 0.015$	$-0.490 \pm 0.493 \pm 0.155$
0.020–0.030	0.025	2.5	$-0.032 \pm 0.059 \pm 0.018$	$-0.198 \pm 0.360 \pm 0.100$
0.030–0.040	0.035	3.1	$-0.098 \pm 0.073 \pm 0.021$	$-0.417 \pm 0.312 \pm 0.078$
0.040–0.060	0.050	3.7	$+0.096 \pm 0.067 \pm 0.025$	$+0.283 \pm 0.197 \pm 0.060$
0.060–0.100	0.079	4.6	$+0.013 \pm 0.070 \pm 0.030$	$+0.023 \pm 0.127 \pm 0.043$
0.100–0.150	0.123	5.6	$+0.144 \pm 0.095 \pm 0.037$	$+0.162 \pm 0.107 \pm 0.031$
0.150–0.200	0.173	6.9	$+0.168 \pm 0.143 \pm 0.042$	$+0.128 \pm 0.109 \pm 0.024$
0.200–0.300	0.241	9.0	$+0.245 \pm 0.154 \pm 0.046$	$+0.122 \pm 0.077 \pm 0.017$
0.300–0.400	0.343	12.0	$+0.170 \pm 0.286 \pm 0.050$	$+0.047 \pm 0.080 \pm 0.010$
0.400–0.600	0.470	15.5	$+0.031 \pm 0.456 \pm 0.054$	$+0.004 \pm 0.059 \pm 0.005$

uncertainty, we have carefully analysed the variations of all detector efficiencies between pairs of data sets preceding and following a polarisation reversal. The largest possible contribution to the systematic uncertainty was then estimated by a Monte Carlo simulation using the largest efficiency variations observed within these pairs. In a second method the same variations were artificially imposed on the experimental data. The acceptance changes obtained with both methods are in good agreement and lead to an upper limit $\Delta r/r < 2 \times 10^{-3}$. The systematic error on A_1^d is then given by

$$\Delta A_1^d = \frac{1}{4 f P_\mu P_T D} \frac{\Delta r}{r} . \qquad (5)$$

Additional systematic errors arise from the uncertainties on the beam and target polarisations, the dilution factor, the radiative corrections, the momentum measurement, the depolarisation factor D, and from a small contamination of protons in the target. The individual systematic errors are combined in quadrature (table 1).

In order to check the consistency of our data, we divided them into different subsets according to a variety of criteria (e.g. data taking periods, radial vertex position, events reconstructed in different parts of the spectrometer). The asymmetries from such subsets were in agreement with each other.

The longitudinal spin structure function $g_1^d(x)$ is obtained from the asymmetry A_1^d by the relation

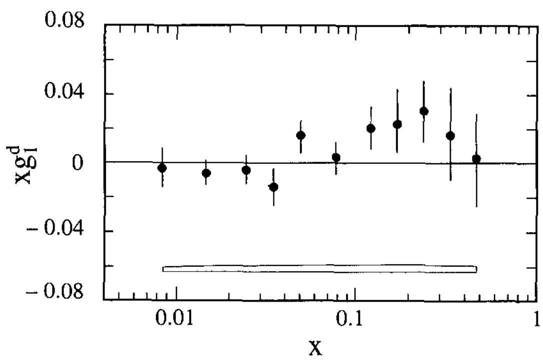

Fig. 2. The spin-dependent structure function $xg_1^d(x)$ as a function of the Bjorken scaling variable x. Only statistical errors are shown. with the data points. The size of the systematic errors is indicated by the shaded area.

$$g_1^d(x) = \frac{A_1^d(x) F_2^d(x,Q^2)}{2x[1 + R(x,Q^2)]} . \qquad (6)$$

We adopt here the convention that g_1^d and F_2^d are the average structure functions of the nucleon in the deuteron. We have taken $F_2^d(x,Q^2)$ and $R(x,Q^2)$ at the average Q^2 of the data, $Q^2 = 4.6$ GeV^2. The values of $F_2^d(x,Q^2)$ were taken from the NMC parametrisation [20] and those of R from a global fit of the SLAC data [21]. Uncertainties in F_2 and R are included in the systematic error. The results are shown in fig. 2 and are also given in table 1. The data indicate that for $x < 0.04$, g_1^d becomes negative.

The integral of g_1^d over the measured range of x is

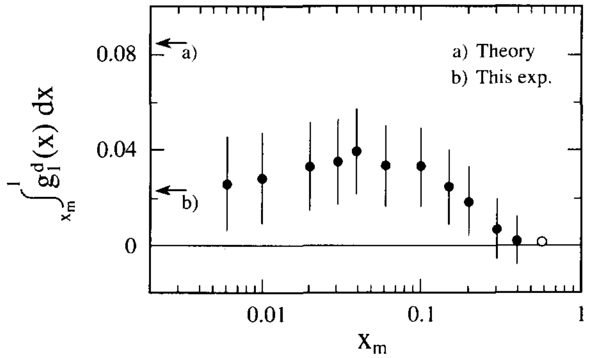

Fig. 3. The integral $\int_{x_m}^{1} g_1^d(x)\,dx$ as a function of the lower integration limit x_m. The error bars are statistical only. The open point represents the extrapolation to large x. The sum rule prediction is discussed in the text.

$$\int_{0.006}^{0.6} g_1^d(x)\,dx = 0.024 \pm 0.020\ (\text{stat.}) \pm 0.014\ (\text{syst.})\,. \tag{7}$$

To estimate the integral in the unmeasured region at small x, we fit the lowest three data points in x assuming a behaviour $g_1^d(x) \propto x^{-\alpha}$, with $-0.5 < \alpha < 0$ [22]. This contribution amounts to -0.003 ± 0.003. To estimate the integral at $x > 0.6$, we use a parametrisation which is constrained to $g_1^d(x) = 0$ at $x = 1$. To estimate the uncertainty in this extrapolation, we use the bound $|A_1| \leqslant 1$. This contribution amounts to 0.002 ± 0.004. The result for the first moment of $g_1^d(x)$ is thus (fig. 3)

$$\Gamma_1^d = \int_0^1 g_1^d(x)\,dx = 0.023 \pm 0.020\ (\text{stat.}) \pm 0.015\ (\text{syst.})\,. \tag{8}$$

The systematic errors on Γ_1^d are detailed in table 2.

The sum of the first moments of the spin structure functions $g_1(x)$ of the proton and the neutron can be computed from the measured Γ_1^d using the relation $\Gamma_1^p + \Gamma_1^n \simeq 2\Gamma_1^d/(1 - 1.5\omega_D)$, where ω_D is the probability of the deuteron to be in a D-state. Using $\omega_D = 0.058$ [23], we find $\Gamma_1^p + \Gamma_1^n = 0.049 \pm 0.044$ (stat.) $\pm$ 0.032 (syst.). The Ellis–Jaffe sum rules [3] predict $\Gamma_1^p + \Gamma_1^n = 0.187 \pm 0.010$ for ${}_s = 0.26$. This is more than 2 standard deviations above the measured value.

Table 2
Contributions to the error on Γ_1^d.

Source of the error	$\Delta\Gamma_1^d$
acceptance variation Δr	0.0130
neglect of A_2	0.0041
extrapolation at high x	0.0040
extrapolation at low x	0.0030
beam polarisation	0.0015
uncertainty on F_2	0.0012
target polarisation	0.0010
dilution factor	0.0010
radiative corrections	0.0009
kinematic resolution	0.0008
momentum measurement	0.0005
uncertainty on R	0.0005
proton background	0.0005
total systematic error	0.0148
statistics	0.0200

The value of $\Gamma_1^p + \Gamma_1^n$ can be expressed in terms of the SU(3) matrix elements a_8 and a_0 of the axial vector currents [2]. Using $a_8 = (1/\sqrt{3})(3F - D) = 0.397 \pm 0.020$ as derived from hyperon decay [24,2], we obtain

$$a_0 = 0.05 \pm 0.16\ (\text{stat.}) \pm 0.12\ (\text{syst.})\,, \tag{9}$$

in agreement with the result from the measurement of Γ_1^p: $a_0 = 0.098 \pm 0.076$ (stat.) $\pm$ 0.113 (syst.) [2]. Using a more recent analysis of hyperon decay data [25], we obtain a similar result on a_0. In the quark–parton model, a_0 is proportional to the sum of the quark spin contributions Σ to the nucleon spin. Our result corresponds to

$$\Sigma = \Delta u + \Delta d + \Delta s = 0.06 \pm 0.20\ (\text{stat.}) \pm 0.15\ (\text{syst.})\,. \tag{10}$$

Combining our result on Γ_1^d with $\Gamma_1^p = 0.126 \pm 0.010$ (stat.) $\pm$ 0.015 (syst.) from ref. [2], we can determine the first moment of the neutron spin structure function:

$$\Gamma_1^n = -0.08 \pm 0.04\ (\text{stat.}) \pm 0.04\ (\text{syst.})\,, \tag{11}$$

while the Ellis–Jaffe sum rule predicts $\Gamma_1^n = -0.002 \pm 0.005$. This allows us to test the sum rule for the difference $\Gamma_1^p - \Gamma_1^n$ that was originally found by Bjorken

[8] and later derived as a rigorous QCD prediction [26]:

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_A \left(1 - \frac{\alpha_s(Q^2)}{\pi}\right) = 0.191 \pm 0.002(12)$$

at $Q^2 = 4.6$ GeV^2. From this experiment, we find:

$$\Gamma_1^p - \Gamma_1^n = 0.20 \pm 0.05 \text{ (stat.)} \pm 0.04 \text{ (syst.)}, \quad (13)$$

in agreement with the prediction of the Bjorken sum rule.

In conclusion, we have performed the first measurement of the spin-dependent structure function g_1^d of the deuteron. The first moment of $g_1^d(x)$ is smaller than the prediction obtained from the Ellis–Jaffe sum rules and indicates that the contribution of quark spins to the nucleon spin is compatible with zero. This is similar to the observation that the EMC made for the proton. Using the EMC data, we have inferred the integral of the structure function $g_1^n(x)$ of the neutron. The difference of the first moments of the spin structure functions g_1 of the proton and the neutron is in good agreement with the prediction of the fundamental Bjorken sum rule.

References

[1] SLAC E-80, M.J. Alguard et al., Phys. Rev. Lett. 37 (1976) 1261; 41 (1978) 70;
SLAC E-130, G. Baum et al., Phys. Rev. Lett. 51 (1983) 1135;
G. Baum et al., Phys. Rev. Lett. 45 (1980) 2000.

[2] EMC Collab., J. Ashman et al., Phys. Lett. B 206 (1988) 364; Nucl. Phys. B 328 (1989) 1.

[3] J. Ellis and R.L. Jaffe, Phys. Rev. D 9 (1974) 1444; D 10 (1974) 1669.

[4] For a review, see e.g.: H. Rollnik, Proc. 9th Intern. Symp. on High energy spin physics (Bonn 1990), eds. K.-H. Althoff and W. Meyer (Springer, Berlin, 1991) Vol. 1, p. 183;
E. Reya, Dortmund preprint DO-TH 91/09.

[5] The Spin Muon Collab. (SMC), Measurement of the spin-dependent structure functions of the neutron and proton, CERN/SPSC 88-47 (SPSC/P242) (1988), unpublished.

[6] E142 Collab., R. Arnold et al., A proposal to measure the neutron spin dependent structure function, SLAC Proposal E142 (1989), unpublished;
E143 Collab., R. Arnold et al., Measurements of the nucleon spin structure at SLAC in end station A, SLAC Proposal E143, unpublished.

[7] The HERMES Collab., A Proposal to measure the spin-dependent structure functions of the neutron and the proton at HERA, DESY-PRC 90/01 (1990), unpublished.

[8] J.D. Bjorken, Phys. Rev. 148 (1966) 1467; Phys. Rev. D 1 (1970) 1376.

[9] EMC Collab., O.C. Allkofer et al., Nucl. Instrum. Methods 179 (1981) 445.

[10] NMC Collab., P. Amaudruz et al., Nucl. Phys. B 371 (1992) 3.

[11] SMC Collab., to be submitted to Nucl. Instrum. Methods.

[12] L. Gatignon, M2 Handbook (CERN, March 1991), unpublished;
L. Gatignon et al., The muon beam at the SPS, to be published in Nucl. Instrum. Methods.

[13] T.O. Niinikoski, Nucl. Instrum. Methods 192 (1982) 151.

[14] S.C. Brown et al., Proc. 4th Intern. Workshop on Polarised target materials and techniques (Bad Honnef, 1984), ed. W. Meyer, p. 102.

[15] SMC Collab., to be published.

[16] R. Brun et al., GEANT 3 Users Guide, CERN-DD (1987).

[17] V.W. Hughes and J. Kuti, Annu. Rev. Nucl. Part. Sci. 33 (1983) 611.

[18] H. Khan and P. Hoodbhoy, Phys. Lett. B 298 (1993) 181.

[19] I.V. Akushevich, N.M. Shumeiko and N.N. Tarasenko, Program "POLRAD", private communication (1992).

[20] NMC Collab., P. Amaudruz et al., Phys. Lett. B 295 (1992) 159.

[21] L.W. Whitlow et al., Phys. Lett. B 250 (1990) 193.

[22] J. Ellis and M. Karliner, Phys. Lett. B 213 (1988) 73.

[23] M. Lacombe et al., Phys. Lett. B 101 (1981) 139.

[24] M. Bourquin et al., Z. Phys. C 21 (1983) 27.

[25] Z. Dziembowski and J. Franklin, J. Phys. G: Nucl. Part. Phys. 17 (1991) 213.

[26] J. Kodaira et al., Phys. Rev. D 20 (1979) 627; Nucl. Phys. B 159 (1979) 99;
J. Kodaira, Nucl. Phys. B 165 (1980) 129.