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EXPERIMENTAL LIMITS ON CHARGE INDEPENDENCE AND SYMMETRY OF STRONG INTERACTIONS AT INTERMEDIATE ENERGY

Luigi SATTA

INFN - Laboratori Nazionali di Frascati, P.O. Box 13, 00044 Frascati, Roma, Italy

Charge independence and charge symmetry are the first invariance principles formulated in an abstract space, distinct from ordinary space-time, introduced in physics. These symmetries applied originally to nucleons bounded in nuclei. Then they were generalized to all hadrons, elementary or composite. In this paper a few experimental problems connected with the validity limits of these principles are reviewed. Particular attention is devoted to the reaction $d+d \rightarrow {}^4He+\pi^\circ$, presently under study at the Laboratoire National Saturne in Saclay, with the participation of the author.

1. INTRODUCTION

The first formulation of the charge independence of strong interactions dates back to about 1930, with the experimental observation that the forces acting between protons and neutrons in pp and np elastic scattering are approximately equal, if the coulomb interaction is subtracted.

In 1936 Condon and Cassen[1] gave the current formal treatment of charge independence for the nucleon-nucleon system using the isospin variable previously introduced by Heisenberg[2]. In their treatment the nn, np and pp interactions were assumed to be the same, although no experimental data on nn scattering were available. In 1938 the isospin concept was extended to pions by Kemmer[3]. As a consequence of this generalization, the existence of the neutral pion, at that time still unknown, was predicted.

The easiest example of isospin treatment is for the p-n system. These two particles are represented as two states of the same object, the nucleon, as

$$X_p = \binom{1}{0} \qquad X_n = \binom{0}{1}$$

The algebra operating on these states is identical to the one for 1/2 spin particles, and the properties of the isospin operators are the same as those of angular momentum. For nucleons they are the Pauli matrices, and the generalization to more complex systems is straightforward.

Let $\underline{T}$ represent the total isospin operator of a system of hadrons. The request of charge independence is equivalent to that of isotropy of the isospin space and is expressed by the commutation of the system hamiltonian H_s with $\underline{T}, [H_s, \underline{T}] = 0$. The formal analogy with angular momentum is complete, and the stationary states of the system are degenerate multiplets. For nucleons this means that the forces acting between p-n, p-p, n-n are indistinguishables as long as the nucleons are in the same space and spin states.

Charge symmetry is a less stringent request on the properties of the isospin space. It is equivalent to the invariance for reflection through a plane perpendicular to the isospin quantization axis, usually indicated as T_3. The corresponding operator is $P_{cs} = \exp[i\pi T_2]$, and charge symmetry is expressed as $[P_{cs}, H_s] = 0$. For nucleons this commutation relation implies only that the forces acting between n-n and p-p are the same.

Both these symmetries are assumed valid for strong interactions, and are known to be violated by electromagnetic and weak interactions. Neglecting weak effects, the e.m. ones are expected to be small perturbations, of order α, by means of which the details of the strong interactions can be studied. They are currently classified in two categories: direct and indirect effects, which are defined as follows. The first ones are e.m. effects that would be present even if the strong interaction could be switched off. They are for instance due to the neutron-proton mass difference, or to the magnetic interaction between nucleons, and are, at least in principle, well known and calculable .

In opposition, the indirect effects are intimately bound to the strong interaction, and would vanish if it could be switched off. A well known example is the term induced by the neutron-proton mass difference at the πNN vertex. These effects, unfurtunately, can not be calculated reliably, even in principle.

Thus, the problem of the experimental verification of charge independence or charge symmetry is a subtle one: one has to compare the data, corrected for indirect effects, to the expectations in absence of direct effects.

This rapid survey of isospin definition and treatment, which could be called "classical", misses an essential point: why does the strong interaction exhibit this symmetry? Or, differently stated, can it be justified at the quark level? The answer to these questions is as yet unknown. In the QCD lagrangian the only explicit dependence from the quark flavors is through the mass term $\Sigma_f m_f \Psi_f \overline{\Psi}_f$. If one considers only the d and u quarks, which are the most relevant for nuclear physics, a global SU(2) symmetry appears naturally if the masses of the d and u current quarks are the same. But it is known that $\{(m_u - m_d)/\langle m \rangle\}_{cur}$ is O(1), and one expects that isospin is badly broken. On the other hand, at distances greater than Λ_{QCD} current quarks evolve into constituent quarks, with $m_u \simeq m_d \simeq 300$ MeV, restoring isospin symmetry. From this point of view, isospin symmetry could be accidental[4].

These qualitative considerations reflect the duality of our present description of low energy hadron physics. The experimental study of charge independence and symmetry can contribute valuable information for a deeper understanding of the problem.

In the following I will review the experimental limits on the validity of these symmetries, beginning with the results derived from the static properties of nuclei and from low energy measurement. Then I will spend a few more words on recent measurements in the intermediate energy region.

2. STATIC PROPERTIES OF NUCLEI AND LOW ENERGY MEASUREMENTS

The binding energies of mirror nuclei should be the same if charge symmetry holds, a part from a direct coulomb correction due to the extra proton in one of the two nuclei. This is approximately true, but, as a general rule, the coulomb correction that is calculated does not explain the measured differences. Of course, the reliability of the calculation decreases as the number of nucleons increases, and for this reason a good deal of theoretical work has been performed on the simplest couple of mirror nuclei: ^{3}H and ^{3}He. In essence the experimental difference between the binding energies of these nuclei is 764 keV, while the calculated one is 680 keV.

Are these missing 84 keV a clear indication that charge symmetry is broken? It might be, but one should remember two facts. From one side the calculation of the binding energy, even for three bodies, is quite complicated. From the other side no mechanism that has been invented up to now is able to account, even approximately, of the 84 keV. In this sense the indications coming from the study of mirror nuclei do not give a conclusive answer.

In the low energy field the validity of charge independence and symmetry has been extensively studied by means of the nucleon-nucleon scattering. Low energy scattering is completely characterized by two parameters: the scattering length a and the effective range r_o.

If the potentials between p-p, n-n and n-p are the same, the a's and the r_o's of these three systems must also be the same.

The scattering length is of particular interest, since the two nucleon system tends to bind, as shown by the existence of the deuteron. For this reason, a small difference in the interaction strength between the two nucleons shows up as a great variation of the scattering length.

From the experimental point of view a_{pp} and a_{np} can be accurately determined with relative easy. The measurement of a_{nn} is complicated, since there are no free neutron targets. It must be deduced from the study of three body final states with two neutrons, as those of the reactions $\pi^- d \to nn\gamma$ or $nd \to nnp$. Besides, the comparison between experimental results is furthermore complicated by the relevant e.m. correction that must be applied to the pp scattering.

I quote the following world averages from Ref. 5:

$$a_{nn} = -16.6 \pm 1.2 \text{ fm}$$
$$a_{np} = -23.74 \pm 0.01 \text{ fm}$$
$$a_{pp} = -17.9 \pm 2 \text{ fm}$$

Comparing a_{nn} and a_{pp}, charge symmetry seems to be valid between errors, but it is worth noting that the measured value of a_{pp} is -7.8 fm, so that the coulomb correction is 140%.

Comparing a_{np} with the other two values, there seems to be a clear violation of charge independence. But, as usual, the e.m. corrections (this time indirect) must be evaluated and, via the same mechanism that makes the scattering length sensitive to small differences in the interaction potential, a small error in the calculation of these corrections is amplified and can cause a great difference in the scattering lengths.

Moreover a recent measurement of a_{nn} performed at SIN with the reaction $\pi^- d \to nn\gamma$[6] gives $a_{nn} = -18.5 \pm 0.5$ in disagreement with the previous world average.

From this rapid survey it appears that the low energy data can not provide a definitive answer to the problem of the limits of validity of charge independence and symmetry.

3. INTERMEDIATE ENERGY MEASUREMENTS

In the uncertainty of the low energy situation described above, since the appearance of good beams of protons, neutrons and light nuclei at intermediate energy, the research has turned toward the study of reactions where the coulomb corrections are expected to be small, or where the observation of an unambiguous violation could be possible.

I will now rapidly present the results of a few experiments in this field. Then I will discuss a recent measurement where for the first time a clear violation of charge symmetry has been observed, and I will end up with a somewhat more detailed presentation of the experiment on the dd $\rightarrow {}^4He\pi^\circ$ reaction, where I am directly engaged.

It is to be noted that the majority of the reactions to be considered is concerned with charge symmetry. This is natural, since a violation of charge independence is expected a priori from the fact that nn or pp can only exchange π°, while np can exchange charged and neutral pions, whose masses are different. This is well known but is difficult to take properly into account, and could mask more interesting effects.

3.1. Comparison of the total π^+p and π^-p cross sections

The amplitudes of equal isotopic spin of these reactions should be the same, if charge independence holds. There is a very precise measurement[7], in the energy region around the excitation of the $\Delta(1232)$. The authors claim to observe a 1.5% violation of charge symmetry. This result is not completely clean, since the isolation of the T=3/2 amplitude is ambiguous.

3.2 Comparison of the pd $\rightarrow {}^3H\pi^+$ and pd $\rightarrow {}^3He\pi^\circ$ reactions

a) Charge independence, through simple decomposition in isospin states, imposes that the cross sections ratio be 2. Coulomb corrections bring this ratio to 2.2±0.07. There are several measurements, whose results range between 2.13±0.06 and 2.36±0.11[8].

b) Since the coulomb interaction is intrinsecally scalar, the polarization observables should be only partially affected by the direct e.m. effects. There is a recent measurement of the percentual difference of the proton asymmetry of the two reactions, performed with polarized proton at 733 MeV and at 12° of the recoiling nucleus[9]. The result is $\frac{\Delta A}{A}$ = (1.63±1±0.46)%.

3.3. Comparison of the total π^+d and π^-d cross sections

If charge symmetry holds, the cross sections must be equal. From the measurement quoted in (7) it appears that the difference between the cross sections for π^- and π^+ oscillates between -12 mb and +5 mb when the incident pion energy crosses the region of excitation of the $\Delta(1232)$.

3.4. Comparison of the angular distributions for the elastic scattering of π^+ and π^- on deuterons.

Again for charge symmetry these angular distributions must be identical. There are several measurements[10], performed at different energies and at angles varying between 30° and 150° in the center of mass. The asymmetry, defined as $A(\theta) = \frac{\sigma^- - \sigma^+}{\sigma^+ + \sigma^-}$ varies from 0 to 5%.

Taken at face value, points 3.3 and 3.4 indicate a clear charge symmetry violation. Nevertheless one must remember that even if the π^+ and π^- have the same initial energy, the actual scattering of the two particles takes place at different energies, since the coulomb interaction with the deuteron is different for the π^+ and the π^-. The ensuing correction is by no means obvious to calculate.

3.5. Comparison of the elastic cross section of π^+ and π^- on ^3H and ^3He.

Always because of charge symmetry these four cross sections must be identical. The ratio

$$R = \frac{\pi^+ \, ^3H}{\pi^- \, ^3He} \quad \frac{\pi^- \, ^3H}{\pi^+ \, ^3He}$$

has been recently measured[11]. R should be, at least at first approximation, free from the problem outlined for points 3.3 and 3.4. The result, obtained with incident pions of 180 MeV kinetic energy, is that R varies with the angle from 1 to 1.3. This last value corresponds to a pion scattering angle of 65° in the laboratory.

3.6. Forward-backward asymmetry in the reaction $np \to d\pi^\circ$.

If charge symmetry holds, this reaction must be identical to the $pp \to d\pi^+$ reaction, which is symmetric in the two center of mass hemispheres, since the particles in the initial state are identical. The existence of a non charge symmetric term in the amplitude of $np \to d\pi^\circ$ can intodruce an asymmetry in the angular distribution.

Two remarks are in order here:

a) in this reaction there is no direct term capable of producing the asymmetry;

b) the theoretical estimates[12] attribute the possible asymmetry (which is always very small) essentially to a term where an η meson exchanged between the nucleons becomes a π° before being reabsorbed.

The asymmetry, defined as

$$A_{fb} = \frac{\int_0^{\pi/2}\sigma d\theta - \int_{\pi/2}^{\pi}\sigma d\theta}{\int_0^{\pi}\gamma d\theta}$$

has been measured a few years ago[13], and is consistent with zero: $A_{fb} = -(0.15 \pm 0.50)\%$. The theoretical estimates for A_{fb} vary around 0.10%.

A new measurement of A_{fb} is presently underway at TRIUMF, aimed at a precision on order of magnitude better.

I will now discuss the only experiment[14] which has up to now measured a charge symmetry violation beyond any reasonable doubt.

The experiment compares the proton and veutron asymmetry in the elastic np scattering. If charge symmetry holds, the two asymmetries must be the same, as can be seen from Fig. 1[15]. At left is sketched the scattering at an angle θ

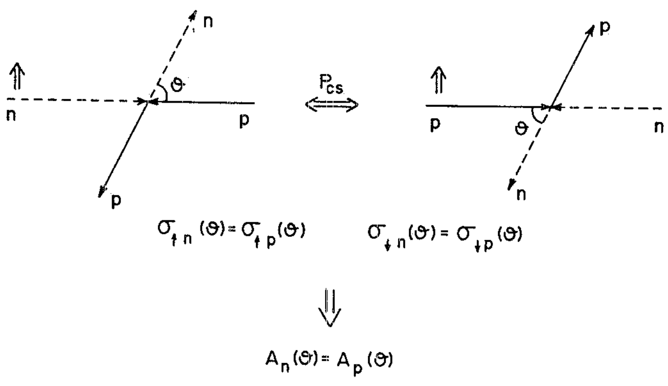

FIGURE 1
The drawing gives an intuitive account of the fact that, if charge symmetry holds, the proton and neutron asymmetries must be the same in the reactions $\vec{n}p \to np$ and $n\vec{p} \to np$

in the center of mass of a polarized neutron on a proton. By means of the charge symmetry operator this reaction is transformed to the one sketched at right, which is the scattering, always at the angle θ, of a neutron on a polarized proton. The two cross sections must be the same for any spin orientation, that is An=Ap.

The experiment measures the neutron asymmetry with a polarized neutron beam and a non polarized proton target, and the proton asymmetry with a non polarized neutron beam and a polarized proton target. This difficult experiment has been performed at TRIUMF at T_n=477 MeV. The actual measurement is the difference of the neutron and proton asymmetries, at an angle where it crosses zero. That way the result does not depend very much on a precise knowledge of beam and target polarization.

The measured value is

$$\Delta A = (37 \pm 17 \pm 8) \times 10^{-4}$$

Its interpretation is complicated by the fact that the direct exchange of a photon can make ΔA different from zero. The calculations show that in the angular region of the measurement the contribution of this term is quite small. The theoretical interpretation[16] of this result is that the main contribution to ΔA comes from the pion exchange term, with a symmetry violation at the πNN vertex. It does not seem, therefore, that from this measurement information at the quark structure level can be easily obtained.

As a last point I will present the result of a measurement of the $dd \to {}^4He\pi^0$ reaction, which is still going on in Saclay. This reaction is doubly forbidden. From charge independence, since the isospin of the initial state is zero, while that of the final state is one. From charge symmetry, since deuteron and ^4He are self-conjugated states with eigenvalue of P_{cs}+1, while the π^0 has eigenvalue -1.

There are several estimates of the cross section of this process, but I shall quote only one[17], which, although phenomenological, seems to be a good approximation of reality. According to this model, the reaction proceeds as shown in Fig. 2.

At first an η meson is produced (the reaction $dd \to {}^4He\eta$ is allowed), which transforms into a π^0 via the $\Delta I=1$ transition matrix element $\langle\pi^0|H|\eta\rangle$.

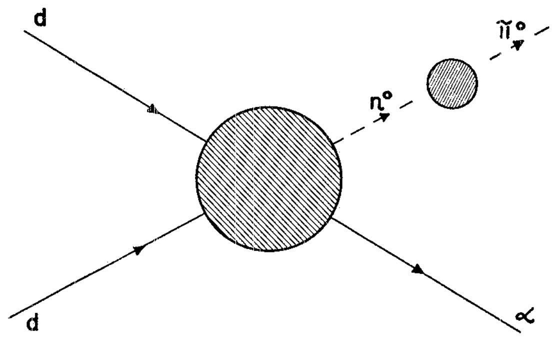

FIGURE 2
The graph shows one of the proposed mechanism for the $dd \to {}^4He\pi^\circ$ reaction

In this scheme the cross section for π° production is proportional to that for η production times the squared modulus of the $\pi^\circ \leftrightarrow \eta$ matrix element. The authors of ref. 17 estimated the π° cross section by means of the only published measurement of η production[18] and a theoretical evaluation of $\langle\pi^\circ|H|\eta\rangle$. In the kinematical region where the η was measured (T_d=1.95 GeV), θ^*_η=146°) the π° should have a cross section of 0.12 pbarn. This is a very small number, but, according to this model, the observation of the π° would be a direct measurement of $|\langle\pi^\circ|H|\eta\rangle|^2$. At present its numerical value can only be deduced from the decay $\eta \to 3\pi^\circ$ and $\eta' \to 3\pi^\circ$, in a rather complicated and indirect way.

It must be stressed that it is interesting to know the $\pi^\circ \leftrightarrow \eta$ matrix element, since the e.m. contribution to the $\pi \leftrightarrow \eta$ mixing should be small, and the purely hadronic component of the matrix element, according to various models, is simply connected to the u and d quark mass difference[19].

The measurement of the $dd \to {}^4He\pi^\circ$ reaction has been attempted several times. In table I a summary of the existing measurements is reported.

Without discussing in detail these measurements, they have all been performed with a single arm magnetic spectrometer where the ^4He is detected. The existence of the π° is deduced from the kinematics. All these measurements detected a few π°, which were still present when the deuteron target was replaced by a hydrogen target.

The next step is to add a photon detector to identify the π° in coincidence with the ^4He.

TABLE I

T_d(GeV)	θ_{CM}	$d\sigma/d\Omega$(pb/sr)	Reference 20
0.4	45°	7×10^3	Akimov (1960)
0.4	55°	1.3×10^3	Akimov (1961)
0.4	55°	9×10^2	Akimov (1962)
0.46	90°	1.8×10^3	Poirier (1961)
0.46	90°	97	Poirier (1963)
0.79	79°	19	Banaigs (1974)

This measurement is underway at the Laboratoire National Saturne in Saclay. The members of the collaboration are listed in ref. 21. In the following I will describe the result obtained in the first part of the experiment.

The apparatus is shown in Fig. 3. It is composed of a magnetic double focusing spectrometer (SPES IV), where particles are identified by the combined measurement of time of flight between the intermediate and final images and dE/dx in the plastic scintillator counters indicated in a). Typical figures of the spectrometers are a momentum resolution of 0.2% over a range of ±4%

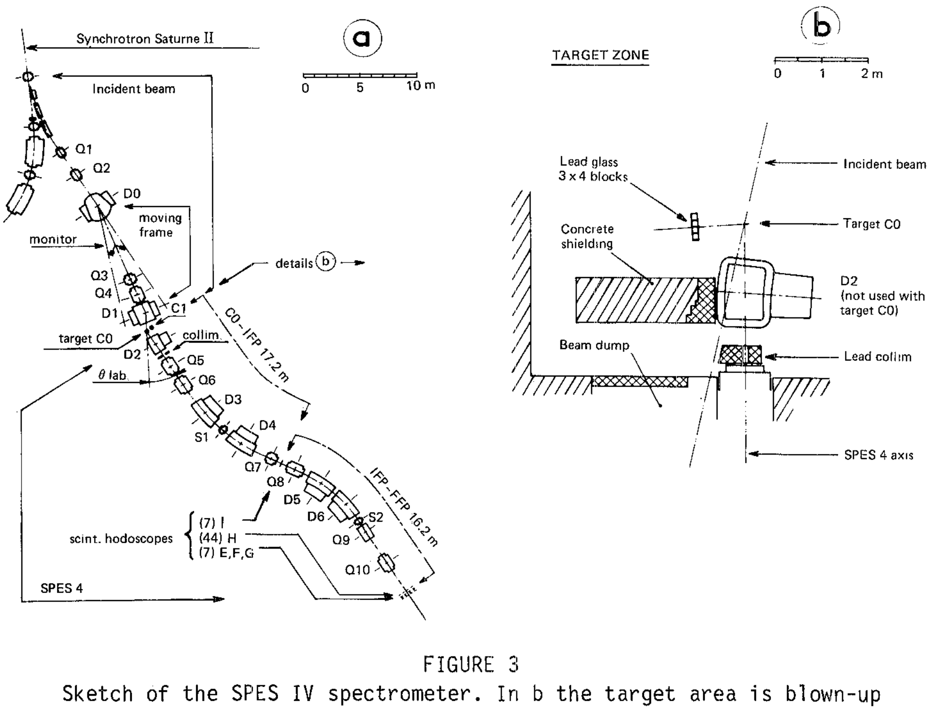

FIGURE 3
Sketch of the SPES IV spectrometer. In b the target area is blown-up

with respect to the central trajectory. In b) it is indicated where the photon detector has been installed. In the measurement I am describing it was composed of 12 lead glass counters of 15x15x15 cm^3. In the final measurement we used a lead glass wall with a surface area of 1 m^2 and 10 radiation length depth.

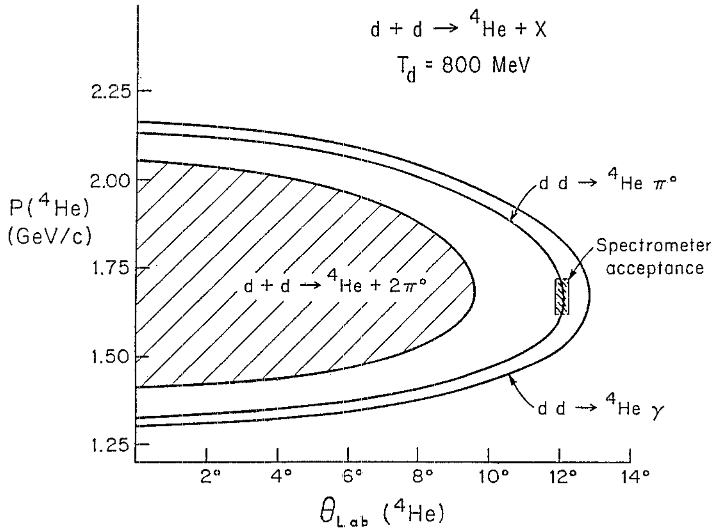

FIGURE 4
Kinematics of the dd → ^{4}Heπ° and nearby reactions. The dashed rectangle indicates the spectrometer acceptance.

Fig. 4 shows the kinematics of the dd → ^{4}Heπ° together with that of the physical background. The spectrometer acceptance is set at the maximum of the kinematics, where the jacobian is highest, to exploit the large Lorentz transformation factor from the laboratory to the center of mass system.

Fig. 5 shows a blow-up of the kinematics, with the four angular settings of the measurement, indicated by the arrows. As can be seen one angle is centered on the kinematics of the dd → ^{4}Heγ, one is centered where the π° is expected, and two are off kinematics, to explore the background as a function of the angle. The π° is well separated in angle from the neighbouring reactions, much more than the spectrometer angular resolution. But one must remind that the two π° are produced at threshold with a cross section of the order of the μbarn (ABC effect). At the level of a fraction of a picobarn, where the experi-

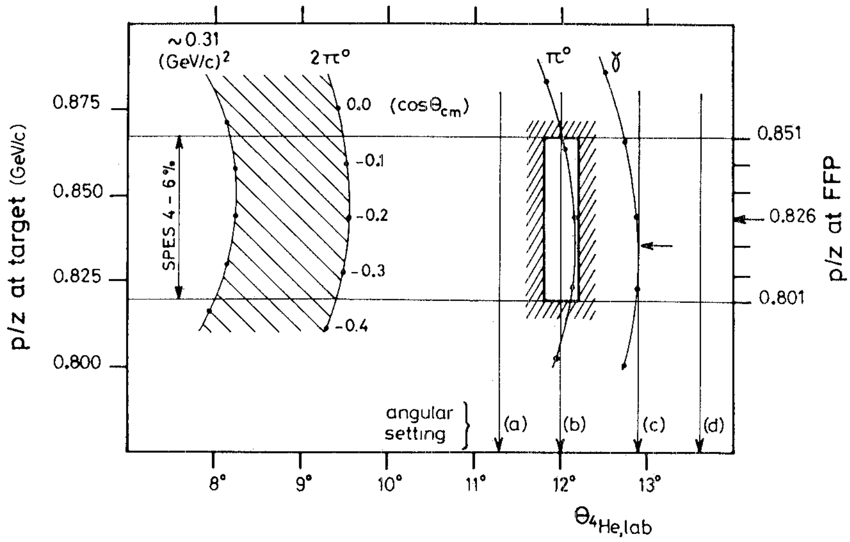

FIGURE 5
Detail of the maximum of the kinematics of Fig. 4. The actual angular settings are indicated by the arrows.

ment is aimed at, the effects of nuclear rescattering, by which the ^{4}He can be driven at an angle greater than that allowed by the kinematics, become important. These rescatterings inside the target account rather well for the shape of the background measured at the smallest angle. This can be seen in section a) of Fig. 6, where the final event sample is shown as a function of the energy of the detected photon, at the four measured angles. The continuous curve of section a) shows the result of a Monte Carlo calculation based on the processes

$$dd \to dx$$
$$dd \to {}^4\mathrm{He}\ 2\pi^\circ$$

and

$$dd \to {}^4\mathrm{He}\ 2\pi^\circ$$
$${}^4\mathrm{He}d \to {}^4\mathrm{He}d$$

From Fig. 6 it was decided to eliminate the events with photons of energy less than 250 MeV. That way an inefficiency is introduced for the "good" events, but this can be evaluated with a Monte Carlo, whose results are indicated in Fig. 6 by the dashed lines "π°" and "γ".

Let us now consider section c) in Fig. 6. The one photon production is allowed and is a two body reaction. Among the events that survive the energy cut, it is then easy to identify those due to the $dd \to {}^4He\gamma$ reaction, since they must be contained in the central lead glass counter. There are 28 such events, and the corresponding cross section is 4.7±1 pb/sr at 102° in the center of mass.

In section b), 7 events remain after the energy cut. Nothing can be said for each one of those events, but there is a rather compelling argument by which they can all be considered as due to background.

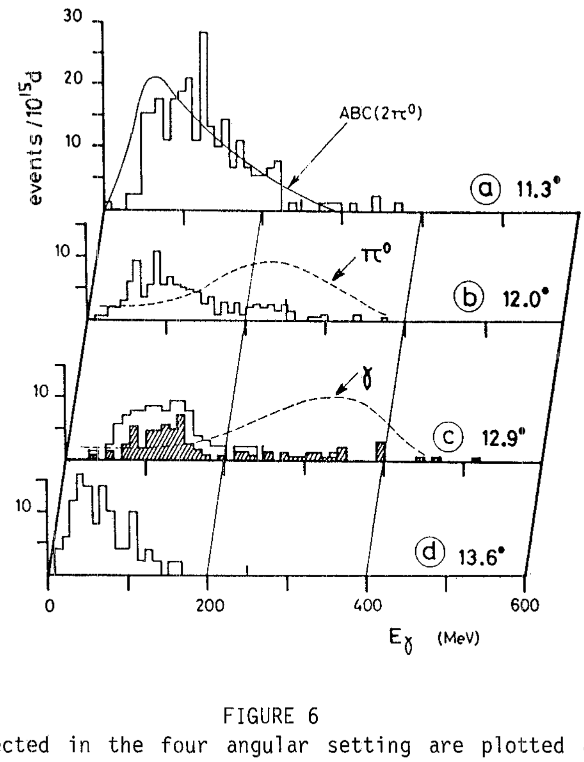

FIGURE 6
The events collected in the four angular setting are plotted as a function of the energy detected in the lead glasses.

In Fig. 7 is shown, as a function of the angle, the cross section calculated from the events surviving the energy cut at each measured angle, eliminating those identified as due to the $dd \to {}^4He\gamma$ reaction. The points lie on a smooth curve, and in the π^0 region does not appear any accumulation.

As a consequence we state that the measured cross section of 0.8 pbarn is actually an upper limit.

Once completed this measurement, we increased the solid angle covered by the photon detector and the number of radiation length of each counter.

We have made a long run, with an integrated flux of 2.3×10^{16} deuterons on the target in a kinematic slightly different from the one just described. The choice has been made by mediating different requirements, which can be met only in different experimental conditions, such as the minimum width of the π° acceptance curve, a great value of the jacobian, a small $2\pi^\circ$ production cross section, and the highest probability of detecting both π° photons.

The analysis of this run is in progress, and nothing can be said yet. But I can state that, even if the π° is not there, the upper limit for the cross section will be less than 0.1 pbarn/sr, i.e. 10^{-37} cm^2.

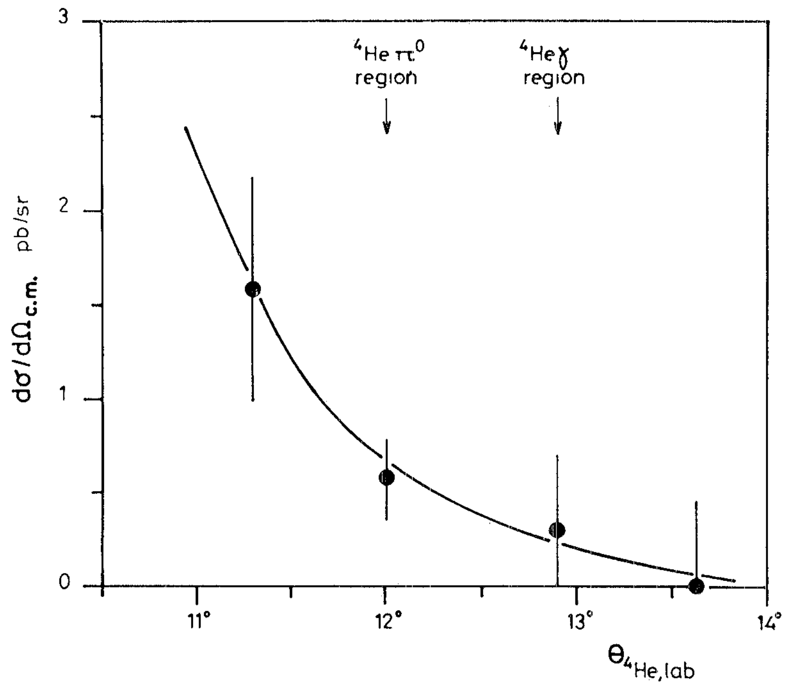

FIGURE 7
The cross section measured in the four angular settings is plotted versur the angle. At 12.9° the photons identified as due to the dd$\rightarrow{}^4$Heγ reaction have been subtracted.

As a final remark I stress that I have ignored the tests of charge independence and symmetry made with e.m. probes. They should of course be reviewed separately, but it can be said that the limits of these symmetries are elusive also for these probes, that are usually considered as easier to handle than the hadronic ones. As an example, until quite recently, from the (γp) and (γn) photodisintegration cross sections of the ^{4}He, the existence of a relevant non charge symmetric component of the nuclear force seemed ascertained. This component was assumed to mix up 1^- states with different isospin in the ^{4}He[22]. This possibility, which is inconsistent with our results, seems now ruled out by recent measurements[23] of the Ladon group on the ^{4}He photodisintegration, and by absorption measurements of π^+ and π^- on ^{4}He[24].

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21) Here are listed the members of the collaboration for the measurement described in this paper:
- ER54 (IN2P3, Laboratoire National Saturne):
  J. Banaigs, J. Berger, L. Goldzahl, F. Plouin.
- Laboratori Nazionali di Frascati:
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- Ecole Polytechnique (Palaiseau):
  P. Feury.
- Oregon State University:
  A. Stetz.
- U.C.L.A.:
  J. Carrol, G. Igo.
- D. Ph. N/ME Saclay:
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