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O.D.Dalkarov, I.S.Shapiro, R.T.Tyapaev*)

ANNIHILATION OF NONRELATIVISTIC ANTIPROTONS

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*) Moscow Engineering Physics Institute

A b s t r a c t

The influence of nuclear interaction between nucleon (N) and antinucleon ($\bar{N}$) on the probability of low energy antiproton annihilation is investigated. On the basis of calculations carried out in the framework of unitary scheme of coupled channels with realistic one boson exchange potentials (OBEP) it is shown that just strong attraction between N and $\bar{N}$ gives rise to large observed annihilation cross-section. The width of p- and d- levels of quasinuclear baryonium turn out rather small (of the order of tens MeV and several MeV correspondingly). At the same time annihilation, elastic scattering and charge-exchange($\bar{p}p \to \bar{n}n$) cross-sections both absolute value and energetic behaviour agree with experimental data. The physical significance of this results is turned out. The possible informative experiments (for problems discussed here), using modern low energy antiproton beams, are considered.

I. Introduction

It is known that the annihilation of nonrelativistic antiprotons takes place at the distances of the order of their compton wavelengths and therefore is essentially relativistic process not so much in the kinematical sense as in dynamical one. That is why other treatment of the annihilation problem, exept quantum-field theory one, can not be convincing. However the calculation of $N\bar{N}$ annihilation cross-section, proceed from initial principles of a strong interaction field theory (even using most wide-spread version - QCD), is not possible now. In any case such problem is not even propoused (in the published works).

Meanwhile, a question of the low-energy antiproton annihilation probability became urgent after the idea of possible existence of many bound and resonant quasinuclear type states in $N\bar{N}$ system was expressed /1/. The two facts were grounds for this prediction: possibility of a strong nuclear attraction between N and $\bar{N}$ and above mentioned smallness of annihilation region radius ($r_a \sim 1/2m_1 \approx 0.1$ fm) *) compared with the radius of nuclear forces ($R \approx 1$ fm). In these works it was shown also that due to existence of small parameter $r_a/R \approx 0.1$ the following factorization relations take place

$$v\sigma_a = v\bar{\sigma}_a \left|\Psi_v(0)\right|^2 , \quad \Gamma_a = v\bar{\sigma}_a\Big|_{v\to 0} \left|\Psi_B(0)\right|^2 \qquad (1)$$

where v is a N and $\bar{N}$ relative velocity, σ_a is a total annihi-

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*) Here and in the following $\hbar = c = 1$, m_1 is the nucleon mass.

lation cross-section, Γ_a is an annihilation width of quasinuclear level. In the formulae (1) $\psi_v(r)$ and $\psi'_B(r)$ are the wave functions of continuous and discrete spectrum correspondingly, which are determined by nuclear interaction completely. As for $\bar{\sigma}_a$, its value is determined by "proper" annihilation processes. Since the exact calculations of annihilation cross-sections as emphasized above are not possible now, the factorization relations have particular importance-they show a method of the determination of quasinuclear resonance width from the observed annihilation cross-section (and vice versa). Due to the effect of factorization it is possible to find out quantitative characteristics of nuclear interaction using an experimental data on the cross-sections and spectrum of quasinuclear levels in $N\bar{N}$ system. Necessary data will be available in the near future owing to low energy antiproton ring (LEAR) which is in operation now /2/. This question will be discussed in Section 6 in more detail.

In the works /1/ using factorization relations it was shown that in spite of the large annihilation cross-section for low-energy antiprotons, widths of quasinuclear baryonium levels do not exceed the normal hadron widths ($\sim$ 100 MeV). In the states with nonzero orbital angular momentum ℓ of N and $\bar{N}$ relative motion these widths can be much smaller (of the order of tens and several MeV for p- and d- levels correspondingly). Such conclusion is based on the fact that the nuclear wave function ψ_B(r) for discrete spectrum is concentrated at the distances $r \sim 1$ fm. That is why the probability of N and $\bar{N}$ drawing close up to annihilation distances is not large. The wave function of the continuum $\psi_v(0) \sim f^{-1}(-k)$ ($f(-k)$ is a Jost function for nuclear $N\bar{N}$ interaction). If there are bound and resonant near-threshold $N\bar{N}$ states the coefficient $|\Psi_{\nu}(0)|^2$ leads to considerable enhancement of pure annihilation cross-section σ_a (due to the near-threshold zeros of Jost function $f(-k)$ corresponding to such states). Hence strong nuclear attraction between N and $\bar{N}$ gives rise to both the large annihilation cross-section for slow $\bar{p}$ and rich spectrum of rather narrow levels of quasinuclear type in $N\bar{N}$ system. Demonstration of reliability of the qualitative estimations cited above (see also review /3/) is the purpose of this work. For this aim $\bar{p}p$ annihilation, elastic scattering and charge-exchange cross-sections are calculated and compared with experimental data. The quasinuclear baryonium spectrum is obtained also. The calculations are performed in the framework of a coupled channel model with realistic one boson exchange potential (OBEP).

The plan of the paper is the following. In Section 2 we expound our point of view on existent approaches to the problem of nonrelativistic antinucleons annihilation. Section 3 is devoted to treatment of the model which is used here to describe the interaction of slow N and $\bar{N}$. In Section 4 some physically important results, obtained in our former works using the same model, are considered. The cross-sections energetic behaviour and spectrum of quasinuclear baryonium levels calculated in this work are presented in Section 5. The conclusions, important for experimental study with modern antiproton low energy beam (LEAR), are considered in Section 6. Finally Section 7 contains the brief resume of main results.

2. MODELS FOR DESCRIPTION OF NONRELATIVISTIC ANTIPROTON ANNIHILATION

With the increase of experimental activity in the study of slow $\bar{p}$ /4/ interaction the keen interest to the problem of annihilation appeared. Many theoretical papers were published in which in authers opinion the probability of baryonium annihilation was calculated (but not evaluated as in ref./1/) using experimental data on annihilation, elastic and charge-exchange cross-sections. This works could be divided in two groups.

1. A calculations in the framework of optical model with realistic nuclear real part and phenomenological imaginary one to describe an annihilation processes /5/, /6/ *). The number of works, in which the model energy and quantum numbers dependence of imaginary part obtained either from quark "rearrangement model" /8/, /9/ or from the calculation of definite set of annihilation diagrams /10/ is introduced, also belong to this group. In these works the good description of experimental data on annihilation, elastic and change-exchange cross-sections is reached with annihilation radius $r_a \lesssim 0.2$ fm. However the imaginary part of potential in this case is so large even at nuclear distances that, as a rule, baryonium widths are large (several hundred MeV practically for any orbital momenta **)). The point is that the optical model is sensitive to wave function asymptotics but not to its behaviour at the range of nuclear forces. Therefore such model could be very useful for scattering description but not for a calculations of positions and widths of discrete spectrum levels.

*) It should be noted that there are some works /7/, in which the potential described annihilation has a real part also. However the results are not changed qualitatively in this case.

**) In the work /9/ the calculated widths for some baryonium levels are not large (several MeV). The peripheral annihilation model which was used in this work has not, for our opinion, sufficient physical grounds.

The "boundary condition model" /11/ should be also related to optical model. In detail the question of optical model applicability was considered in review /3/.

2. A calculations with N/D-method used the discontinuity of Born nuclear amplitude (instead of exact one) on the left (dynamical) cut in complex energy plane /12/. The discontinuity of annihilation amplitude was aproximated by δ - function with coupling constant of elastic channel with annihilation one as varied parameter. The same sense has a model calculation on the basis of integral equations of scattering theory /13/. In this works a satisfactory description of experimental data on $\bar{p}p$ interaction cross-sections is achieved. The obtained baryonium widths $\Gamma_a \gtrsim 100$ MeV independently on orbital angular momentum of states. A quasinuclear resonances are not manifest themselves even in corresponding partial cross-sections and Argan diagrams. At the same time S- matrix poles, created by annihilation interaction, appear just near $N\bar{N}$ threshold. The positions of such singularities (unlike a qusinuclear ones) depend strongly on the details of nuclear dynamics at small distances where potential approach, which was used, has no sense. As it was shown in the work /14/, the results with "Born N/D method", differ strongly from exact ones. The obtained baryonium spectrum do not agree with exact solution of Schrödinger equation even in the absence of annihilation /15/. The main defect of such approach is that the restriction by first Born approximation in the case of intensive nuclear interaction between N and $\bar{N}$ is insufficient.

Let us mention also the works /16/ in which the widths of quasinuclear levels are determined by quadratic diagrams for annihilation rescattering. Such calculations give a several narrow baryonium levels, however the $N\bar{N}$ interaction cross-sections are not calculated.

Finally, in works /14/, /17-20/ coupled channel approach was developed for model demonstration of qualitative conclusions for quasinuclear baryonium theory.

We are passing now to description of this method.

3. COUPLED CHANNEL FORMALISM

In our opinion the method which is used for description of nonrelativistic antinucleons annihilation should takes into account at least the following main features of annihilation interaction.

1. Smallness of its radius ($r_a \sim 1/2m_1 \approx 0.1$ fm).

2. Unitarity, i.e. the fact that particles not only leave $N\bar{N}$ channel, but came back due to annihilation rescattering.

The coupled channel model (first proposed for description of slow antiprotons annihilation in ref. /17/) satisfies these demands. We consider two coupled channels. Channel I ($N\bar{N}$) contains two particles with equal masses m_1. Since we take an interest in the energy region closed to $N\bar{N}$ threshold this particles are treated as nonrelativistic. Channel 2 (products of annihilation) corresponds to two particles with masses $m_2 < m_1$. These particles are treated as nonrelativistic also. In our approach this channel is not identified with concrete two-boson annihilation decay channel but effectively takes into account all annihilation processes.

The c.m.s. momenta K_1 and K_2 in channels I and 2 are related to total energy E by the following way

$$K_i = [m_i(E-2m_i)]^{1/2} \quad , \quad i=1,2 .$$

So S- matrix as a function of the energy E has two square root branch points: $E = 2m_i$, $i = 1, 2$. Therefore the correspondin Reeman surface has four sheets. The cuts are drawn from branch points to the right along the real axis. The joining of the sheets and their numeration are defined by the inequalities

$$\text{I.} \left.\begin{matrix} Im K_1 > 0 \\ Im K_2 > 0 \end{matrix}\right\}, \quad \text{II.} \left.\begin{matrix} Im K_1 > 0 \\ Im K_2 < 0 \end{matrix}\right\}, \quad \text{III.} \left.\begin{matrix} Im K_1 < 0 \\ Im K_2 < 0 \end{matrix}\right\}, \quad \text{IV.} \left.\begin{matrix} Im K_1 < 0 \\ Im K_2 > 0 \end{matrix}\right\}.$$

Then the poles corresponding to below-threshold quasinuclear states, which can decay only into channel 2, will then located on sheet II and to abovethreshold resonances (decaying both into channel 1 and channel 2) will be on sheets III and IV.

Two-channel S- matrix as a function of momentum K_1 is defined on two-sheet Reeman surface. If the cuts are drawn from branch points $K_1 = \pm i[2m_1(m_1 - m_2)]^{1/2}$ up and down along the imaginary axis, then the poles location on second sheet will be symmetric (relatively to this axis) reflection of the picture on first sheet. On the latter, the poles, corresponding to resonances in channel 1, are located in third and fourth quadrants above bisector, while those, corresponding to bound states, are above bisector of the second quadrant.

The interaction between the particles in channel 1 is described by a potential V_{11} with an average radius $R \sim 1$ fm. The particles in channel 2 are treated as noninteracting (as in all works considered in the previous Section). The coupling of channels is described by a potential V_{12} with an average radius, corresponding to compton wave-length of nucleon ($r_a \sim 1/2m_1 \simeq$ 0.1 fm).

Hence the Hamiltonian of the considered two-channel system is the following Hermitian 2 x 2 matrix

$$\hat{H} = \begin{bmatrix} K_1^2/m_1 + \tilde{V}_{11} & V_{12} \\ V_{12} & K_2^2/m_2 \end{bmatrix} \qquad (2)$$

In the following Section we consider some physically important results obtained before in the framework of this model.

4. CALCULATIONS WITH SEPARABLE POTENTIAL V_{12}

The model, described in the previous Section, was used in ref. /14/ and ref. /17-20/ to study a behaviour of quasinuclear poles on Reeman surface E (or K_1) in the dependence of annihilation intensity. The orbitel momentum $\ell = 2$ was considered in ref. /19/ and $\ell = 0$ - in the all other works. The corresponding partial cross-sections were calculated for annihilation of low energy antiprotons, the factorisation relation (1) was checked up in ref. /14/, nuclear enhancement of "proper" annihilation cross section was studied in /20/.

In abovementioned works the potential V_{12} was chosen in the separable form

$$\langle \vec{r} | V_{12} | \vec{r}\,' \rangle = \lambda \xi(r) \xi(r') P_\ell(\cos\theta) \qquad (3)$$

with form-factor ξ (r) falling exponentially at $r \sim 1/2m_1$. Either a model potential of Yukava type (as in ref. /14/) or separable type potential (3) with a form-factor corresponding to the radius R $\approx$ 1 fm were used for potential V_{11}. In this model calculations all particles are considered as spinless for simplicity.

The mass $m_2 = 0.75 m_1$.

The equation for $N\bar{N}$ radial wave function in such model has a form

$$\varphi''(r) + \left(K_1^2 - \frac{\ell(\ell+1)}{r^2} - m_1 V_{11}(r)\right)\varphi(r) - \lambda^2 m_1 \xi(r)\langle\xi|G_2|\xi\rangle \int_0^\infty \xi(r')\varphi(r')\,dr' = 0 \quad (4)$$

where G_2 is a Green function of radial Schrödinger equation for noninteracting particles in channel 2. The generalized optical potential, described in (3) an annihilation processes, is nonlocal, energy and quantum numbers dependent unlike to usual optical model. It has not only imaginary but real part also which for nonrelativistic N and $\bar{N}$ is attractive (see ref./19/).

The main physical results, obtained in ref./14/, /17-20/, are the following.

1. Annihilation widths of quasinuclear levels have an upper limit for any coupling constants λ (if $r_a/R \simeq 0.1$). For instance, in the case of S- wave pole, the behaviour of which in the dependence of coupling constant λ is shown in Fig.1 (from ref. /14/), we have $\Gamma_a \leq 240$ MeV. In the case of $\ell = 2$ $\Gamma_a \leq 4$ MeV (see Fig.2 taken from ref. /19/).

2. Partial cross-sections for the annihilation of slow antiprotons can be comparable with corresponding unitary limit. Meantime an annihilation widths are not large (in any case for orbital momenta $\ell \neq 0$). For example the width $\Gamma_a = 4$ MeV corresponds to point 1 in Fig.2. At the same time the unitary limit for d-wave is saturated up to 90% at the momentum $K_1 = 300$ MeV/c. In Fig.1 the $\lim_{v\to 0} v\,\sigma_a$ values are shown (near corresponding point) where V is a relative velosity of p and $\bar{p}$ ($\lim_{v\to 0} v\,\sigma_a = 15$ mb corresponds to the half of unitary limit for S- wave at $K_1 = 150$

Mev/c).

As it was emphasized above large value of partial annihilation cross-section in spite of the small annihilation radius achieved due to strong nuclear attraction between N and $\bar{N}$ (see [20]). Such attraction leads to existence of nearthreshold quasinuclear $N\bar{N}$ states and consequently gives rise to strong enhancement "proper" annihilation cross-section.

3. Factorization relations are satisfied with good accuracy up to the values λ for which sufficiently large annihilation cross-section is reached (for Fig.1 up to $\lim_{v \to 0} v\sigma_a$ = 24 mb).

4. Annihilation may leads to noticeable diminition of total width of abovethreshold quasinuclear resonances (see Fig.3 taken from [19], where total width decrease from Γ = 15 MeV at $\lambda = 0$ to Γ = 5 MeV for point 1 in Fig.3). The reason of phenomenon is an additional attraction between nonrelativistic N and $\bar{N}$ due to annihilation rescattering. Such attraction leads to decrease of resonance exitation energy (weakly excited resonances may become subthreshold) and elastic width simultaneously. The same reason leads to the increase of subthreshold levels binding energy within the limits of several tens MeV.

In the works considered in this Section annihilation constant λ was not fixed and the behaviour of annihilation cross-sections, widths and shifts of quasinuclear levels as a function of λ was studied, using model potentials V_{11}. Now we shall discuss the results obtained with realistic potentials V_{11} and with intensity of annihilation fixed by experimental data on the cross-sections for interaction of low energy $\bar{p}$ with p.

5. ANNIHILATION WIDTHS OF QUASINUCLEAR BARYONIUM AND $\bar{p}p$ CROSS-SECTIONS

We consider two-body system of two coupled channel, which is described by the Hamiltonian (2).

In this section we'll use the potential V_{11}, obtained by G-transformation from realistic NN OBEP/21/ *) for description of nuclear $N\bar{N}$ interaction. Tensor forces are unimportant for qualitative aspects of $N\bar{N}$ interactions. Such forces, which lead to the mixing of the triplet states with $\ell = j \pm 1$ (- total angular momentum), have been thrown away for simplicity. At distances smaller than r_c we set the potential equal to zero. In this paper the following cutoff radii r_c ($^{2S+1}\ell_j$, S- spin) have been used:

$$r_c(^1S_0) = r_c(^3S_1) = 0{,}55\,fm;\; r_c(^3P_1) = 0{,}57\,fm;$$

$$r_c(^3P_0) = r_c(^3P_2) = r_c(^1P_1) = 0{,}65\,fm;\; r_c = (^3D_1) = 0{,}65\,fm;$$

$$r_c(^3D_2) = r_c(^3D_3) = r_c(^1D_2) = 0{,}68\,fm.$$

The local Yukawa "potential"

$$V_{12}(r) = \lambda_\ell \exp(-r/r_a)/r$$

with radius r_a = 0.11 fm is taken for nondiagonal annihilation interaction. The varied parameter - annihilation constant λ_ℓ -

*) We also have used the real part of Bryan-Phillip potential /5/ for nuclear $N\bar{N}$ interaction. The qualitative results are the same.

depends on orbital angular momentum ℓ only. The radial equation for $N\bar{N}$ wave function with definite quantum numbers has the form:

$$\varphi''(r)+[m_1E-\frac{\ell(\ell+1)}{r^2}-V_{11}(r)]\varphi(r)-\lambda_\ell^2 m_1\frac{\exp(-r/r_a)}{r}\int_0^\infty\frac{\exp(-r'/r_a)}{r'}G_2(r,r')\varphi(r')dr'=0 \quad (5)$$

Here G_2 is the Green function of radial Srödinger equation for noninteracting particles (with mass m_2 = 763 MeV) in annihilation channel 2. The only difference between (4) and (5) is the factorization of φ and G_2 in (4). The generalized optical potential in (5) (as in (4)) is nonlocal, energy and quantum number dependent and has both the imaginary and the real parts. The integrals in (5) and (4) are proportional to nuclear $N\bar{N}$ wave function $\varphi(0)$ (because of the annihilation interaction short range character). So the effective constant $\lambda_\ell^2\varphi_v(0)(\varphi_v(0)\sim 1/f(-k)$, $f(-k)$ is Jost function for nuclear $N\bar{N}$ interaction), determined the annihilation from continuous spectrum is much lager than parameter $\lambda_\ell^2\varphi_B(0)$ ($\varphi_B(0)\sim(r_a/R)^{\ell+1}$, R $\approx$ 1 fm is the radius of quasinuclear state), determined the annihilation from discrete spectrum state. Therefore considered generalized optical potential essential differ from the usual nonunitary optical potential, used in ref./5-10/.

Let us consider now the results of our model calculations. The $v\sigma_a$ as a function of the total energy E from $N\bar{N}$

threshold (1878 MeV) to 2000 MeV *) has been plotted in Fig.4 (annihilation constants are

$$\lambda_0 = \lambda_1 = 86, \quad \lambda_2 = 100 \;).$$

The $\bar{p}p$ elastic scattering (σ_e - curve 1) and $\bar{p}p \to \bar{n}n$ change exchange (σ_c - curve 2) cross-sections are given in Fig.5. The figures demonstrate that the results of our calculations are in satisfactory agreement with the experimental data /22/, /23/.

The quasinuclear baryonium p- and d- levels are given in Table 1. There are a few p- levels with annihilation widths Γ_a = = 10-50 MeV below $N\bar{N}$ threshold. This feature isn't specific for considered $N\bar{N}$ potential. There are a few belowthreshold p- levels in all OBEP (/3/, /15/, /25/) used for description of $N\bar{N}$ nuclear interaction. The d- levels annihilation widths are by the order of magnitude smaller and equal to 1-10 MeV. The effect of centrifugal barrier, which prevents $\bar{N}$ come nearer to N up to annihilation range, account for the significant decreasing of levels annihilation widths with the orbital angular momentum ℓ increasing. So the annihilation widths of belowthreshold levels with $\ell \geq 3$ will be smaller than 1 MeV and the total width of abovethreshold resonance with $\ell = 3$ in S- meson region will be $\Gamma \lesssim 5$ MeV. For example, we show in Table 1 the $^3F_2$ (1937) isoscalar resonance with total width $\Gamma = 3$ MeV, obtained at the annihilation constant $\lambda_3 = 195$

*) The partial waves with $\ell \leq 2$ only give appreciable contribution to the total cross-sections in this region. Energies E > 2 GeV haven't been considered, because it is necessary to take into account the strong coupling with $\Lambda\bar{\Lambda}$ and $\Sigma\bar{\Sigma}$ channels at such energies (see /24/). We'll investigate the effect of these channels in other paper.

and cutoff radius r_c ($^3F_2$) = 0.64 fm. Its contribution to the total cross-sections are shown by dashed lines in Fig.4 and Fig.5.

The levels energies and widths without annihilation ($\lambda_0 = \lambda_1 = \lambda_2 = \lambda_3 = 0$) are presented in Table 2. As it was expected, the annihilation leads to the increasing of binding energies by a few tens MeV and decreasing of abovethreshold resonances excitation energies and their total widths. The levels experimental manifestations are discussed in next Section.

As it mentioned in Section 1, the strong nuclear attraction leads to significant enhancement of "proper" annihilation cross-section $\overline{\sigma_a}$. To investigate the nuclear interaction effect quantitatively, we have calculated annihilation cross-section $\overline{\sigma_a}$ with the nuclear interaction turned off ($V_{11} \equiv 0$). The enhancement factors $\sigma_a / \overline{\sigma_a}$ for S-, p- and d- waves partial cross-sections are given in Fig.6 (curves 1, 2 and 3 correspondingly). The figure shows that the strong nuclear attraction enhances the proper annihilation cross-section by the order of magnitude. The existence of the belowthreshold p- levels account for the rapid p- wave enhancement factor increasing when the energy come nearer to $N\bar{N}$ threshold. The d- wave enhancement factor behavior is explained by the abovethreshold d- wave resonances (firstly, by $^3D_1$ (1935) isotriplet resonance).

It's important to emphasize the striking difference of our results from the ones, obtained in optical /5-10/ and other /12-13/ models. All approaches describe the cross-sections experimental data equally well. But the baryonium levels annihilation widths in coupled channel model are by the order of magnitude smaller than in others.

At the end of this section we note that the model, considered above, takes into account the main physical features of $N\bar{N}$ annihilation processes only (the strong nuclear attraction together with the short range "proper" annihilation interaction). The accurate (from the fundamental principles of quantum field theory) calculations of the $N\bar{N}$ annihilation properties require the $N\bar{N}$ short range relativistic dynamics knowledge and aren't possible now. Our results should be treated as a model demonstration of reliability of the quasinuclear approach qualitative estimations.

6. EXPERIMENTAL CONSEQUENCES

The investigations of the nonrelativistic $N\bar{N}$ interactions are in qualitative development now. Due to the low energy antiproton storage ring LEAR [2] it's possible to carry out the number of experiments, which are of great importance for the nearthreshold $N\bar{N}$ interactions understanding. Here we'll point out some of them.

1. First of all we'll mention of the checking theoretical relation of the baryonium levels annihilation widths to corresponding annihilation cross-sections. This relation, obtained from (1), is the following:

$$\Gamma_a = v\sigma_a|_{v\to 0}\, |\Psi_B(0)|^2 / |\Psi_v(0)|^2 \qquad (6)$$

where $\Psi_B(0)$ and $\Psi_v(0)$ are the bound and scattering states wave functions with the same quantum numbers. The annihilation cross-sections $v\sigma_a|_{v\to 0}$ can be taken:

a) from the phase-shift analysis of the nearthreshold $\bar{p}p$ data;

b) from the measurement of the $\bar{p}p$ atom (protonium) levels energy shifts and widths (the second way is more precise).

Thus, in this point, the quasinuclear approach suggest the following programme: the $N\bar{N}$ nuclear potential reconstruction from the baryonium spectrum and $\bar{p}p$ cross-sections energy dependence. Then $N\bar{N}$ wave functions are calculated and factorization formula (6) is checked.

2. The belowthreshold p- and d- baryonium levels should manifest themselves in the electromagnetic transitions from the $\bar{p}p$ atom states to quasinuclear ones. The corresponding γ - lines spectrum and their relative intensities were predicted in /26/ long before the first experimental indications of its existence /27/. The observed γ - lines widths are close to the belowthreshold levels annihilation widths, calculated here.

The discrete γ - spectrum of the stopped $\bar{p}$ annihilation on p is the direct evidence of the belowthreshold quasinuclear $N\bar{N}$ levels existence. Moreover, the γ - spectrum investigation will make it possible to determine the baryonium levels quantum numbers (either by the annihilation decay products or by the simultaneous study of protonium X - rays spectrum and protonium $\rightarrow$ baryonium transitions γ - spectrum)

3. The abovethreshold resonances clearly manifest themselves in the partial cross-sections and corresponding Argan plots (see, for example, Fig.7 and Fig.8). At the same time it is difficult to select a separate resonance contribution to the total cross-sections experimentally, as it is seen from Fig.4 and 5. So phase-shift analysis $\bar{p}p$ data should be required for unambiguous discovery of abovethreshold quasinuclear resonances.

4. In the light of preceding paragraph the investigation of the annihilation modes, corresponding to definite quantum numbers,

is of considerable interest. Specifically, it concerns $\bar{p}p \to e^+e^-$ annihilation cross-section, which must be enhanced by the factor $|\psi_v(0)|^2$ (wave function with $J^{PC} = 1^{--}$). The enhancement factor increases with energy coming nearer to $N\bar{N}$ threshold. Such behaviour leads to the $\bar{p}p \to e^+e^-$ cross-section deviation from 1/v law. The electromagnetic form-factor G energy dependence is determined by the enhancement factor $|\psi_v(0)|^2$ also. Therefore form-factor G must be increased with the energy coming nearer to $N\bar{N}$ threshold (see /28/). One can effectively use experimental information about such quantities behavior at low energy for the $N\bar{N}$ nuclear potential parameters reconstruction.

5. For study of $\bar{p}p$ interactions in 2-2.5 GeV region it's necessary to take into account strong coupling with $\Lambda\bar{\Lambda}$ and $\Sigma\bar{\Sigma}$ channels. We'll consider this question in other paper. Now let us point out only that $\bar{p}p$ cross-sections energy dependence must have a definite irregularities near $\Lambda\bar{\Lambda}$ and $\Sigma\bar{\Sigma}$ thresholds due to the $\Lambda\bar{\Lambda}$ and $\Sigma\bar{\Sigma}$ quasinuclear states existence (see /24/). Significant part of the heavy quasinuclear mesons annihilation decay channels must contain strange particles. In this connection let us note that isoscalar 2^+ resonances with mass 2160 and 2320 MeV, recently discovered in $\varphi\varphi$ system /29/, may be quasinuclear $\Lambda\bar{\Lambda}-\Sigma\bar{\Sigma}$ states. In this case 2320 MeV resonance should decay to $\Lambda\bar{\Lambda}$ channel with significant probability.

7. Conclusion

The main conclusion from results, obtained above, is the following. Our model calculations show, in agreement with the qualitative estimations /1/, /3/, that in quasinuclear approach the existence of narrow (with widths $\Gamma_a = 1 \div 50$ MeV) baryonium states naturally combines with the satisfactory low energy $\bar{p}p$ data description. This results are in striking contradiction with the optical /5-10/ and other model /12 -13/ calculations. All approaches describe $\bar{p}p$ cross-sections data equally well. But the baryonium levels annihilation widths in coupled channel model are by the order of magnitude smaller than in others.

At the same time we note that our model takes into account only the main physical features of $N\bar{N}$ annihilation (the strong nuclear attraction together with the short range "proper" annihilation interaction). The accurate (from fundamental principles of quantum field theory) $N\bar{N}$ annihilation properties calculation requires $N\bar{N}$ short range relativistic dynamics knowledge and isn't possible now.

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APPENDIX

For calculation of reaction K - matrix we use variable phase approach /30/, which leads to equation:

$$K'(r) = -[Y(r) + K(r)Z(r)]\,W(r)\,[Y(r) + Z(r)K(r)] \qquad (A.1)$$

with boundary condition $K(0) = 0$. Here $K(r)$ is reaction matrix for potential

$$\tilde{V}_{ij}(r') = V_{ij}(r')\,\theta(r - r'),$$

$$W_{ij}(r) = (m_i m_j)^{1/2}\,V_{ij}(r),$$

m_i is the particle mass in channel i,

$$Y_{ij}(r) = k_i^{-1/2}\, j_\ell(k_i r)\,\delta_{ij}\,; \quad Z_{ij}(r) = -k_i^{-1/2}\, n_\ell(k_i r)\,\delta_{ij}$$

for open channel,

$$Y_{jj}(r) = (-1)^{\ell+1}(2|k_j|)^{-1/2}\,[j_\ell(i|k_j|r) - i\,n_\ell(i|k_j|r)],$$

$$Z_{jj}(r) = i^{\ell+1}(2|k_j|)^{-1/2}\,[j_\ell(i|k_j|r) + i\,n_\ell(i|k_j|r)]$$

for close channel,

$$k_j = [m_j(E - 2m_j)]^{1/2},$$

E is the total energy,

$j_\ell(x)$ and $n_\ell(x)$ are known spherical Bessel and Neuman functions. In considered two coupled channel case, matrix equation (A.1) reduces to three nonlinear first order equations system for independent elements of $K(r)$ matrix. Thi system is solved numerically by the scheme, described in /31/.

It's easy to calculate S - matrix by known K - matrix:

$$S(E) = (1 - iK)^{-1}(1 + iK).$$

Resonances parameters are determined by the S - matrix energy dependence:

$$S_{jj}(E) = \exp(2i\delta_j^b)[1 - i\Gamma_j/(E - m_R + i\Gamma/2)].$$

Here δ_j^b is background phase (slow changed function of energy). Resonance mass m_R is the energy, at which $\dot{S}$ - matrix most rapidly change. Total width Γ and partial width Γ_1 are calculated according to the formulas

$$\Gamma = 4(|S_{11}'| + |S_{22}'|)^{-1}, \quad \Gamma_1 = |S_{11}'|\,\Gamma^2/4$$

where all derivatives are taken at $E = m_R$.

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Table 1

Quasinuclear baryonium levels with nonzero orbital angular momentum with annihilation

$^{2S+1}L_J$	$I^G(J^P)$	Mass, MeV	Total width, MeV	$\Gamma_{N\bar{N}}/\Gamma$
$^1P_1$	$1^+ (1^+)$	1875	50	—
$^3P_0$	$1^- (0^+)$ $0^+ (0^+)$	1842 1590	65 8	— —
$^3P_1$	$1^- (1^+)$ $0^+ (1^+)$	1756 1585	55 10	— —
$^3P_2$	$1^- (2^+)$ $0^+ (2^+)$	1885 1875	50 55	0,35 —
$^1D_2$	$1^- (2^-)$ $0^+ (2^-)$	1990 2050	85 130	0.32 0.15
$^3D_1$	$1^+ (1^-)$ $0^- (1^-)$	1935 1637*; 1815**	37 1*; 8**	0.27 —
$^3D_2$	$1^+ (2^-)$ $0^- (2^-)$	1975 1970	80 76	0.38 0.43
$^3D_3$	$1^+ (3^-)$ $0^- (3^-)$	2000 2000	95 96	0.26 0.25
$^3F_2$	$0^+ (2^+)$	1937	3.4	0.49

* at cutoff radius $r_c = 0.63$ fm.

** at $r_c = 0.68$ fm.

Table 2

Quasinuclear baryonium level with nonzero orbital angular momentum without annihilation

$^{2S+1}L_J$	$I^G(J^P)$	Mass, MeV	Width, MeV
$^1P_1$	$1^+(1^+)$	1897	38
$^3P_0$	$1^-(0^+)$ $0^+(0^+)$	1882 1645	2.5 —
$^3P_1$	$1^-(1^+)$ $0^+(1^+)$	1847 1672	— —
$^3P_2$	$1^-(2^+)$ $0^+(2^+)$	1900 1894	64 22
$^1D_2$	$1^-(2^-)$ $0^+(2^-)$	> 2050 > 2050	> 500 > 500
$^3D_1$	$1^+(1^-)$ $0^-(1^-)$	2010 1715*; 1875**	320 —
$^3D_2$	$1^+(2^-)$ $0^-(2^-)$	2020 2015	450 400
$^3D_3$	$1^+(3^-)$ $0^-(3^-)$	> 2050 > 2050	> 500 > 500
$^3F_2$	$0^+(2^+)$	1982	10

* At cutoff radius r_c = 0.63 fm.

** At r_c = 0.68 fm.

FIGURE CAPTIONS

Fig. 1 Motion of quasinuclear S-wave bound state pole with annihilation constant increasing, E is the kinetic energy of $N\bar{N}$ pair. Numbers are $v\sigma_a/_{v\to 0}$ values in mb. Figure is taken from ref. /14/.

Fig. 2 Motion of quasinuclear d-wave bound state pole with annihilation constant increasing. Point 1 corresponds to $\sigma_a/\sigma_a^{UL} = 0.9$ at momentum $K_1 = 300$ MeV/c (σ_a^{UL} is d-wave annihilation cross-section unitary limit). Figure is taken from ref. /19/.

Fig. 3 Motion of quasinuclear d-wave resonance poles with annihilation constant λ increasing. Point 1 correspond to the total width minimum value $\Gamma = 5$ MeV ($\Gamma = 15$ MeV at $\lambda = 0$). Figure is taken from ref. /19/.

Fig. 4 Annihilation cross-section: $v\sigma_a$ as a function of the total energy E. Dashed line is the contribution of isoscalar $^3F_2$ (1937) resonance. Experimental data are taken from ref./22/ (points) and ref./23/ (crosses).

Fig. 5 Elastic $\bar{p}p$ scattering cross-section σ_e (curve 1) and charge exchange ($\bar{p}p \to \bar{n}n$) cross-section (curve 2) against E. Dashed lines are the contribution of isoscalar $^3F_2$ (1937) resonance. Experimental data are taken from ref. /22/.

Fig. 6 Ratio of partial annihilation cross-section with (σ_a) and without $(\bar{\sigma}_a)$ nuclear interaction taken into account for orbital angular momentum $\ell = 0$, 1 and 2 (curves 1, 2 and 3 correspondingly).

Fig. 7 Dependence of $^3D_1$ (isospin I = 0) annihilation cross-section $v\sigma_a$ (curve 1), elastic $N\bar{N}$ cross-section (curve 2) and scattering cross-section of particles in boson annihilation channel (curve 3) on E in vicinity of $^3D_1$ (1935) resonance.

Fig. 8 Argan diagram for $K_1 f_{11}$ (curve 1) and $K_2 f_{22}$ (curve 2) (f_{11} and f_{22} are $^3D_1$ amplitudes with isospin I = 0 for elastic $N\bar{N}$ scattering and scattering of particles in annihilation channel). Numbers near points are the total energy E in MeV. Dashed curve is the unitary circumference.

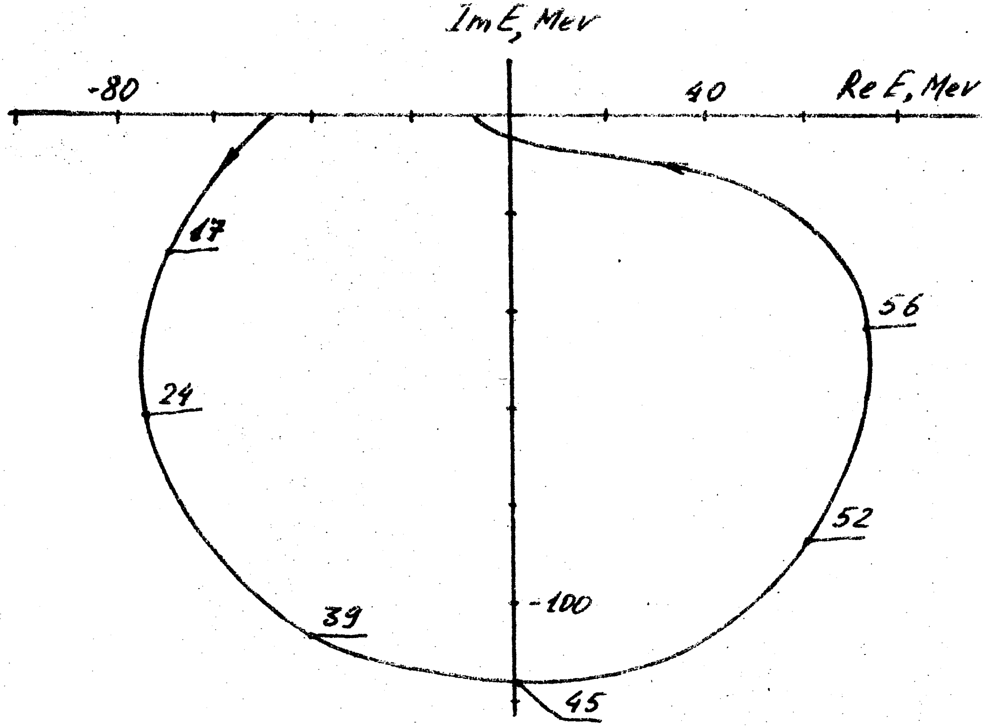
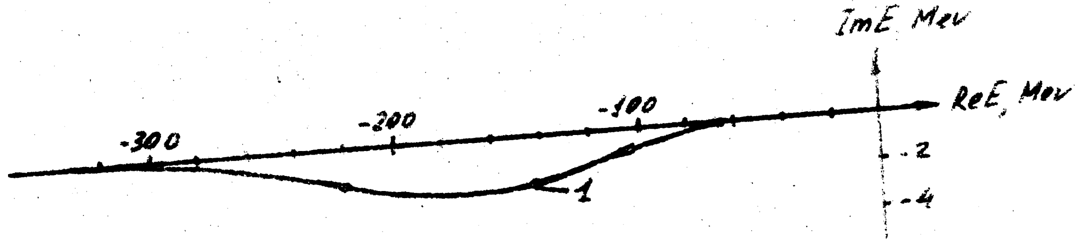


Fig. 1.



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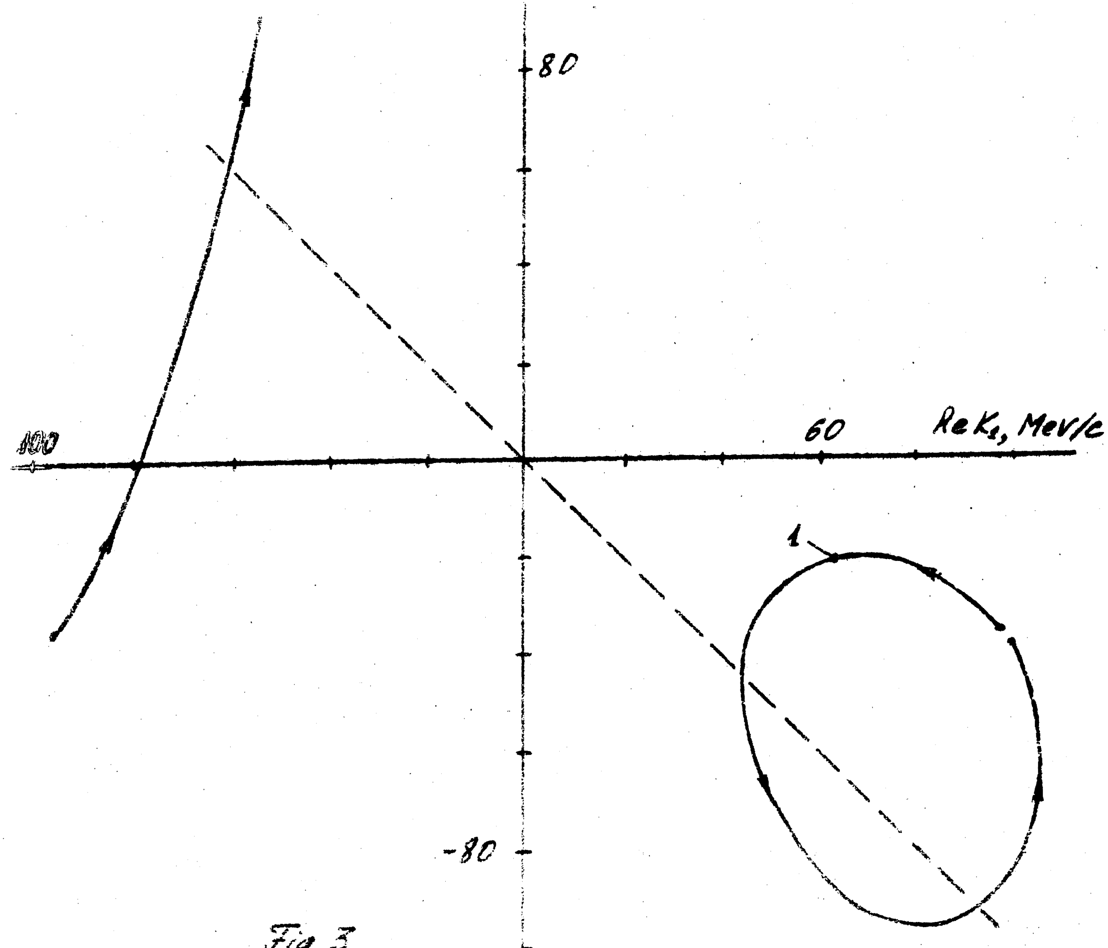
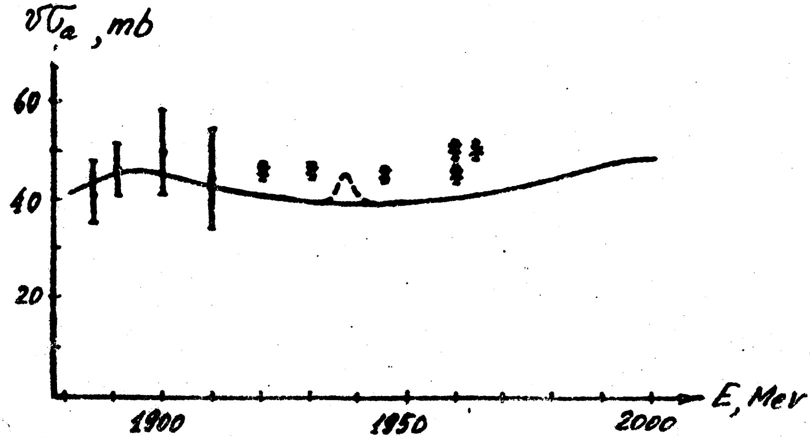


Fig. 3



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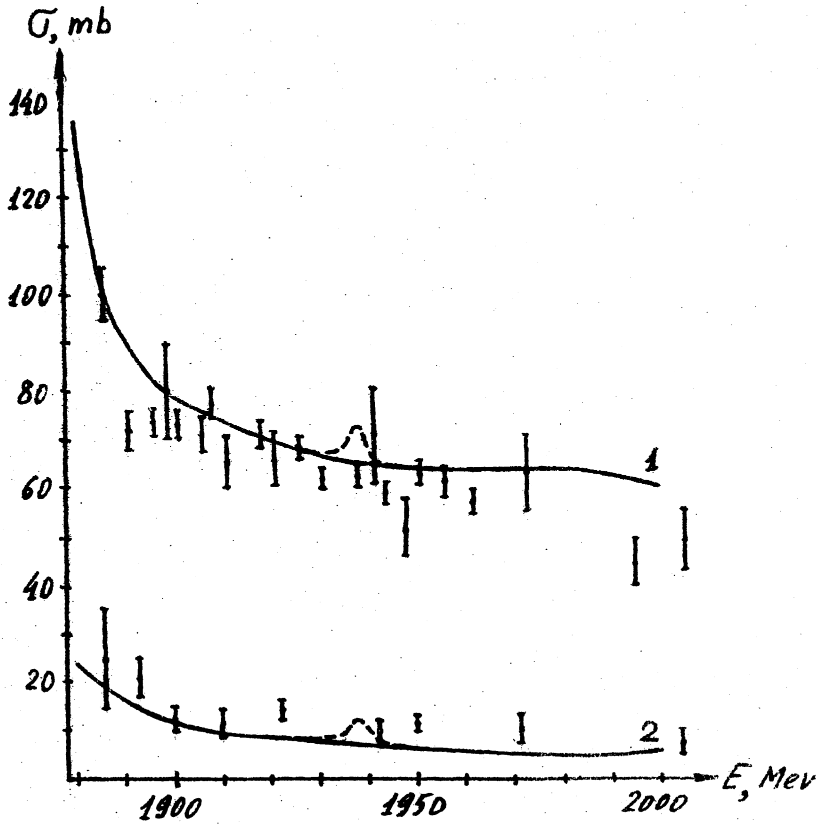

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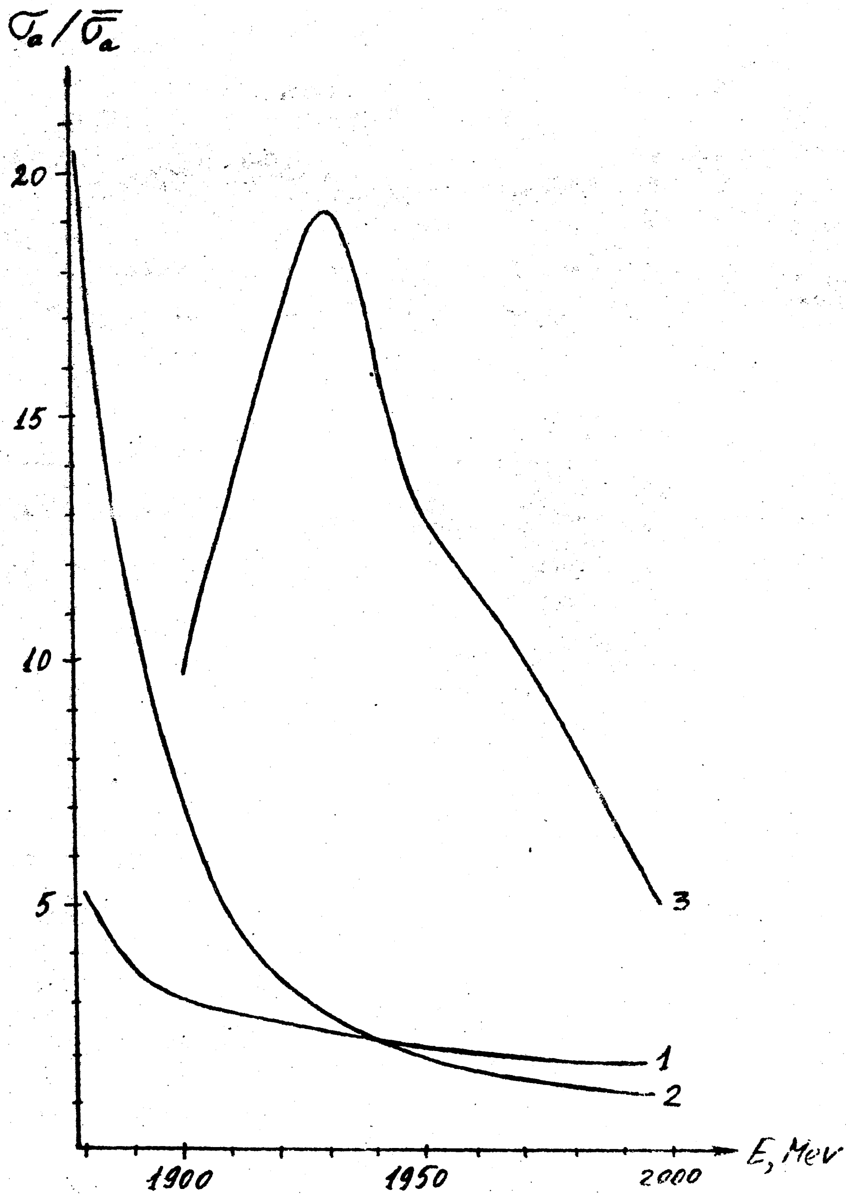

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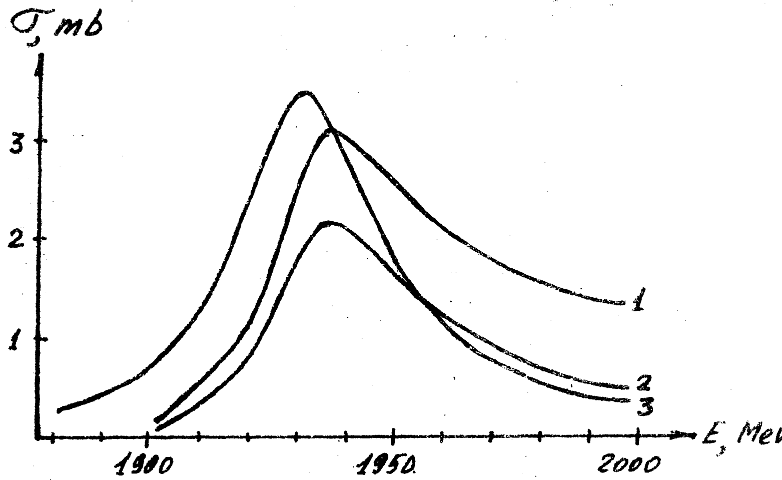

Fig. 7.

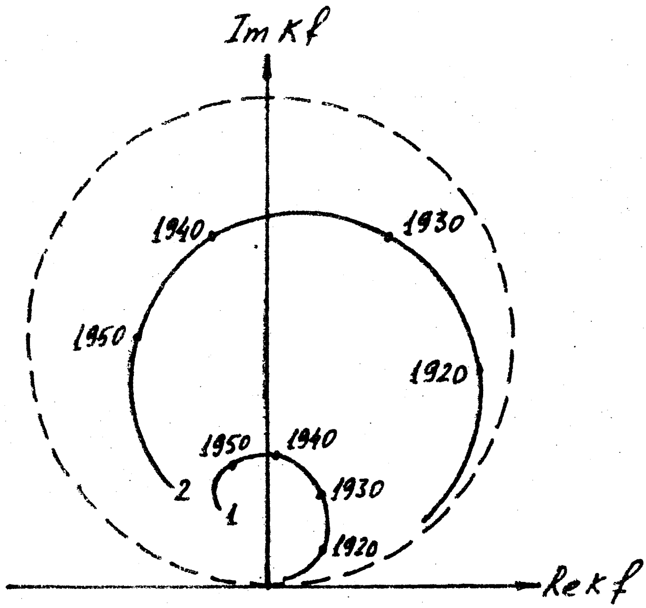

Fig. 8.

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