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Abstract

The depolarization parameter D_{onon} in $\bar{p}p$ elastic scattering has been measured at LEAR for thirteen momenta between 679 and 1550 MeV/c in the backward angular region. Striking disagreement with theoretical models is observed.

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Introduction

The pre-LEAR differential cross section measurements in the $\bar{p}p$ elastic and charge exchange reactions below 2 GeV/c incident momentum, have provoked the publication of many papers [1] describing these data in terms of $\bar{N}N$ potential models. Although differing in details, all models are based on the same idea: the long range part of the potential is given by a G-parity transformed successful NN potential, to which a phenomenological short range part is added. The latter has a few free parameters, which are fixed by a fit to the available experimental data. All these models are capable of describing the differential cross section data. The real test came only, when asymmetries were measured. Experiments at CERN's Low Energy Antiproton Ring have sofar published: elastic scattering asymmetries in the momentum ranges $679 \leq p_{lab} \leq 1550$ MeV/c [2] and $439 \leq p_{lab} \leq 697$ MeV/c [3] respectively and a charge exchange asymmetry for one momentum $p_{lab} = 656$ MeV/c [4].

Astonishingly, the predictions of all models disagreed largely with the data. However, most potentials could be adapted to *postdict* the asymmetries, by choosing a suitable function for the short range part of the potential. This means that the models have little predictive power and thus shed doubts on the explanation of the physics behind the data. In fact, models that give a good fit to the elastic asymmetry data, describe very poorly the charge exchange asymmetry data and vice versa.

In this letter we present the first measurement of another spin observable in the reaction $\bar{p}p \rightarrow \bar{p}p$, the depolarization parameter D_{onon} (or shortly D_{nn}). The four indices refer to the orientation of the polarization of the scattered, recoil, beam and target particles in the reaction (following the definition of [5]).

Set-up and data acquisition

The experiment was done at LEAR. The depolarization data were taken in parallel with the data taking for the asymmetry measurement [2] using a standard polarimeter with a carbon target. We collected data in the backward angular region, where the recoiled proton has the largest energy, at several momenta between 679 and 1550 MeV/c. The experimental set-up is sketched in figure 1. The polarized target consisted of a 3 cm long cylinder, 1 cm in diameter, containing n-pentanol. Its polarization was typically 75%, with an estimated absolute accuracy of ±4%. A dummy target containing teflon was used for the evaluation of the background from quasi-elastic events on carbon and oxygen in the polarized target.

The outgoing particles were detected in three MWPCs, placed around the target. All chambers had two planes of vertical wires and at least one plane of cathode strip read-out. Two arrays of eight or nine scintillators counters, part of the event trigger, surrounded the MWPCs. The beam trigger was given by a coincidence of three beam counters placed at 24 m, 50 cm and 2 cm upstream of the target respectively. The beam intensity was typically a few times 10^5 s^{-1}. Two veto counters, mounted just above and below the target, rejected annihilation events. More details on the set-up can be found in [2].

In the left hemisphere of the set-up a polarimeter analyzed the polarization of the recoil protons. (The analyzing power of carbon for antiprotons is, unfortunately, close to zero [6].) The target of the polarimeter consisted of a variable number of one cm thick carbon plates. Most data were taken with a target thickness of six cm. The polarimeter consisted of seven MWPCs –three upstream and four downstream of the carbon target– each with horizontal and vertical wire-planes. The chambers had between 96 and 256 wires with 2 mm wire spacing. The polarimeter was positioned at an angle where it accepted mainly forward going protons coming from the polarized target, e.g. the initial scattering had $\theta_{cm} > 90°$.

Event reconstruction.

The useful events were identified in two stages. Elastic events in the polarized target were identified off-line using a reconstruction method that fitted complete two-body events to the hits in the chambers. This method is decribed in detail in [7]. Protons that traversed the polarimeter, were found by simple straight line fits in the xz- and yz-projections in the chambers before and after the polarimeter target. Two out of three chambers downstream of the carbon and three out of four chambers upstream were required to have a hit. Events were accepted for the depolarization parameter sample, if they fell within the following cuts:

- the minimum distance between the incident and scattered track less than 4 mm;
- $|v_z| < 60$ mm, where v_z is the longitudinal coordinate of the reconstructed vertex;
- the proton scattering angle θ_C between 3° and 25°;
- no second track in the polarimeter.
- χ^2 per degree of freedom for the reconstruction of the elastic scattering less then 10.

These cuts resulted in samples of 150 to 1200 events per momentum. About 0.8% of all elastically scattered events had a useful second scattering in the carbon target. The final results do not appear to be very sensitive to these cuts. As described in the next section, we assigned to each event a weight, which depended principally on the analyzing power of carbon for the event, and thus on the scattering angle. Varying the cut on the scattering angle in the range from 2° to 4° does change the number of accepted events by a factor two, but changes hardly their total weight, as below 4° the analyzing power drops quickly to zero.

The vertex cut assures a scattering on carbon. Although events with small scattering angles have a badly defined vertex (the resolution deteriorates from 20 mm at 16° to 60 mm at 3°), these events do not influence much the result, just because of their small scattering angle and hence small weight.

Evaluation of D_{nn}

The depolarization parameter was extracted from the final data sample by a method of weighted events. Such a method avoids cuts to symmetrize the geometrical acceptance as well as lenghty Monte Carlo calculations to determine an asymmetrical one. In our case of rather low statistics it is therefore suitable.

In the following the subscripts H and C refer to the scattering of the antiproton on hydrogen and the scattering of the proton on carbon, respectively. The numbers of good events N^+ and N^-, counted with target polarization up and down respectively, that are found in a certain bin around the four scattering angles θ_H, ϕ_H (in the center of mass system) θ_C and ϕ_C (in the laboratory system) are given by

$$\begin{aligned} N^{\pm}\ (\theta_H,\phi_H,\theta_C,\phi_C)\ \propto\ \eta\sigma_C\sigma_H\ (1+A_H(\theta_H)P^{\pm}\cos\phi_H)\times \\ (1+\ e_n^{\pm}\ P_C(\theta_C)\cos\phi_C -\ e_s^{\pm}\ P_C(\theta_C)\sin\phi_C) \end{aligned} \quad (1)$$

where

η is the geometrical acceptance of the bin (dependent in general on the all four scattering angles, the polarimeter position and the incident antiproton momentum;
σ_C and σ_H are the unpolarized cross-sections on carbon and hydrogen respectively;
$A_H(\theta_H)$ is the asymmetry parameter A_{ooon} due to the first scattering and depends on the incident momentum and the scattering angle θ_H of the *first* scattering;
$P_C(\theta_C)$ is the analyzing power of carbon and depends on the recoil momentum of the proton and the scattering angle θ_C of the *second* scattering;
P^+ and P^- are the target polarizations, averaged over the events in the bin.

The asymmetries $e_n^{\pm}$ and $e_s^{\pm}$ that occur in the expression may be expressed as functions of the two depolarization parameters D_{nn} and D_{ss}:

$$e_n^{\pm} = \frac{A_H(\theta_H) + D_{nn}P^{\pm}\cos\phi_H}{1 + A_H(\theta_H)P^{\pm}\cos\phi_H} \qquad e_s^{\pm} = \frac{-D_{ss}P^{\pm}\sin\phi_H}{1 + A_H(\theta_H)P^{\pm}\cos\phi_H} \tag{2}$$

To eliminate the unknown geometrical acceptance η we introduce the asymmetry

$$\epsilon = -\frac{N^+ - N^-}{P^-N^+ - P^+N^-} \tag{3}$$

Substituting (1) into (3), we see that ϵ is linearly dependent on D_{nn} and D_{ss}:

$$\epsilon = A + BD_{nn} + CD_{ss} \tag{4}$$

where

$$A = \frac{1}{\Delta}A_H\cos\phi_H \qquad C = \frac{1}{\Delta}P_C\sin\phi_H\sin\phi_C$$
$$B = \frac{1}{\Delta}P_C\cos\phi_H\cos\phi_C \qquad \Delta = 1 + A_HP_C\cos\phi_C \tag{5}$$

The term CD_{ss} is proportional to $\sin\phi_H$ and may be dropped since the scattering on the polarized target is essentially in the horizontal plane. Then for each bin centered around $(\theta_H, \phi_H, \theta_C, \phi_C)$ an estimator for D_{nn} is constructed in terms of ϵ as

$$\hat{D}_{nn} = \frac{\sum w_{bin}D_{bin}}{\sum w_{bin}} = \frac{\sum w_{bin}\frac{\epsilon - A}{B}}{\sum w_{bin}} \tag{6}$$

where

$$w_{bin} = (\sigma^2_{D_{bin}})^{-1} \tag{7}$$

Although ϵ is defined in terms of event numbers in a bin of finite size, one can imagine shrinking the bins to contain at most one event. Equation 3 then reduces to $\epsilon = 1/P_{ev}$, where P_{ev} is the target polarization for the event. This leads to

$$D_{ev} = \frac{1}{B}\left(\frac{1}{P_{ev}} - A\right)$$
$$w_{ev} = \frac{1}{4}P_{ev}^2B^2 = \frac{1}{4}\frac{P_C^2P_{ev}^2\cos^2\phi_H\cos^2\phi_C}{(1 + A_HP_C\cos\phi_C)^2} \tag{8}$$

Substituting these expressions in the formula for $\hat{D}_{nn}$ (equation 6), we obtain the expression

$$\hat{D}_{nn} = \frac{\sum PB - \sum P^2BA}{\sum P^2B^2} \tag{9}$$

so that $\hat{D}_{nn}$ is obtained as a weighted sum over the events.

In the derivation we assumed that the number of incoming antiprotons on the polarized target is equal for polarization up and down. If $B^+ \neq B^-$ the formalism is still valid if we replace N^+ by N^+/B^+ etc. This implies that the weight of all events taken with positive target polarization are multiplied by $(B^-/B^+)^2$ and all events with negative target polarization by $(B^+/B^-)^2$ when summing over the events.

The subtraction of the background due to scattering on protons bound in carbon and oxygen nuclei in the polarized target, gives a similar change. The event weight changes by a factor f^2, where f is the ratio "signal" over "signal plus background" in the χ^2 bin in which the event falls in the overall kinematic fit of the elastic scattering in the polarized target. The background amounted to about 10-15% and was evaluated from runs at 1089 and 1434 MeV/c with the dummy target.

The assumption that D_{ss} may be ignored in our data has been checked, by evaluating D_{nn} with D_{ss} put to either -1 or +1. This shows indeed very small differences with the results obtained for $D_{ss} = 0$.

The method to extract D_{nn} from the data was tested using a Monte Carlo method. Events were generated with a given D_{nn} and D_{ss} and $\hat{D}_{nn}$ was calculated from the event numbers. This showed that the estimator is unbiased only if the average target polarizations P^+ and P^- are equal. In our data this is not strictly the case, but the difference of the two polarizations (a few percent) is small enough, to cause a bias much smaller than the statistical errors.

To show that the data sample used to evaluate D_{nn}, is not biased by the reconstruction and the cuts, we calculated the asymmetry of the elastic scattering with this sample and with a similar method of weighted events. Within errors the results are consistent with those of [2].

In the evaluation of the D parameter the asymmetry A_H was taken from the Legendre fits to our asymmetry data. The analyzing power of carbon P_C was calculated from the high energy parametrization given in [8].

Results and comparison with theoretical models.

Data with the polarimeter were taken for all momenta between 679 and 1550 MeV/c, where we measured the asymmetry parameter. The events were summed for each momentum in five bins between $-1 < \cos\theta_{cm} < 0$. In each bin the weighted value of $\cos\theta_{cm}$ was also calculated. All data points having statistical errors smaller than 1 are listed in table 1. This cut on the error leaves 23 data points for 10 momenta. The four momenta that have the best statistics are shown in figure 2 and compared with the predictions of four models: Dover–Richard model I [9], Bonn model A [10], the Nijmegen P-model [11] and the Paris model [12]. The Dover–Richard model is calculated using relativistic kinematics. Of the three Bonn models, model A compares best to our asymmetry data. Model B and C do slightly better in predicting the depolarization parameter. The Nijmegen model and the Paris model have their parameters adjusted, taking the available elastic asymmetry data into account, as well as the pre-LEAR differential cross section data.

The model predictions differ greatly from the data. The trend of *all* models is a value of D_{nn} close to unity over the whole angular range except in the neighbourhood of the minima in the differential cross sections. The difference becomes even more striking, if the events are summed over the whole backward angular region. In figure 3 this is done and the data are shown as a function of momentum to show their energy dependence and compared with the Dover-Richard model I. The sum corresponds to the value of D_{nn} at about cos $\theta_{cm} = -0.5$ as the weighted event distribution peaks at that value. In figure 3 one can see the dip in D_{nn} corresponding to the diffraction minimum in $d\sigma/d\Omega$ cross cos $\theta_{cm} = -0.5$ at about $p_{lab} = 1350$ MeV/c.

The data indicate that D_{nn} is close to zero for cos $\theta_{cm} = -0.5$. Parametrizing the scattering matrix M in terms of the five complex amplitudes a,b,c,d,e [5]

$$\begin{aligned} M(\vec{\sigma}_1,\vec{\sigma}_2) = \frac{1}{2} \; [\; (a+b) \; + \; (a-b)(\vec{\sigma}_1\vec{n})(\vec{\sigma}_2\vec{n}) \\ + \; (c+d)(\vec{\sigma}_1\vec{m})(\vec{\sigma}_2\vec{m}) \; - \; (c-d)(\vec{\sigma}_1\vec{l})(\vec{\sigma}_2\vec{l}) \\ + \; e(\vec{\sigma}_1+\vec{\sigma}_2)\vec{n} \;] \end{aligned} \tag{10}$$

the depolarization parameter may be expressed as

$$\frac{d\sigma}{d\Omega}\,(1-D_{nn}) = |c|^2 + |d|^2 \tag{11}$$

We conclude that, although the models predict D_{nn} to be close to one over most of the angular range –implying that c and d are relatively small–, the experimental data seem to indicate otherwise. This disagreement obviously calls for a more accurate remeasurement of this and other spin observables in $\bar{p}p$ elastic scattering.

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Table 1

p (MeV/c)	number of events	$< \cos\theta_{cm} >$	D_{onon}
679	367	-0.491	-0.169±.465
783	111	-0.625	0.828±.668
	907	-0.487	0.054±.251
	180	-0.368	-0.009±.648
886	158	-0.653	-0.077±.661
988	242	-0.689	-0.669±.491
	353	-0.503	-0.098±.389
	428	-0.297	-0.441±.367
1089	195	-0.683	0.321±.685
	265	-0.499	-0.385±.550
	373	-0.298	-0.304±.408
1291	107	-0.711	1.185±.957
	141	-0.496	0.705±.763
	200	-0.289	0.967±.530
	59	-0.166	0.052±.991
1359	107	-0.698	-0.675±.791
	175	-0.488	-0.230±.791
	164	-0.291	0.171±.529
	103	-0.165	-0.942±.741
1400	103	-0.289	-0.498±.921
1416	102	-0.290	1.212±.889
1501	105	-0.697	-0.031±.880
	128	-0.295	0.369±.870

Table 1. All D_{onon} data points are calculated summing over bins of width 0.2 between $-1 < \cos\theta_{cm} < 0$, using the method of weighted events described in the text. The value of $\cos\theta_{cm}$ given is the weighted average over the events in the bin. Only points with a statistical error smaller than one are tabulated.

Figure 1. Schematic view of the experimental setup.
B,J,C,L,R: multiple wire proportional chambers; HL,HR: hodoscope counters; M: polarized target magnet; T: cryostat with polarized target; polarimeter: multiple wire proportional chambers of polarimeter; carbon: carbon target of polarimeter. Superimposed is an elastic event with scattering angle θ_H (in the laboratory frame) for the elastic interaction and scattering angle θ_C for the scattering on carbon.

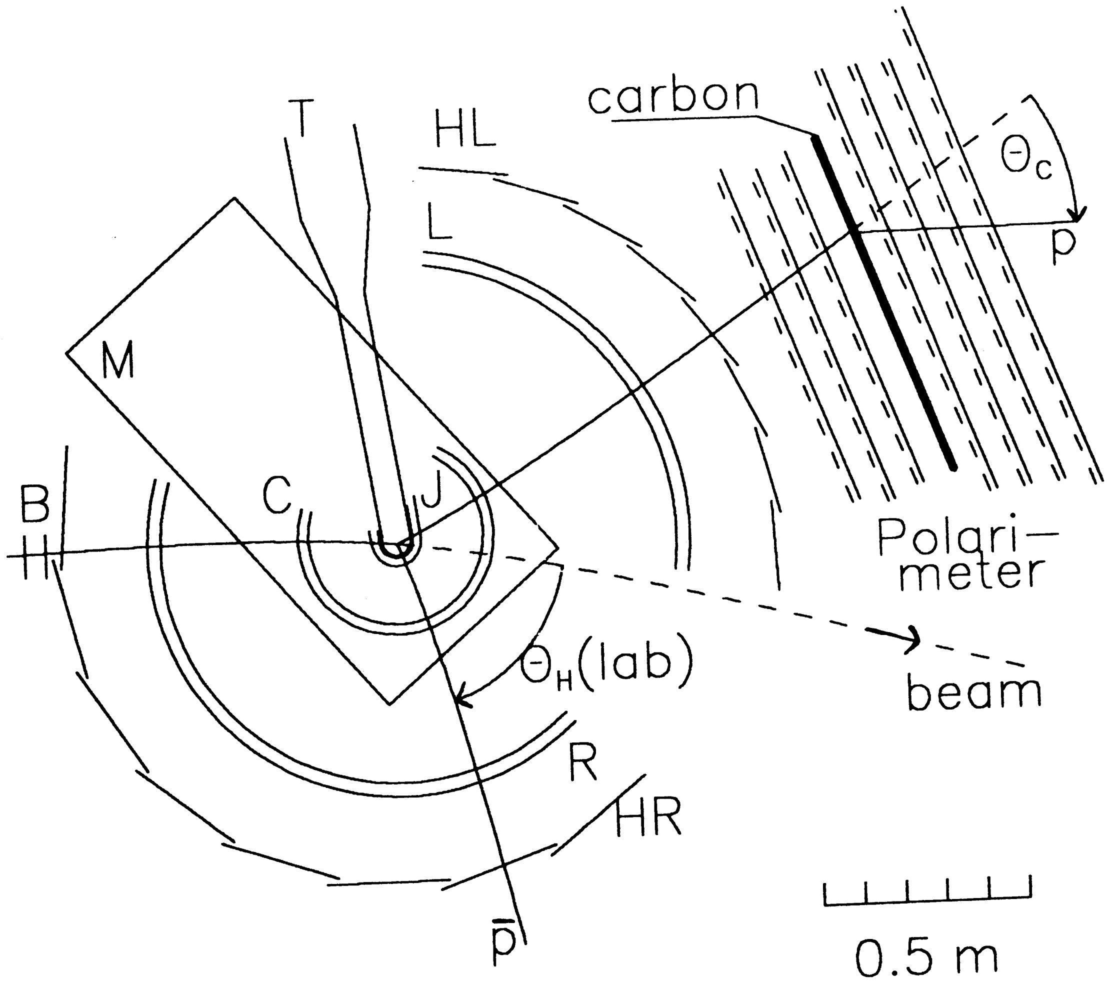

Figure 2. D_{onon} as a function of $\cos\theta_{cm}$ for the four momenta with the best statistics. The curves are the predictions of the relativistic Dover-Richard I model (solid line) [9], the Bonn model A (dashed line) [10], the Nijmegen P-model (dashed-dotted line) [11] and the Paris model (dotted line) [12].

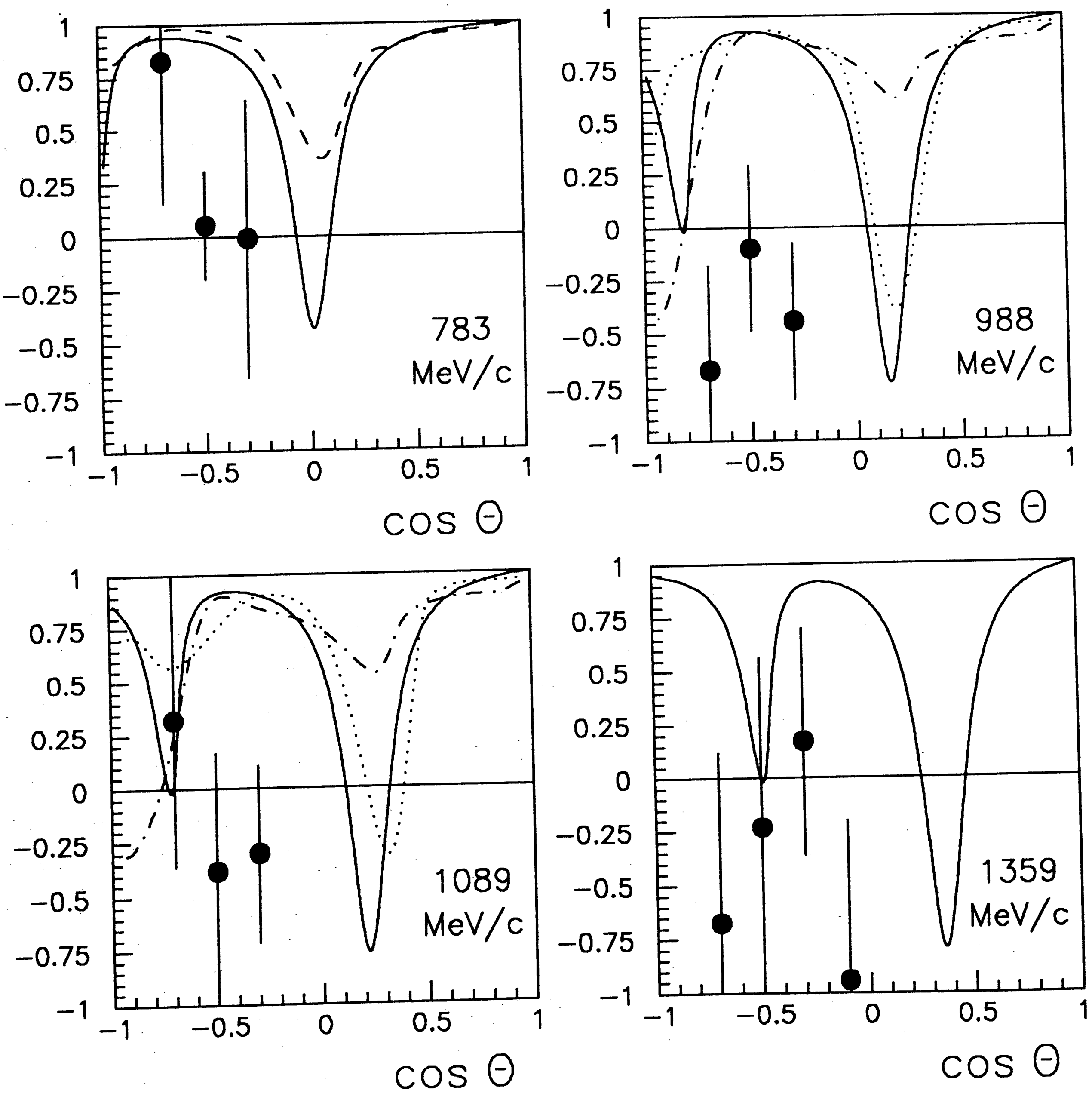

Figure 3. D_{onon} as a function of momentum for $\cos\theta_{cm} \approx -0.5$. The data are obtained by summing over the whole backward angular region per momentum. Furthermore, the data of 1400, 1416, 1449 MeV/c and 1467, 1501, 1550 MeV/c were summed to give the two points at 1415 and 1500 MeV/c respectively. The solid line is the prediction of Dover Richard model I [9].