Краткие сообщения ОИЯИ № 21-87　*JINR Rapid Communications No. 21-87*
УДК 539.125.46 + 539.172.6

ANNIHILATION OF STOPPING ANTIPROTONS IN ^{4}He AND ^{3}He

Yu.A.Batusov, S.A.Bunyatov, I.V.Falomkin, F.Nichitiu,
G.B.Pontecorvo, M.G.Sapozhnikov, V.I.Tretyak
Joint Institute for Nuclear Research, Dubna

F.Balestra, S.Bossolasco, M.P.Bussa, L.Busso, L.Fava,
L.Ferrero, D.Panzieri, G.Piragino, F.Tosello
Instituto di Fisica Generale dell'Universita' di Torino
and INFN-Sezione di Torino, Turin, Italy

G.Bendiscioli, A.Rotondi, P.Salvini, A.Zenoni
Dipartimento di Fisica Nucleare e Teorica dell'Universita'
di Pavia and INFN-Sezione di Pavia, Pavia, Italy

C.Guaraldo, A.Maggiora
Laboratori Nazionali di Frascati dell'INFN, Frascati,
Italy

E.Lodi Rizzini
Dipartimento di Automazione Industriale dell'Universita'
di Brescia and INFN-Sezione di Pavia, Pavia, Italy

A.Haatuft, A.Halsteinslid, K.Myklebost, J.Olsen
Institute of Physics, University of Bergen, Norway

F.O.Breivik, T.Jacobsen, S.O.Sorensen
Institute of Physics, University of Oslo, Norway

Annihilation of antiprotons stopping in ^{4}He and ^{3}He has been studied at the LEAR facility of CERN using a streamer chamber in a magnetic field. Measured are charged particle multiplicities. The ratio is determined between the annihilation probabilities on the neutron and the proton bound in the nucleus; this ratio has turned out to be nearly two times smaller than the corresponding value measured in the case of antiproton annihilation in deuterium. The causes of this discrepancy are discussed.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Аннигиляция остановившихся антипротонов в ^{4}He и ^{3}He
Ю.А.Батусов и др.

На ускорителе LEAR в ЦЕРНе с помощью стримерной камеры в магнитном поле изучалась аннигиляция остановившихся антипротонов в ^{4}He и ^{3}He. Измерены множественности заряженных частиц. Определено отношение вероятности аннигиляции на нейтроне к вероятности аннигиляции на протоне в ядре, которое оказалось почти в два раза меньшим, чем соответствующее отношение, измеренное в случае аннигиляции антипротонов в дейтерии. Обсуждаются причины возникшего расхождения.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

A most important issue of low-energy antiproton physics is the determination of the structure of the nucleon-antinucleon interaction amplitude, for instance, the investigation of $\bar{N}N$ -interaction in various isospin states. For this purpose experimental information is necessary on the scattering and annihilation of antiprotons both on protons and neutrons. The $\bar{p}n$ -interaction has not been studied sufficiently well, owing to the absence of good antineutron beams. For this reason it becomes particularly important to investigate the interaction of antiprotons with the lightest nuclei, such as ^{2}H, ^{3}He, ^{4}He, to derive information on the properties of the $\bar{p}n$ -scattering amplitude.

Earlier we carried out a series of measurements of antiproton annihilation in ^{4}He at 20, 50 and 180 MeV /1-3/, as well as with stopping antiprotons /4/. The ratio R between the annihilation probabilities on the neutron and the proton bound in the ^{4}He nucleus,

$$R = \frac{W_n^{ann}}{W_p^{ann}}, \tag{1}$$

was found to be less than unity within the energy range from 0 to 180 MeV /4/, while in the case of stopping antiprotons $R = 0.42\pm0.05$. This value is nearly twice as small as the corresponding ratio found experimentally from annihilation of antiprotons in deuterium to be $R = 0.75\pm0.02$ /5/, or, from the results of Ref. /6/, $R = 0.82\pm0.03$. There are several plausible explanations of such a discrepancy. Thus, the experiments reported in Ref. /5,6/ were performed with bubble chambers, and, as it is well known, in a liquid antiprotons annihilate from high levels of S-states owing to a strong Stark effect[7]. Now in our experiments the antiprotons were stopped in a gas target, in which they are annihilated mainly from low-lying P- and D-levels. Then, it must be taken into account that in Refs.[5] and[6] the momenta of the antiprotons considered to be stopping were actually only less than 260 and 300 MeV/c, respectively. In contrast, for our experiments the LEAR beam with a well defined initial momentum 105 MeV/c ($\Delta p/p \sim 10^{-3}$) was utilized; the distribution of the antiproton stopping points along the beam direction inside the chamber volume exhibits a clear peak (see Fig. 1).

Finally, one cannot exclude the possibility of the observed value of R being small due to non-trivial physical effects. For instance, since the $\bar{p}n$ -interaction occurs in the pure isospin state with I = 1, while both the state with I = 1 and the one with I = 0 contribute to the $\bar{p}p$ -interactions, the small value of the ratio R points to an anomalously strong interaction in the state with I = 0, that could, for example, be caused by resonances in the $\bar{N}N$ system, the existence of which, in the vicinity of the threshold, cannot, as yet, be excluded[8,9]. Moreover, in $\bar{p}p$ -scattering some strange oscillations of the ratio $\rho = \mathrm{Re}\, f(0)/\mathrm{Im}\, f(0)$ are observed[10,11] precisely in the vicinity of the threshold. Bearing in mind the importance of this problem, we have made an attempt to determine R in a way differing from the one adopted in ref.[4], utilizing another part of the data on $\bar{p}\,{}^4\mathrm{He}$ - annihilation, and also for the ${}^3\mathrm{He}$ nucleus.

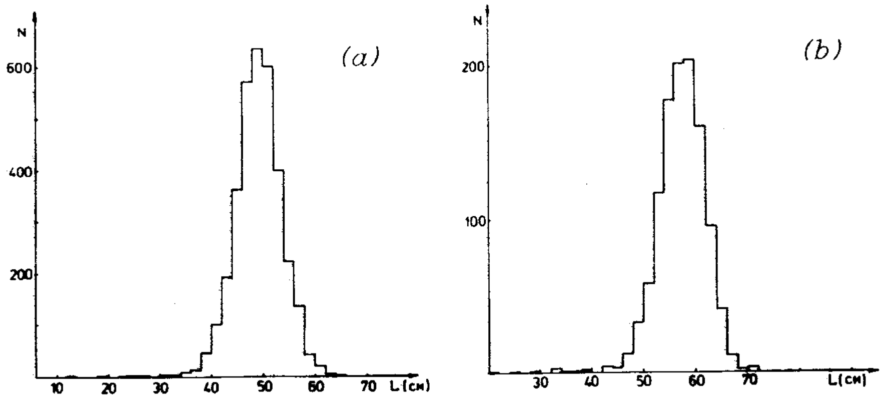

Fig. 1. Distribution of the antiproton stopping points along the beam direction in the chamber volume plotted for annihilation events in ^{3}He *(a) and* ^{4}He *(b).*

A detailed description of the experimental apparatus may be found in Ref./12/, so here we shall only recall its main features. A self-shunted streamer chamber /13/ placed in a 0.22 T magnetic field and filled with ^{4}He or ^{3}He at atmospheric pressure served simultaneously as the target and the detector. The chamber volume was 70x90x x18 cm^3. The target thickness was 15 mg/cm^2. The triggering system consisted of scintillation counters before the chamber. An important feature of the LEAR antiproton beam is that it is free of any pion contamination whatsoever. The total energy losses of the beam in the trigger scintillation counters and the entrance window to the chamber were made to be such that upon passing ~50 cm the incident antiprotons with an energy of ~2.5 MeV came to a stop in central region of the chamber volume. The distribution of the stopping points along the beam inside the chamber is shown in Fig. 1. A clear peak is seen, and its position coincides with the calculated value, while its width is determined by the natural straggling of the antiprotons.

Photographs of the streamer chamber volume were taken using two cameras equipped with Leitz lenses. The optical axes of the lenses were parallel to the electric and magnetic fields, and the distance between them was 280 mm. Each photograph represented a picture of only a single antiproton interaction event. A triple scanning of the film was performed with an efficiency of 99.5%.

For achieving a good track quality a C_4H_{10} admixtures of 0.14% was included in the ^{3}He gas filling of the chamber. Events occuring within a 25 cm long central region in the chamber were analyzed. A total of 3127 $\bar{p}^3$He annihilation events were found inside this fiducial volume. The charged prong multiplicity distribution for these events is given in Table 1.

As one can see from Table 1, 12.8% of the events involve an even number of charged particles. Now, since the total charge of the final state in $\bar{p}^3$He-annihilation equals +1, no such events with an even number of tracks should be observed, when the streamer chamber is filled with pure ^{3}He, and given a 100% detecting efficiency. However, owing to the interaction of antiprotons with the C_4H_{10} admixture and to the ineffective operation of the chamber, which may lead to some of the dim tracks of weakly ionizing high-energy pions being lost as well as to the loss of the short tracks (less than 0.5 cm long) of spectator protons (~3% of the total statistics), a certain number of events may appear to be with an even number of tracks. Since the admixture to the filling gas of

Table 1

Relative probabilities B_A *of* $\bar{p}\,^3He$ *annihilation channels with differing charged particle multiplicities*

N_{ch}	N_{ev}	B_A with account of "odd" events only		N_{ev}	B_A,%
		N_{ev}	B_A,%		
0	2				
1	148	148	5.43 ± 0.43	150	4.8 ± 0.4
2	119				
3	1098	1098	40.3 ± 0.9	1217	38.9 ± 0.8
4	213				
5	1252	1252	45.9 ± 1.0	1465	46.9 ± 0.9
6	57				
7	218	218	8.0 ± 0.5	275	8.8 ± 0.5
8	8				
9	10	10	0.37 ± 0.12	18	0.58 ± 0.14
10	1				
11	0				
12	1				
Σ	3127	2726		3125	

Note: two events with N_{ch} equal to 10 and 12 were considered to be annihilation events on the admixture.

the chamber was sufficiently small (we estimated the events due to annihilation on the admixture to make up for only ~ 2.4% of the total number of events), such cases were not taken into account in determining the charged prong multiplicity distribution. The correction related to the inefficiency of the chamber operation was made assuming that only a single charged particle track may be lost in a given annihilation events. Then, in calculating the relative probability B_A of obtaining N_{ch} charged particles each number N_{ch} corresponding to events of odd track multiplicity was enhanced by the preceding number (N_{ch} - 1) of events with even track multiplicity. The final result is given in the last column of Table 1. The above assumption concerning, the loss of a single particle track is justified by the results given in the 4th column of Table 1. These figures are obtained by discarding all the events with even prong multiplicities and taking into account only events with odd track multiplicities for calculating the respective branching ratios B_A. One can see that within the experimental error the adopted procedure does not alter the branching ratios of the various annihilation channels.

For analysis of antiproton annihilation in ^{4}He 1009 events were chosen. The corresponding charged prong multiplicity distribution is given in Table 2.

Table 2

Relative probabilities B_A *of* $\bar{p}\,^4$He *annihilation channels with differing charged particle multiplicities*

Number of prongs, N_{ch}	Number of events, N_{ev}	B_A,%
1	28	2.8 ± 0.5
2	57	5.7 ± 0.7
3	320	31.7 ± 1.5
4	123	12.2 ± 1.03
5	354	35.1 ± 1.5
6	42	4.2 ± 0.6
7	76	7.5 ± 0.8
8	3	0.30 ± 0.17
9	3	0.3 ± 0.17
10	2	0.20 ± 0.14
11	1	0.10 ± 0.10
Σ	1009	

The admixtures present in the ^{4}He gas filling of the chamber were $\leq 0.1\%$. In ^{4}He less short tracks of spectator protons, than in ^{3}He, were lost. We estimated the amount of events in which a track was lost to be $\sim 0.1\%$ of the total number of events.

It must be stressed that a streamer chamber operating at low pressure represents a very good instrument for studying charged particle multiplicities. Thus, for instance, the tracks of a 250 keV α-particle or of a 160 keV proton are 1 cm long in the chamber and are quite visible. In contrast, the tracks of spectator protons in $\bar{p}d$ -annihilation events registered in a bubble chamber /14/ were not detected in 73% of the events.

The relative probabilities of different annihilation channels involving different charged particle multiplicities may be conventiently compared, for differing nuclei, by comparing the number of negative pions produced. It is readily shown that in the case of annihilation on ^{3}He

$N_{\pi^-} = (N_{ch} - 1)/2$, while in the case of $\bar{p}\,{}^4He$-annihilation the charged prong multiplicities $N_{ch} = 1$, 2+3, 4+5, 6+7, ... correspond, respectively, to events with $N_{\pi^-} = 0$, 1, 2, 3, ... In Table 3 presented are the relative probabilities, B^i_A, of negative pion production in annihilation of stopping antiprotons on the ${}^3He$ and ${}^4He$ nuclei, and on ${}^2H$ (from Ref./6/). One can see that, although the values of B^i_A for the different isotopes of helium differ little, they differ quite noticeably from the corresponding quantities for $\bar{p}d$-annihilation.

Table 3

Relative probabilities of negative pion production in annihilation of stopping antiprotons with different nuclei

Nucleus	Number of negative pions N_{π^-}				
	0	1	2	3	4
${}^2H$ (from ref./6/)	2.9 ± 0.3	30.7 ± 0.9	52.1 ± 1.4	14.1 ± 0.8	
${}^2H$ (theory)	2.9	31.7	52.6	12.5	0.16
${}^3He$	4.8 ± 0.4	38.9 ± 0.8	46.9 ± 0.9	8.8 ± 0.5	0.58 ± 0.14
${}^4He$	2.7 ± 0.5	36.8 ± 1.5	47.6 ± 1.6	12.1 ± 1.0	0.6 ± 0.18

The relative probabilities B^i_A can be computed knowing the yields b^i_p and b^i_n of negative pions in $\bar{p}p$- and $\bar{p}n$-annihilation, respectively, as well as the ratio R from (1):

$$B^i_A = W_p^{ann} \cdot b^i_p + W_n^{ann} \cdot b^i_n . \qquad (2)$$

Here W_p^{ann} and W_n^{ann} represent the annihilation probabilities on the proton and neutron, respectively, in the nucleus; i is the number of negative pions. If one assumes the annihilation probability on the proton or on the neutron in the nucleus to depend only on their number and on the ratio R_0 for free nucleons, then

$$W_p^{ann} = \frac{Z}{Z + NR_0} ; \qquad W_n^{ann} = \frac{NR_0}{Z + NR_0} , \qquad (3)$$

where Z and N, respectively, are the number of protons and neutrons in the nucleus, and R_0 represents the ratio between the annihilation probabilities on the neutron and on the proton in the case of free nucleons. It is readily seen that, when Z = N, R equals R_0.

In Table 3 the calculated values are given of B_A for $\bar{p}d$ -annihilation. The relative outputs b_p^i for $\bar{p}p$ annihilation are from Refs.[15,16] with account of kaon production in the final state. The relative outputs b_n^i are taken from Ref.[17]. R_0 is assumed to be $R_0 = 0.8$. One can see that the multiplicity distribution for negative pions produced in $\bar{p}d$ annihilation is described well by relations (3)-(4). However, from (4) it follows that for a given R_0 the multiplicity distributions for any nuclei with Z = N should be identical. Actually, this is not so, which is confirmed by the results for annihilation in ^{4}He presented in Table 3.

A possible explanation of the above discrepancy is that the pions produced in annihilation may undergo interaction in the final state with the nucleons of the residual nucleus and, thus, alter the relative probabilities B_A^i. In annihilation an average of 5 pions is created with a mean energy of $T \sim 220$ MeV. Such pions may quite effectively interact with the residual nucleus. However, not any final-state interaction (FSI) will lead to an alteration of the spectrum B_A^i. A change in the number of negative pions will only take place owing to reactions of the charge-exchange type:

$$\pi^- + p \rightarrow \pi^0 + n \quad , \qquad (4)$$

$$\pi^0 + n \rightarrow \pi^- + p \qquad (5)$$

or to pion absorption:

$$\pi^- + {}^3He \text{ --- } p + 2n. \qquad (6)$$

Processes (4) and (6) lead to the loss of one negative annihilation pion, while reaction (5) results in the production of an additional negative pion. Thus, variation of the negative pion multiplicity distribution is due to two processes counteracting each other.

In Figs. 2, 3 the relative probabilities B_A^i are presented for annihilation of antiprotons in ^{3}He and ^{4}He computed with account of FSI. The probability for a pion to undergo interaction in the final state with a nucleon of the residual nucleus was taken to be $W_{FSI} = 0.2$, while the probability of losing a negative pion through charge

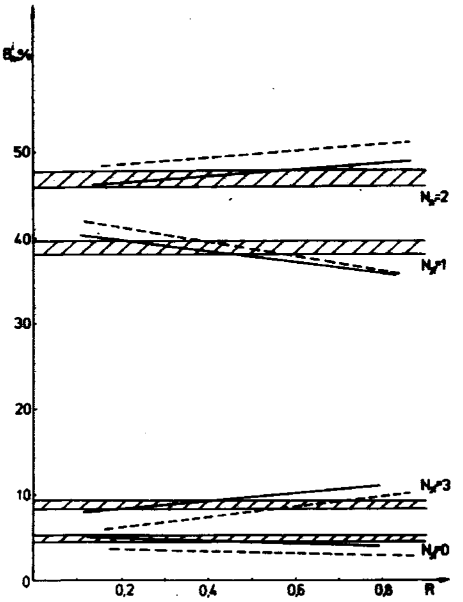

Fig. 2. Relative probabilities B_A *for annihilation in* ^{3}He *computed with account of FSI (solid lines) and without account of FSI (dashed lines). The shaded areas represent the experimental error corridors for channels with different negative pion multiplicities,* N_{π^-}.

exchange in the final state was assumed to be $W_{CEX} = 0.2$ (approximately equal to the ratio of the cross section of reaction (4) to the total $\pi^- p$-interaction cross section in the Δ_{33} -resonance region). The probability for the FSI to result in the production of an additional negative pion was considered equal to W_{CEX}. In calculations the relative probability of each exclusive $\bar{p}p$ and $\bar{p}n$ annihilation channel, in which a given number of negative and neutral pions is produced, was taken into account, as well as the fact that the loss of a negative pion in the i-th $\bar{p}A$ annihilation channel led to the appearence of an additional event in the (i-1)-th bin of the multiplicity distribution. The results of calculations for different R_0 are represented by solid lines in the plots of Figs. 2 and 3. One can see that taking into account the FSI does not alter the multiplicity distribution significantly, but the general agreement with the experimental data does become better.

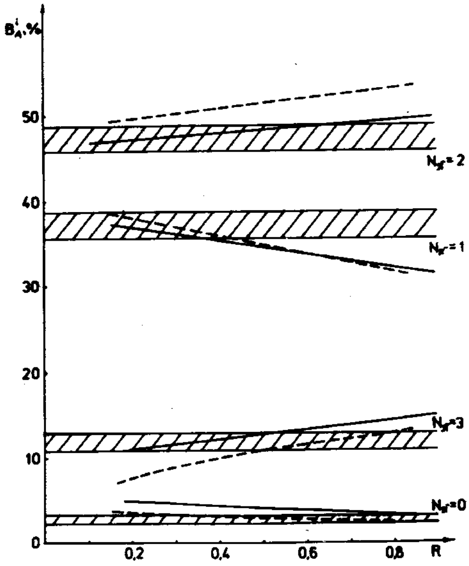

Fig. 3. Relative probabilities B_A *for annihilation in* ^{4}He. *The notations adopted are the same as in Fig. 2.*

It must be stressed that, although taking into account of the FSI on the whole, leads to small changes in the probabilities B_A^i, charge exchange processes are, nevertheless, themselves quite significant (see Table 4) and occur in a great part (~10-20%) of the annihilation events.

Table 4

Influence of interaction in the final state on the relative probabilities B_A *for* R_0 *= 0.8.*

		W_{FSI} = 0.2, W_{CEX} = 0.2			W_{FSI}=0.4, W_{CEX}=0.2		
N_{π^-}	B_A,% without account of FSI	Change in B_A (%) due to $\pi^0 \to \pi^-$	Change in B_A (%) due to $\pi^- \to \pi^0$	B_A,% with account of FSI	Change in B_A (%) due to $\pi^0 \to \pi^-$	Change in B_A (%) due to $\pi^- \to \pi^0$	B_A,% with account of FSI
0	2.9	-0.3	+1.5	4.1	-0.4	+2.7	5.1
1	32.2	-3.1	+4.4	32.4	-4.9	+7.4	32.5
2	52.6	-3.4	+1.4	49.4	-5.8	+2.2	46.5
3	12.5	-0.5	+0.02	14.0	-0.9	+0.03	15.2

When the quantities R_0 and W_{FSI} are treated as free parameters, the best agreement with experimental data is obtained with the following values:

$$R_0 = 0.35 \pm 0.07, \quad W_{FSI} = 0.15 \pm 0.03 \quad \text{for } {}^3\text{He},$$
$$R_0 = 0.48 \pm 0.1, \quad W_{FSI} = 0.08 \pm 0.05 \quad \text{for } {}^4\text{He}. \qquad (7)$$

These values are in agreement with the previous result, R = 0.42±0.05, of ref. /4/, in which the numbers of annihilation events on a proton and a neutron of the ^{4}He nucleus were measured directly using a smaller statistic of events and neglecting FSI effects.

How can one interpret the extremely interesting fact that R_0 deduced drom the data on $\bar{p}\,{}^3$He and $\bar{p}\,{}^4$He annihilation turns out to be twice as small as the value derived from $\bar{p}d$ annihilation? First of all, one can express doubt whether the simple relationship (3) between the annihilation probabilities on bound nucleons, W_n and W_p, and the corresponding probabilities on free nucleons is justified. It may turn out that the relation between R_0 and W_n, W_p changes significantly owing to the screening of nucleons in the nucleus. Let us estimate the screening effects utilizing simple semi-classical arguments, such as the ones made use of by Glauber in Ref./18/. Let δ_{pn} be the probability for the proton happen to be in the "shadow" of a neutron; then

$$\delta_{pn} = \frac{f_n}{4\pi r_{NN}^2} , \tag{8}$$

where f_n is the annihilation probability on a free neutron, which is determined solely by the effective dimensions of the neutron, $f_n = \pi r_{ann}^2$, where r_{ann} is the effective annihilation radius. The quantity r_{NN} occuring in (8) is the mean distance between the nucleons in the nucleus. Then, it is not difficult, for instance, for $\bar{p}\,{}^4He$ annihilation, to write out the probabilities W_p and W_n with account of the mutual screening of the nucleons:

$$\begin{aligned} W_p &= 2f_p(1 - \delta_{pp} - 2\delta_{pn}), \\ W_n &= 2f_n(1 - \delta_{nn} - 2\delta_{np}), \end{aligned} \tag{9}$$

where δ_{pp}, δ_{nn} and δ_{np} correspond to screening corrections in the (pp), (nn) and (np) systems, which are determined as in (8). Then, making use of (8)-(9) and taking into account that $f_n/f_p = R_o$ one can obtain the follwing relationship between R and R_o:

$$R = R_o \frac{1 - 1/4(r_{ann}/r_{NN})^2(R_o + 2)}{1 - 1/4(r_{ann}/r_{NN})^2(1 + 2R_o)} . \tag{10}$$

The screening is most significant, when $r_{ann} = r_{NN}$. In this case, if $R_o = 0.8$ is substituted into (10), we obtain R = 0.69, which is noticeably larger than the experimentally observed values (7). If, which is more probable, the effective annihilation radius is smaller than the average distance between the nucleons in the nucleus, for example, $r_{ann} = r_{NN}/2$, then from (10), under the same assumption that $R_o = 0.8$, it follows that R = 0.79. Thus, the screening effect is small.

In conclusion we note that in this work relative probabilities have been measured of the production of different numbers of charged particles in the annihilation of stopping antiprotons in ${}^3He$ and ${}^4He$. It has been found that the multiplicity distributions differ quite significantly from the corresponding distributions for $\bar{p}d$ annihilation. Analysis of the obtained results has revealed that the said difference cannot be due only to interaction in the final state of the annihilation pions or to screening effects of nucleons in the nucleus. It was obtained that the annihilation probability on a proton bound in the nucleus is approximately twice as high as the probability of annihilation on a neutron. This fact points to a significant domination of annihilation in the state with isospin I = 0 near the threshold.

The authors are grateful to S.I.Merzlyakov for technical assistance and G.A.Kulkova, M.N. Shelaeva and L.A.Vasilenko for their essential help in scanning and measuring the experimental material.

References

1. Balestra F. et al. Phys.Lett.B, 1984, 149, 69.
2. Balestra F. et al. Phys.Lett.B, 1985, 165, 265.
3. Batusov Yu.A. et al. JINR Rapid Comm., No.12-85, Dubna, 1985, p.6.
4. Balestra F. et al. Preprint CERN-EP/86-104, Geneva, 1986; Nucl.Phys. (in press).
5. Kalogeropoulos T., Tzanakos G.S. Phys.Rev.D, 1980, 22, 2585.
6. Bizzarri R. et al. Nuovo Cim. A, 1974, 22, 225.
7. Day T.B., Snow G.A., Sucher J. Phys.Rev., 1960, 118, 864.
8. Dover C. Preprint BNL-38285, Upton, 1986.
9. Sapozhnikov M.G. JINR Preprint, P4-86-695, Dubna,1986.
10. Bruckner W. et al. Phys.Lett.B, 1985, 158, 180.
11. Linssen L. Ph.D.Theses, NIKHEF-H, Amsterdam, 1986.
12. Balestra F. et al. Nucl.Instr.and Meth., 1985, 234, 30.
13. Falomkin I.V. et al. Nucl.Instr.and Meth., 1967, 53, 266.
14. Gray L., Hagery P., Kalogeropoulos T. Phys.Rev.Lett., 1971, 26, 1491.
15. Armenteros R. et al. CERN Preprint, PSCC/80/101, Geneva, 1980.
16. Ghesquiere C. Proc.of Symp.on NN-Interactions, Liblice, CERN-74-18, 1974.
17. Ofranidis S.I., Rittenberg R. Nucl.Phys.B, 1979, 59, 570.
18. Glauber R.Y. Phys.Rev., 1955, 100, 242.

Received on January 12, 1987.