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ON A UNITARY DESCRIPTION OF LOW-ENERGY PION-NUCLEUS SCATTERING

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1. The description of the pion-nucleus scattering in terms of an optical potential has raised much attention in recent years[1-8]. The simple first-order optical models give a correct description of the elastic scattering data in the 120-250 MeV region (pion kinetic energy, T_π, in the lab.system) even on such light nuclei as ^3He and ^4He. A different situation occurs for scattering at lower energies (see review [2]). The disagreement becomes still larger with decreasing energy or given fixed energy, with decreasing of the nuclear size. To obtain a reasonable fit to existing data, one must essentially complicate the originally simple concept of the first-order optical potential. As was mentioned in [2], although the recent calculations [5,6] agree rather well with experiment, the agreement may be fortuitous. An apparent sensitivity of calculations is observed in this energy region to various computational details.

In this situation it would be helpful to apply to a new unitary approach of the description of the pi-nucleus scattering recently proposed in [9,10], based on the method of evolution in coupling constant (CCE) (see review [11]). In this approach, an iteration procedure for the direct calculation of pion-nucleus phase shifts can be developed. The basic element of the given expansion is the so-called two-body pion-nucleon matrix u. This quantity is simply related to πN -partial phase shifts. The general formalism was presented in [10]. The goal of this paper is to apply it to the description of the pion elastic scattering data on light nuclei in the low-energy region. Here we consider the first-order approximation in the two-body u -matrix, which in the present approach plays the role of the first order optical potential.

The paper is organized as follows. Section 2 contains a short review of the formal aspects of the theory. In Sec.3 the first-order approximation for the pi-nucleus phase shifts is considered. Their representation in terms of the elementary πN-phase shifts and nuclear densities is obtained. The numerical results are discussed in Sec.4.

2. In the problem of π -nuclear interaction considered in the framework of the CCE-method the Hamiltonian for the system is [9,10]

$$H = K_\pi + H_A + \lambda U, \quad U = \sum_{i=1}^{A} U^i, \qquad (1)$$

where K_π is the pion kinetic-energy operator, H_A denotes the nuclear Hamiltonian, U^i is the pion interaction with an i-th nuclear nucleon and λ plays the role of the πN coupling constant. The pure nuclear problem with the channel Hamiltonian:

$$h = K_\pi + H_A \qquad (2)$$

is assumed to be known and the system evolution in coupling constant λ from $\lambda=0$ with the switched-off pi-nucleus interaction to the realistic value $\lambda=1$ is considered.

The matrix elements $U_{\mu\nu} = \langle\mu|U|\nu\rangle$ of the potential over the eigenfunctions $|\mu\rangle, |\nu\rangle$, etc., of the Hamiltonian H are the basic quantities in the CCE-method. The exact eigenvalues of H are defined by the known equation $dE_\mu/d\lambda = U_{\mu\mu}$. The partial phases of scattering of two particles (no matter, elementary or composite) are given by the relation *

$$d\delta(k)/d\lambda = -\pi\epsilon(k)\{U_{\mu\nu}(\lambda)\}, \qquad (3)$$

where $|\mu\rangle = |\vec{k}, -\vec{k}|$, $|\nu\rangle = |\vec{k}', -\vec{k}'\rangle$ $(k = |\vec{k}| = |\vec{k}'|)$, $\epsilon(k) = \mathfrak{M}k/2\pi^2$ is the level density; $\mathfrak{M}$, the reduced mass, $\vec{k}$ and $\vec{k}'$ are momenta in the c.m.s. before and after collision. There is a system of the nonlinear integro-differential equations for the potential matrix elements $U_{\mu\nu}$. In /9/ some iteration procedure for solving these equations was developed. The series obtained for $U_{\mu\nu}$ is the expansion in powers of the exact two-particle matrix element u^i_{mn} of the pion interaction with a separate nuclear nucleon (or briefly, the two-body u-matrix). On the energy surface of the two interacting particles it defines the πN-phase shifts by the relation (3). Note, that each term of this expansion is Hermitian. Therefore, we arrive at the scattering matrix which is unitary at each step of successive approximations.

Let eigenfunctions of the channel Hamiltonian h(2) be $|\vec{k},n\rangle$, where $\vec{k}$ denotes pion momenta in the pi-nucleus c.m. (Acm) and n the properly antisymmetrized nuclear state $(n=0,1,2,...;$ $n=0$ denotes the ground state). The matrix element in (3) corresponding to the transition from state $|\vec{k},0\rangle$ to the $|\vec{k}',0\rangle$ ($\vec{k}$ and $\vec{k}'$ are the meson momenta before and after collision)

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*Here we omit indices of the angular momentum, spin and isospin in relations like (3). The braces in r.h.s. of (3) denote appropriate partial harmonics of the matrix element.

can be represented as follows [9]

$$U_{\mu\nu}(\lambda) \equiv \langle \vec{k}, 0 | \hat{U}(\lambda) | \vec{k}', 0 \rangle . \tag{4}$$

Two first terms of the expansion for $\hat{U}$ was explicitly reproduced in [9] along with their graphical image. Here we write only the first term

$$\hat{U}(\lambda) = \sum_{i=1}^{A} \hat{u}^i(\lambda) = \sum_{i=1}^{A} \sum_{n,m} |n\rangle_0 \, u^i_{nm}(\lambda) \, {}_0\langle m| , \tag{5}$$

where $|n\rangle_0$, $|m\rangle_0$, etc., are eigenfunctions of the free Hamiltonian $H_0 = K_\pi + K_A$ (K_A labels kinetic energies of nucleons).

The calculation of the pi-nucleus phase shifts by eq. (3) is appropriate in the case of the very low-energy region, where nucleus can be considered as an elementary particle. At higher energies in full analogy with the optical model method [1-4], it was shown that the many-body problem of π-nucleus elastic scattering can be reduced to the two-body one. The generalization of (3) is

$$d\delta(k)/d\lambda = -\pi\epsilon(k) \, |\langle \vec{k}, 0 | \hat{U}_0(E, \lambda) | \vec{k}', 0 \rangle| , \tag{6}$$

where $\hat{U}_0(E,\lambda)$ is some effective energy-dependent operator. It is connected with $U(\lambda)$ in eq. (4) by an exact integral equation (see ref. [10]). This equation has an iterative solution in powers of $\hat{U}(\lambda)$ and therefore (5) in powers of the two-body matrix u.

Below we shall consider the first-order approximation for $\hat{U}_0$. In general, the exact $\hat{U}_0(E,\lambda)$ -operator is the non-Hermitian. Its non-Hermitian part represents the contribution of inelastic channels to the elastic one. But the first approximation, $\hat{U}_0(E,\lambda) = \hat{U}(\lambda) = \sum_i \hat{u}^i(\lambda)$ (see (5)), is Hermitian and reproduces (6) real phase shifts. Thus one may believe that this approximation will be appropriate at comparatively low energy pi-nucleus-scattering region.

3. In the first order approximation (5) for the pion-nucleus phase shifts, using antisymmetrized target wave functions we have

$$\delta(k) = -\pi A \epsilon_A(k) \int_0^1 d\lambda \, |\langle \vec{k}, 0 | u^1(\lambda) | \vec{k}', 0 \rangle| , \tag{7}$$

where $\epsilon_A(k)$ labels the level density of the π-nucleus scattering states in A cm . The matrix element has the form

$$\langle \vec{k}, 0 | u^1(\lambda) | \vec{k}', 0 \rangle = \int \frac{d\vec{p}}{(2\pi)^3} \langle \vec{p}, \vec{k} | u(\lambda) | \vec{p} - \vec{q}, \vec{k}' \rangle F_{00}(\vec{p}, \vec{p} - \vec{q}) , \tag{8}$$

where $\vec{q}=\vec{k}-\vec{k}'$ is the transfer momentum. The overlap, F_{00}, is defined using the momentum-space ground-state wave function, $\psi(\vec{k}_1, \vec{k}_2,\ldots,\vec{k}_A)$:

$$F_{00}(\vec{p},\vec{p}') = \int \prod_{i=2}^{A} \frac{d\vec{k}_i}{(2\pi)^3} \psi^*(\vec{p}, \vec{k}_2,\ldots,\vec{k}_A)\psi_0(\vec{p}',\vec{k}_2,\ldots,\vec{k}_A)\delta(\vec{p}+\vec{k}+\sum_{j=2}^{A}\vec{k}_j) . \quad (9)$$

In (8) and (9) the summation over spin-isospin variables is also implied.

In [10] we had calculated (7) and (8) in the static limit ($m/M \to 0$, where m and M label respectively the pion and nucleon masses) of the theory. Here we shall consider it in the factorization approximation which is usually employed in the calculation of an optical potential [1-4]. It assumes that u can be taken outside the integral in (8) at some average nucleon momentum called $\vec{p}_0$. Then the matrix element simplifies to the form:

$$<\vec{k},0|\, u^1(\lambda)|\vec{k}',0> = <\vec{k},\vec{p}_0|\, u(\lambda)\, |\vec{k}', \vec{p}_0-\vec{q}>\rho(\vec{q}) , \quad (10)$$

where the nuclear form factor, $\rho(\vec{q})$, is

$$\rho(\vec{q}) = \int F_{00}(\vec{p},\vec{p}-\vec{q})\, d\vec{p}/(2\pi)^3 . \quad (11)$$

The accuracy of (10) depends, of course, on the choice [4] of $\vec{p}_0$.

The next assumption consists in that the two-body u-matrix in (10) is on energy shell (impulse approximation), i.e., describes the free πN scattering*. This simplifies the task of expressing of the π-nucleus phase shifts in terms of the πN-ones (see below). We also admit the picture, in which the nucleons are "frozen" in the target nucleus, and, hence in Acm $\vec{p} = -\vec{k}/A$. All mentioned above assumptions are usually employed in the construction of the first-order optical potential [4].

Thus, in (10) the two-body u-matrix corresponds to the free scattering in Acm. Let us express it in terms of the $\tilde{u}$-matrix in the 2 cm (πN- c.m. system) which directly relates to πN phase shifts by (3). Considering that the u-matrix has the same transformation properties as the scattering matrix, t, we have**

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*This requirement is satisfied in the static limit [10] but in general it is not.

**It immediately follows, for example, from eq. (4), in [10] which connects the u- and t-matrices.

$$<\vec{k},\vec{p}_0\,|u(\lambda)|\,\vec{k}',\vec{p}_0-\vec{q}> = \gamma <\vec{\kappa}\,|\tilde{u}(\lambda)|\vec{\kappa}'>. \tag{12}$$

Here $\vec{\kappa}$ and $\vec{\kappa}'$ denote relative momenta in the 2 cm. The collision energy E_0 and momentum $\kappa = |\vec{\kappa}'| = |\vec{\kappa}|$ in the 2 cm are determined by using the invariance of the four-vector product $s = (P_\pi + P_N)^2$:

$$E_0^2 = s = (\omega_\pi(\kappa) + \omega_N(\kappa))^2 = \\ = (\omega_\pi(k) + \omega_N(k/A))^2 - k^2(1-1/A)^2, \tag{13}$$

where $\omega_\pi(p) = (p^2+m^2)^{1/2}$, $\omega_N(p) = (p^2+M^2)^{1/2}$. The scattering angle in 2 cm $(\cos\theta_{\pi N} = \vec{\kappa}\vec{\kappa}'/\kappa^2)$ is related to the Acm one $(\cos\theta = \vec{k}\vec{k}'/k^2)$ by the relation:

$$\cos\theta_{\pi N} = \alpha + \beta\cos\theta, \tag{14}$$

where $\beta = k^2/\kappa^2$ and $\alpha = 1-\beta$. It follows from the invariance of the four vector products $t = (P_\pi - P_\pi')^2$. The factor γ in (12) is:

$$\gamma = \omega_\pi(\kappa)\,\omega_N(\kappa)\,/\,\omega_\pi(k)\,\omega_N(k/A). \tag{15}$$

By substituting (12) into (7) we get

$$\delta^{(1)}(k) = -A\,\pi\,\epsilon_A(k)\,\gamma\,\{\rho(q)\int_0^1 d\lambda <\vec{\kappa}\,|\tilde{u}(\lambda)|\vec{\kappa}'>\}, \tag{16}$$

where the level density $\epsilon_A(k) = k^2/[2\pi^2\, dE_{Acm}(k)/dk]$, $E_{Acm}(k) = \omega_\pi(k) + \omega_A(k)$ labels the pi-nucleus collisions energy in the Acm-system $(\omega_A(k) = (k^2 + (AM)^2)^{1/2})$.

The spin and isospin structure of the problem was thoroughly analysed in /10/. Below (Sec.4) we consider the pion scattering on nuclei with zeroth total spin and isospin. In this case /10/ the phase shifts $\delta^{(1)}$ are expressed in terms of the spin-independent two-body matrix elements, $<\vec{\kappa}\,|u_c^I(\lambda)|\vec{\kappa}'>$ at a given isotopic πN-state $I = 1/2, 3/2$ as

$$\delta_L^{(1)}(k) = -A\pi\epsilon_A(k)\gamma\,\{\rho_0(q)\int_0^1 d\lambda\,[\tfrac{2}{3}<\vec{\kappa}\,|u_c^{3/2}(\lambda)|\vec{\kappa}'> + \\ + \tfrac{1}{3}<\vec{\kappa}'|\,u_c^{1/2}(\lambda)\,|\vec{\kappa}'>]\}_L, \quad L = 0,1,2,\ldots, \tag{17}$$

where $\rho_0(q)$ is the Fourier transform of the nuclear density, the symbol $\{f(x)\}_L \equiv \frac{1}{2}\int_{-1}^{1} dx P_L(x) f(x)$, where P_L are Legendre polynomials, $x = \hat{k}\hat{k}'$.

To express pi-nucleus phase shifts (17) in terms of πN ones it is necessary to make the partial-wave decomposition of the matrix elements and the nuclear form factor [10]. By substituting these expansions into (17) and integrating over λ with the help of the basic relation (3), we obtain

$$\delta_L^{(1)}(k) = A \frac{\epsilon_A(k)}{\epsilon_2(\kappa)} \sum_{\substack{\ell,\ell',\ell'' \\ j=\ell\pm\frac{1}{2}}} (j+\frac{1}{2}) \begin{pmatrix} L & \ell' & \ell'' \\ 0 & 0 & 0 \end{pmatrix}^2 \times \tag{18}$$
$$d_{\ell\ell'} \rho_{\ell''}(k) [\frac{1}{3} \delta_{\ell_j}^{1/2}(\kappa) + \frac{2}{3} \delta_{\ell_j}^{3/2}(\kappa)],$$

where $\delta_{\ell_j}^I$ denotes πN -phase shifts in each eigenchannel (ℓ, I, j), $\epsilon_2(\kappa)$ labels the level density of the pion-nucleon scattering states in the 2 cm-system: $\epsilon_2(\kappa) = \kappa^2/[2\pi^2 dE_0/d\kappa]$ with $E_0(\kappa)$ defined in (13). The mixing factors, $d_{\ell\ell'}$, enter into (18) due to the angle transformation (14). The expressions for these one can find in [4]. For example, $d_{00}=1$, $d_{10}=\alpha$, $d_{11}=\beta$, where α and β are defined in (14) and $d_{\ell\ell'}=0$ for $\ell'>\ell$. The expression (18) is similar to that of the first order optical potential (see, e.g., (2.36) in [4]). Thus, the pion-nucleus phase shifts can be calculated by (18) using the experimentally defined πN - phase shifts and nuclear form factors.

4. We present now some numerical results for pion-light-nucleus scattering in the low energy region. Our object is not, in fact, a detailed comparison with experiment, but rather the study of the accomplishment of the obtained simple approximation (18) for pi-nucleus phase shifts. Calculations for ^4He were carried out in the 24-120 MeV energy region and for ^{12}C at 30 and 50 MeV. Only s- and p-πN -phase shifts were taken into account. We used the πN- phase shifts from [12,13]. The nuclear form factor was chosen to be of the form used to parametrize electron scattering data (see ref. [4]):

$$\rho_0(q) = (1-\alpha(qa)^2/2(2+3\alpha))\exp(-(qa)^2/4),$$

where $\alpha=(A-4)/6$. The parameter a for ^4He was taken to be 1.38 fm as in [14,15] and for ^{12}C - 1.59 fm [4]. The Coulomb interaction was taken into account approximately by the following formula for the pi-nucleus scattering amplitude:

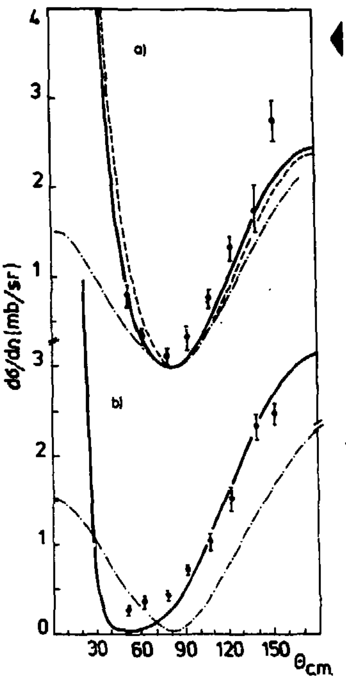
$$f_{\pm}(\theta) = f_c^{\pm}(\theta) + \frac{1}{k}\sum_{L=0}^{\infty}(2L+1)e^{2i\sigma_L} e^{i\delta_L}\sin(\delta_L)P_L(\cos\theta). \tag{19}$$

where $f_c^{\pm}$ is the point-like Coulomb amplitude [16], σ_L label Coulomb phase shifts and δ_L are defined in (18). One can believe[17] that this approximation is not so bad especially in the low-energy region.

The results for the $\pi^{\pm}-{}^4He$ differential cross section are presented in Figs.1-5 along with the experimental data[14,18,19]. The solid lines denote our calculations with (18) and (19), where Solomon's πN-phase shifts[12] (M.S. πN) are used as an input. As in the optical (see refs.[2,6]), calculated results are sensitive to the choice of different sets of πN-phase (see Figs.1a and 2b, where dashed lines show our results with the πN phase shifts from[13]). The M.S. πN-phase shifts give apparently the best description of the experimental data. We also present in Figs.1-5 some optical model calculations based on approximations like (18). In Fig.1 Dedonder's[8] and in Figs.3a and 5b Mach's[7,14] results with the Kisslinger potential are shown. In Fig.2b we present Landau's calculation[5] with the improved optical potential[4] (2-body Energy, M.S. πN). One can see that unlike the standard-optical-model calculations, the agreement of our results with experimental data becomes better with decreasing energy. At energies lower than, say, 70-80 MeV the approximation (18) gives an acceptable description of the $\pi^{\pm}-{}^4He$ scattering data. This also can be seen from the comparison of the calculated by (18) $\pi-{}^4He$-phase shifts with the results of the phase shift analysis (PSA) data[22] (see Figs. 6 and 7). In these figures we also present Nordberg's[18] and Crowe's[19] phase shift data at 24, 51, 68 and 75 MeV and the predictions of the optical model[7,22]. The PSA[22] predicts the absorption P-wave parameter to be unity at energies lower than 70-80 MeV. This is not reproduced by the optical model calculations (see discussion in[22]).

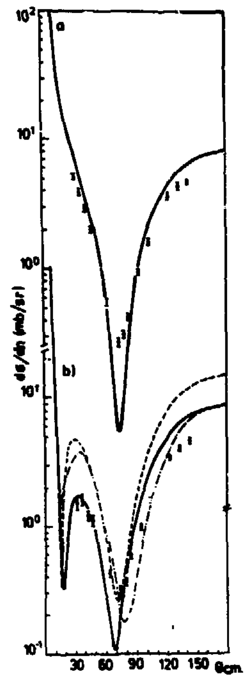
At higher energies our calculations considerably exceed differential cross section data in the large-angle scattering region. This is in accordance with the known fact[21] that the ratio of the inelastic cross section to the elastic one increases with increasing energy, or given a fixed energy, with increasing scattering angle (and A). Note that the dip position is predicted correctly at all considered energies.

Numerical results for $\pi^{+}-{}^{12}C$ elastic scattering at 30 and 50 MeV are presented in Figs.8 and 9 along with the experimental data from Refs.[23,24]. We compare our results (solid lines) with the optical model results of Landau and Thomas[5,6,23]. In Fig.8 the dashed and dash-dotted lines label Landau's results[23], respectively, without and with inclusion of the true pion absorption channel. In these calculations the three body choice of the subenergy for the πN-collisions matrix was taken (3-body Energy). In Fig.9 Landau's results[5,23] without



<u>Fig.1</u>. Pion-^{4}He differential cross sections at T_π=24 MeV (absolute scale). The results of the present unitary approach (eqs. (18) and (19)) are shown by the full (M.S.πN [12]) and dashed (Alm.-L. πN [13]) lines. The dash-dotted line is obtained with the Kisslinger optical potential by Dedonder [8] (without Coulomb, πN phase shifts from ref.[20]). The experimental data are from ref.[18] a)(π^-, ^{4}He) and b) (π^+, ^{4}He).

<u>Fig.2</u>. Pion-^{4}He differential cross sections at T_π = 51 MeV. The results of the unitary approach (eqs. (18) and(19)) are shown by the full (M.S. πN [12]) and dashed (Alm-L. πN [13]) lines. The dash-dotted line shows the Landau calculation[5] with the improved optical potential (2-body Energy, M.S. πN [12]). The experimental data are from ref.[19] a)(π^-, ^{4}He) and b)(π^+, ^{4}He).



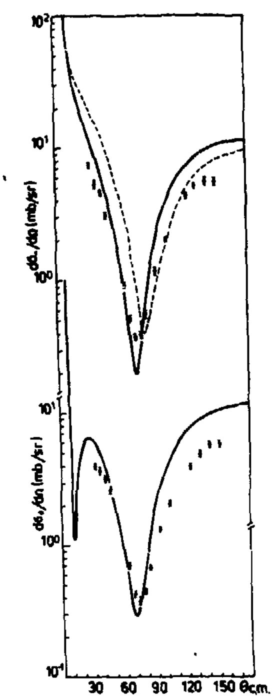


Fig.3. Pion - ^{4}He differential cross sections at $T_\pi = 68$ MeV. The full line is obtained with the unitary approach (eq. (18), M.S. πN). The dashed line is obtained with the Kisslinger type potential by Mach[7,14]. The experimental data are from ref.[19] a) (π^-, ^{4}He) and b) (π^+, ^{4}He).

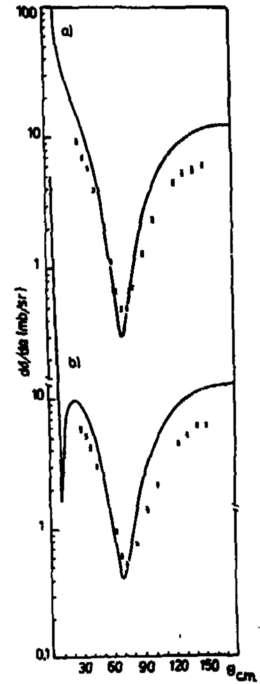


Fig.4. Pion - ^{4}He differential cross sections at $T_\pi = 75$ MeV. The full line is obtained with the unitary approach (eqs. (18) and (19), M.S. πN). The experimental data are from ref.[19]

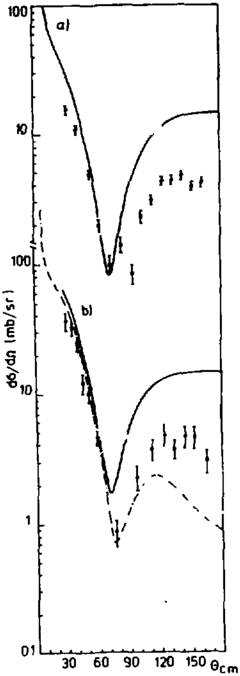


Fig.5. Pion - ^{4}He differential cross section at T_π = 98 and 120 MeV. The full line is obtained with the unitary approach (eqs. (18) and (19), M.S. πN). Mach's optical model calculation /14/ at 120 MeV with the Kisslinger type potential are shown by the dash-dotted line. The experimental data are from ref./14/ a) (π^-, ^{4}He), 98 MeV, b)(π^-,^{4}He), 120 MeV.

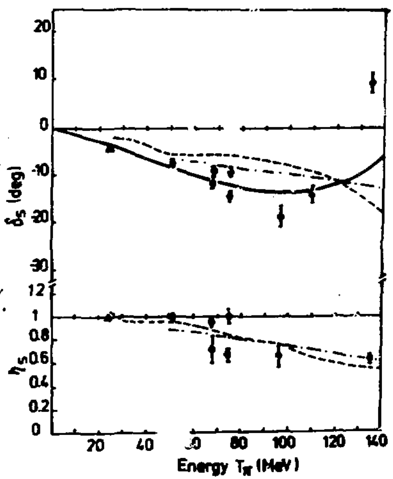


Fig.6. Energy dependence of the π-^{4}He phase δ_S and of the absorption parameter η_S The full line is obtained with the approximation (18) with the M.S. πN/12/(η_S= 1); the dashed lines the optical model calculations/7,22/; the dash-dotted lines the results of the energy dependent PSA/22/. Phase shifts of the PSA/22/ are denoted by the open circles, the Norenberg's result/18/ at 24 MeV by the black triangles and the Crowe's ones at 51, 68 and 75 MeV by the black circles.

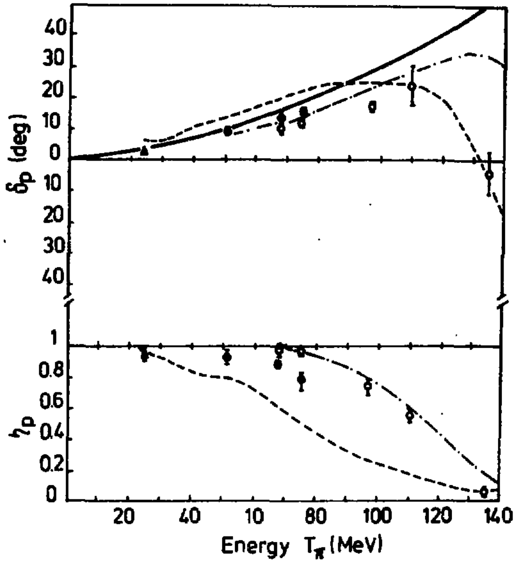
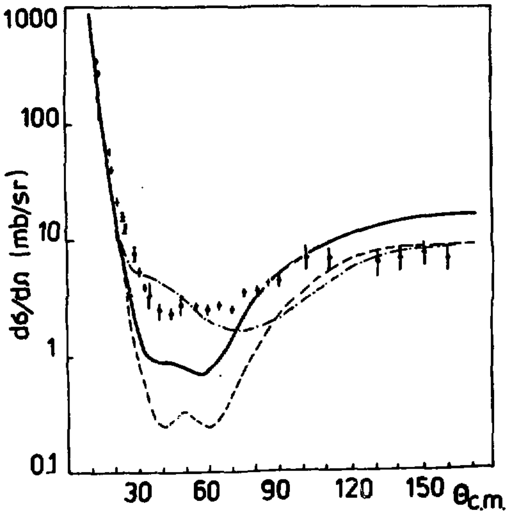


Fig.7. The same as in Fig.6 but for the $\pi-{}^4$He phase δ_P and for the absorption parameter η_P.

absorption, but with two different choices of the subenergy for the πN collision matrix are shown.

From Landau's results it follows that the optical model calculations are essentially sensitive to a specific choice of the πN -subenergy and that the true pion absorption plays a crucial role in obtaining an acceptable fit to data around 30 MeV. But from our results one can see that the absorption effect may not be so strong(see Fig.8).There are two second-order corrections which can, in fact, improve (or destroy) the agreement of our results with data. The first one is the rescattering effects of a pion by a nuclear nucleon, i.e., the correction to (5). Its importance was illustrated in /9/ by a case of the low-energy $\pi-d$ scattering. The second one (see eq. (23) in /10/) reflects the contribution of the possible excitation of a nucleus in intermediate states. Due to this correction the imaginary part of the pi-nucleus phase shifts will arise. A systematic consideration of these corrections will be made in a subsequent paper.



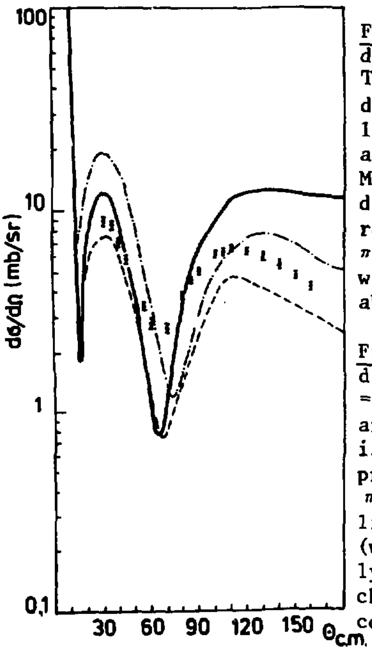


Fig.8. (π^+, ^{12}C) elastic-scattering differential cross section at T_π = 28.4 MeV. The experimental data are from ref.[23]. The solid line is obtained with the unitary approach (eqs. (18) and (19)), M.S. πN [12]). The dashed and dash-dotted lines label Landau's results[23] (3-body Energy, M.S. πN), respectively, without and with inclusion of the true pion absorption channel.

Fig.9. (π^+ , ^{12}C) elastic-scattering differential cross section at T_π = = 49.9 MeV. The experimental data are from ref.[24]. The solid line is obtained with the unitary approach (eqs. (18) and (19), M.S. πN). The dashed and dash-dotted lines label Landau's results[5,23] (without absorption), respectively, with the 3-Body and 2-Body choice of the subenergy for πN-collision matrix.

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