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PION INTERACTIONS WITH VERY LIGHT NUCLEI

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Мах Р. **E4 - 11099**

Взаимодействие пионов с легчайшими ядрами

В работе обсуждены современные теоретические модели для описания рассеяния пионов на ядрах ^2H, ^3He и ^4He. Рассматриваются также некоторые модели для поглощения пионов легчайшими ядрами. Приведен обзор последних экспериментальных данных.

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Pion Interactions with Very Light Nuclei

Present status is reviewed of our understanding of pion reaction mechanisms with very light nuclei. Problems connected with relativistic description of pion-nucleus reactions are briefly discussed. Several recent experimental data on πd, π^3He and π^4He reactions are displayed being confronted with predictions of theoretical models most frequently used.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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1. INTRODUCTION

Considerable progress has been reached in the past few years in both the experimental and theoretical investigations of pion reactions with few nucleon systems. The topic has been comprehensively reviewed at the Pittsburgh conference [1,2] one year ago and also in Zürich [3] this year. There is of course, a certain overlap between our presentation and that of Thomas [3]. However, new experiments are included here, which have not been reviewed previously, and especially the elastic scattering is discussed from a complementary point of view. Some remarks will be made concerning the problems common to the current theoretical models of pion-nucleus reactions. The extent to which these models fit recent experimental data will be demonstrated on several typical examples. Finally, outlooks and suggestions for the future work are presented.

Practically all microscopic calculations of pion-nucleus reactions are based on some version of many body scattering theory. Except for a very low energy region, pion is a relativistic particle (e.g., pion with energy 50 MeV is characterized by $\beta^2 = 0.46$), so that one usually starts from the Bethe-Salpeter equation in deriving both the Faddeev type equations [4,5] for πd reactions and the optical model [6,7], which is currently used for calculations of the pion elastic scattering by $A \geq 3$ nuclei and of related quantities. An alternative approach[8,9,10] to the construction of optical model relies on Goldberger-Watson multiple scattering theory, which is enriched by sophisticated relativistic corrections. The calculations based on the Faddeev equations differ, of course, substantially from the optical model ones. The former can take, in principle, fully into account intermediate excitations of deuteron (in fact, all present day calculations are approximate in this respect), whereas the optical model allows for elastic pion-nucleus scattering in the intermediate states only. Nevertheless, some approximations and shortcomings are common in deriving the two models. When the 3-dimensional reduction of the Bethe-Salpeter equation is performed, all left-hand cuts of the pion-nucleus amplitude are disregarded. Moreover, one neglects all mesonic and antinucleonic degrees of freedom (more precisely, states containing more than one or zero pions), what has the following consequences.

(i) Crossing symmetry of pion-nucleus amplitude is lost. It is not yet known, how important these effects are in the energy region 0-300 MeV. There are some indications[11], that the influence of crossing terms on the pion-nucleus scattering is not negligible for energies below the (3,3) resonance.

(ii) There arises a serious ambiguity[12,13] as to the definition of relative πN momenta and the two-body energy-two quantities that are necessary for evaluation of the πN amplitude used as input in microscopic calculations. This difficulty has probably a very deep origin, consisting in the fact that the trully relativistic theory should be a many body one. There are only two possible ways to coexist with the aforementioned ambiguity. Either all the particles are constrained to their mass shells and we have the Lorentz invariant but not covariant theory (see, e.g., ref. [8]), or having covariant theory we face the problem of constructing nuclear wave functions for off mass shell nucleons[6]. Recent calculations [14,15] seem to indicate that any reasonable choice of the form of relative πN momenta leads to very similar πd cross sections. On the other hand, a specific choice of the two-body collision energy could have important consequences for pion scattering in the whole energy interval 0-300 MeV. As will be discussed later, this is especially true in the case of optical model, where the two-body energy is essentially a free parameter.

(iii) True pion absorption is neglected. This means that the contribution of the pion absorption and reemission is not taken into account in pion-nucleus scattering calculations. Very little is known about the effects of absorption on the pion-nucleus scattering and the absorption itself remains the most obscure part of mesonic physics. Several authors[16-18] have shown that it is not possible to explain the recent elastic scattering data at energies 30-50MeV[19] without taking into account pion absorption at least in a phenomenological way. With decreasing energy the absorption processes will apparently play a still more important role.

In spite of the fact, that the discussed models have obvious drawbacks, the agreement between calculations and experimental data is quite good. Except special kinematical situations and, maybe, some rare reaction channels, the disagreement is not worse than 30-50 per cent. It means that we understand well the gross features of pion reactions with light nuclei, however, hard work will be needed in order we would be able to learn something from the pion-nucleus reactions about both the reaction mechanism (off-shell behaviour of the two-body amplitude, etc.) and the details of nuclear structure.

Appart from the Faddeev type theories and optical model, there are two important tools of investigation of the pion-nucleus reactions - the Chew-Low theory and the Glauber model. We will touch upon the later briefly in the following sections.

2. PION SCATTERING ON DEUTERON

Much attention has been paid to the πd reaction in the past few years, since the three-body problem can be solved with high accuracy and it provides a natural testing ground for current theories of pion-nucleus reactions. There are specific problems in low energy and (3,3) resonance energy region, so that it is convenient to split the discussion into two parts.

2.1. The (3,3) Resonance Region

Rather crude approximations have been done in earlier three-body calculations [20,21]. Either the NN rescattering [20] or nucleon spin [21] have been neglected and simple deuteron wave functions were used. The main aim of such calculations was to check the validity of fixed scatterer approximation and the necessity of various relativistic corrections. It has been established that the fixed scatterer approximation predicts rather poorly the total πd cross section and the large angle scattering [21]. Multiple πN scattering gives an effect of an order of 20-30 per cent for the elastic scattering on large angles [20].

The importance of NN rescattering has been pointed out in refs. [21,23] and clearly demonstrated in recent calculations of Rinat and Thomas [15] and Rivera and Garcilazo [14]. The NN interaction in $^3S_1$ channel lowers the larger angle part of elastic differential cross section by some 30 per cent bringing this part of the angular distribution in better agreement with experiment (the $^1S_0$ channel plays an inferior role only [14]). The calculated results obtained in refs. [14,15] are in good agreement with experiment at E_π = 142 and 180 MeV, however, the experimental errors are rather large (~ 30 per cent). A more complicated situation occurs at E_π= 256 MeV (Fig. 1), where the three-body calculations cannot

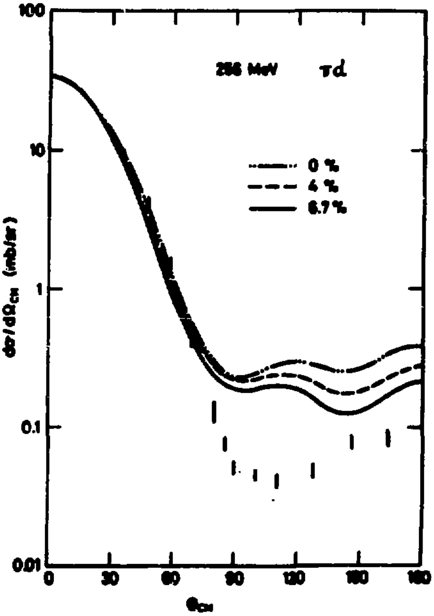

Fig. 1. Comparison of relativistic three-body calculations [15] with data [26].

explain the deep minimum at $\theta \sim 110^{\circ}$. Thomas has pointed out [8] that new LAMPF data [27] at 234 and 325 MeV exhibit a similar minimum, so that something is omitted in the theory. Before being too alarmed due to the discrepancy shown in Fig. 1, more complete calculations are to be performed. These should include NN rescattering in P-waves and besides the resonant πN P_{33}-wave also the remaining P, S and D ones (all these pieces were neglected in refs. [14,15]). There is another possibility, namely that the relativistic effects are not treated accurately enough for energies above the (3,3) resonance. In performing the 3 dimensional reduction of the Bethe-Salpeter equation according to the standard prescriptions, one looses "clustering" properties of dynamical equations. It means that in the existing calculations, even if one of the three particles is noninteracting, its energy will affect the internal energy of the other two particles, and therefore their dynamical interaction. It would be interesting to see the results of three body calculations in formalism, which preserves the usual clustering properties (e.g., in the formalism of Wightman and Gording [28]). More generally speaking, the πd scattering above (3,3) resonance can provide a very useful check of validity of approximations used in 3-dimensional reduction of the Bethe-Salpeter equation.

Finally, several calculations of πd elastic scattering have been done in framework of Glauber model[29]. As usual, the calculations fit the experiment very well in the region of small scattering angles. The Brueckner model was applied to the same reaction in an interesting way by Gabathuler and Wilkin[30]. The successful fit would be probably distroyed, if NN rescattering were included[15].

The previous discussion has concerned mainly the elastic πd scattering since there are no three body calculations of inelastic $\pi d \to \pi NN$ reaction. Recently, several measurements[25,31] have been published on $\pi^{\pm} d \to \pi^{\pm} pn$ and $\pi^+ d \to \pi^0 pp$ reactions, which could be at least qualitatively described by PWIA plus some final state rescattering corrections[31].

2.2. The Low Energy Region

In the energy region $E_\pi = 40 - 120$ MeV, besides the attraction in the P_{33} wave, an important role is played by the repulsion in πN S-waves, and the Coulomb interaction becomes more and more important with decreasing energy. There are only few experimental data on πd elastic scattering in this region. The best of them - πd scattering at 48 MeV-are shown in Fig. 2. Essentially nonrelativistic calculations done by Thomas [33] are in good agreement with the data. It should be mentioned, however, that the calculations are very sensitive in the broad Coulomb-nuclear interference region to various approximations used and to the uncertainties of input. Especially the isodoublet πN phase shifts are not reliably known at these energies.

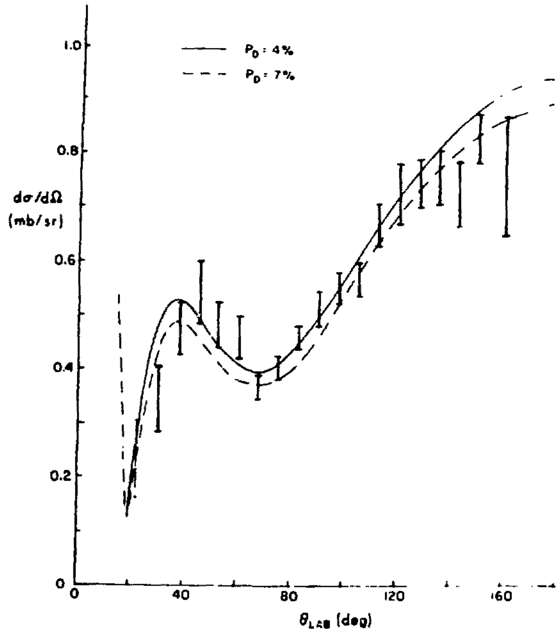

Fig. 2. Comparison of 47.7 MeV πd calculations of ref. [33] with data [32].

There are also several three-body calculations of the πd scattering length $a_{\pi d}$[34]. In the pioneering work of Afnan and Thomas[35] it was realized that considering the nucleon to be a πN bound state, the coupling of the NN and πNN systems could be included. This bootstrap approach permits, therefore, to include the pion true absorption in a rather unambigous way. The obtained $a_{\pi d}$ is in good agreement with experiment, which does not, however, represent a very stringent test of the theory because of large experimental errors. The work of Kopaleishvili et al.[36] seems to indicate, that even zero energy pion is not a nonrelativistic particle. Their values of $a_{\pi d}$ calculated with and without relativistic corrections differ substantially. Needless to say, that precise measurements of $a_{\pi d}$ would be of great significance.

3. PION ABSORPTION AND EMISSION REACTIONS

The reactions (π, N) and their inverse are of principal importance for our understanding of pion absorption and emission mechanisms in nuclei. Because of the large momentum transfer involved, the reaction is believed to be unique source of information about large momentum component of the nuclear wave function. It is well known[37], that the single nucleon absorption mechanism is not effective enough and some pion rescattering is needed to obtain correct order of magnitude of the (π, N) rection cross section. A double counting problem arises, taking the rescattering explicitly into account, since some part of it is already included in the nuclear wave function. There is a rather detailed discussion in the literature (see, e.g., refs.[38]) concerning the proper nonrelativistic form of the πNN vertex.

In the past two years, new experimental data have been published [39,40] on both the differential and total cross sections of the reaction $\pi d \to NN$. Green and Niskanen [41] were able to reproduce gross features of the total cross section including ΔN admixture in the NN wave function via coupled channel calculations. The ambitious relativistic boundary condition model developed by Brayshaw [42] can be considered as an extention of the bootstrap approach of Afnan and Thomas [35]. The model permits one to treat the $NN \to NN$, $NN\pi$, $d\pi$ and $\pi d \to \pi d$, $NN\pi$, NN reactions on the same footing. Several free parameters of the model were chosen so as to fit experimental $NN \to NN$ and $pp \to \pi^+ d$ cross sections. The predicted elastic πd angular distributions are in good agreement with experiment except for the "difficult" energy region $E_\pi \geq 200$ MeV.

Pion rescattering models were used also in calculating the (π,N) reaction on ^3He and ^4He nuclei [43]. More phenomenological approach was adopted by Fearing [44] who started from experimental $\pi d \to NN$ cross sections and took into account the pion and nucleon distortion in initial and final states, respectively. Fresh $^3He(\pi^-,n)d$ and $^4He(\pi^-,n)^3He$ differential cross sections [45] are only marginally fitted by all these calculations. Especially the magnitude of the cross sections is not correctly predicted. More refined theoretical models are obvioulsy needed for description of (π,N) reactions on He isotopes.

4. PION ELASTIC SCATTERING ON A = 3 and A = 4 SYSTEMS

There is an increasingly large amount of works in this field and the most important trends can only be sketched here. In contrast with earlier belief, the optical model appeared to be a very useful tool in studying the pion elastic scattering even on such light nuclei as ^3He and ^4He. The optical model is understood here as an approximation procedure, which leads to the integral equation for the pion-nucleus scattering matrix $T(E)$

$$<0|T(E)|0> = A<0|t(\tilde{E})|0>\{1+G_{00}(E)\frac{A-1}{A}<0|T(E)|0>\}. \qquad (1)$$

Eq. (1) is usually derived from Watson multiple scattering theory in two steps. (i) Only the ground state elastic scattering is retained in the intermediate states (coherent scattering approximation). (ii) Scattering by a bound nucleon is approximated by the free πN collision matrix $t(\tilde{E})$ at some appropriate energy $\tilde{E}$, which is essentially a free parameter of the model (impulse approximation). Pion-nucleon phase shifts and nuclear densities are required in this model as an input.

4.1. Pion Elastic Scattering on ^4He - Optical Model

There are new high quality data obtained in Dubna [46] and CERN [47] in the energy region 70 - - 250 MeV, which invoked a considerable theoretical activity. Because of simplicity of the target nucleus involved, the reaction proved to be a useful check for various sophisticated versions of the optical model. Coordinate space calculations (CSC) including the nucleon and nuclear recoil were done in refs. [10,46]. Several off energy shell extrapolations chosen for the πN collision matrix were also tested in this work, which represents a natural generalization of the Kislinger model. Landau [48] performed momentum space calculations (MSC) using a separable form of the πN interaction. Besides other corrections, he introduced three-body choice of the energy $\tilde{E}$ according to the prescriptions of Revai [49]. In this approach, the target nucleon is assumed to move in a mean field of the other (core) nucleons. Finally, comprehensive calculations have been done by Celenza, Liu and Shakin [50] using the covariant optical model.

The results of CSC are compared with Dubna data in Fig. 3 at two energies. Fit of similar quality

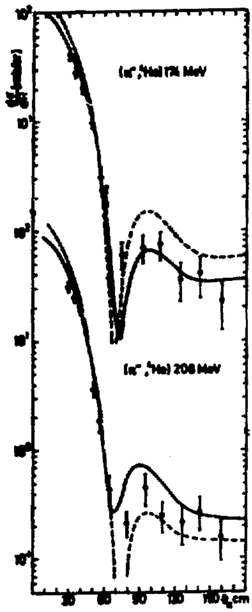

Fig. 3. Comparison of CSC with Dubna data. Two different off shell models were used.

was obtained in the whole (3,3) resonance region. Several qualitative conclusions can be drawn from the aforementioned calculations. (i) All the three versions of the optical model predict correctly the dip position, which occurs at approximately the same angle in the whole resonance region. This feature of π^4He data is in contrast with the pion scattering on heavier nuclei, where the dip occurs rather at fixed momentum transfer. (ii) Nucleon recoil correction (the "angle transformation") is an important constituent of the theory. Inclusion of this effect provides a large build up in the region of secondary maximum bringing this part of angular distributions in better agreement with experiment, Moreover, it ensures also the correct position of the dip of calculated curves. (iii) Because of the P_{33} dominance, pions are strongly absorbed in the elastic channel. As a result, calculations depend rather weekly on details of pion-nucleus dynamics. If the off-shell behaviour of πN amplitude, choice of the energy $\tilde{E}$ and details of nuclear formfactor are varied in reasonable limits, an appreciable effect is observed for pion larger angle scattering only.

A different situation occurs for scattering between 60 - 120 MeV. It is well known for some time, that the standard optical model calculations overestimate experimental data in the small angle scattering region. The disagreement becomes progressively worse with decreasing energy, or given a fixed energy, with decreasing A. The MCS based on the separable πN interaction agree better with experiment in this energy interval than CSC. There are two reasons, which can explain the difference. (i) The separable model of πN interaction provides a more realistic off-shell extrapolation in momentum variables than Kislinger type models. (ii) Salomon's πN phase shifts [51] were used as an input in Landau's MSC, which give weaker πN interaction than older phase shifts [52] used in CSC. Moreover, Landau used the πN phase shifts not directly, but after "Fermi averaging" procedure, which also tends to lower the pion-nucleus cross sections in the energy region considered. Although CSC could be also modified in this way, the momentum space version of optical model is more manageable in practical applications.

At energies lower than say 60 MeV, the differential cross sections at all angles become very sensitive to various details of the pion-nucleus dynamics for the same reasons as in the πd case. The Landau resluts [48] are displayed in Fig. 4 together with Crowe's data [53] at 51 MeV. The two sets of πN phase shifts give apparently different results. There is also a remarkable sensitivity of calculated results to specific choice of the energy $\tilde{E}$. It should be noted, that the inclusion of binding effects means in practice an ad hoc downward shift of the energy $\tilde{E}$ by some 15 - 20 MeV. In order to obtain an acceptable fit to existing data around 30 MeV, it is necessary to take into account also true pion absorption at least in a phenomenological manner. Although

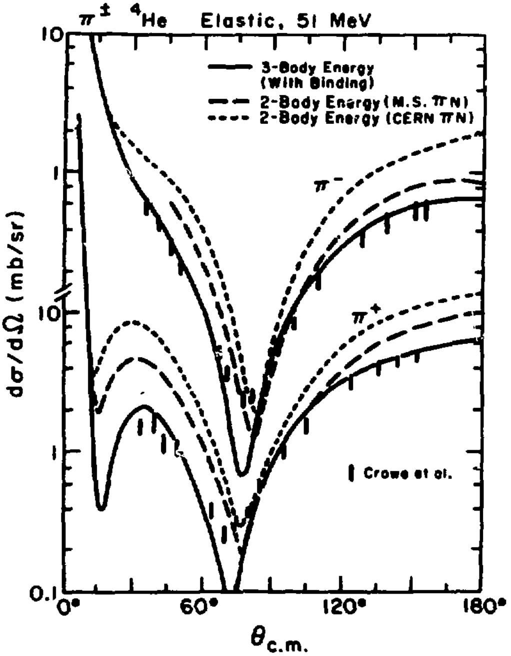

Fig. 4. Comparison of Landau's calculations [48] with Crowe's data [53]. Two sets of πN phase shifts were used: ref. [51] (M.S) and ref. [52] (CERN).

the recent calculations [54] agree rather well with experiment, the agreement may be fortuitous. Having in mind the apparent sensitivity of calculations in this energy region to various computational details, it is well possible, that were some other effects included, e.g., optical potentials of higher order, the agreement would be destroyed. Actually, there are some indications that π^4He elastic scattering is affected by virtual excitations of ^{4}He system. The imaginary part of the forward elastic $\pi\,{}^4He$ amplitude is shown in Fig. 5. The curve obtained from energy dependent phase shift analysis of exciting $\pi\,{}^4He$ data exhibits a remarkable bump in the region 20-30 MeV. Since the most pronounced ^4He excited

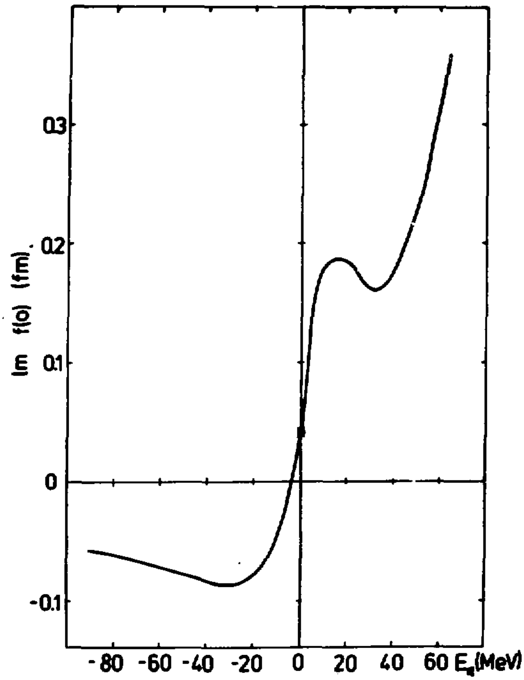

Fig. 5. ImF(0) for $\pi\,{}^4He$ elastic scattering obtained from energy dependent phase shift analysis [48].

states are located in this interval, Fig. 5 seems to indicate that information about these excited states is contained in the experimental differential and total cross sections of $\pi\,^4He$ reaction. It would be interesting to see calculations in which the low-lying excited states were coupled explicitly to the ground state.

In concluding this section I would like to comment on the choice of energy $\tilde{E}$. In spite of the fact that three body choice used by Landau /48/ and Landau and Thomas /54/ brings differential cross sections into better agreement with experiment, it has two obvious drawbacks. Firstly, the distinguishing between "valence" and "core" nucleons is more justified in heavier nuclei than $A = 3$ or $A = 4$ systems. Secondly, using the three body choice (as well as the standard $\tilde{E} = E$ one), one needs to evaluate the πN collision matrix at all energies from $(-\infty)$ to some finite positive value. It follows from the transformations of the πN collision matrix from two body c.m. to pion nucleus c.m. system. We know practically nothig about the form of the collision πN matrix in the nonphysical region and there are no a priori reasons, why it should be approximated well there by the separable model. This may be of particular significance for the low energy scattering, since the energy region lies close to the nonphysical one.

In this context it is interesting to remind the prescription given by Goldberger /55/ a couple of years ago, according to which the energy $\tilde{E}$ is defined as the mean sum of pion and nucleon kinetic energies in the initial and final states. The πN collision matrix is required in this case at positive energies only. Adopting this choice, the 1s π - mesoatomic level shifts and widths were estimated in ref. /56/. The results are encouraging, and they seem to indicate that this choice of energy $\tilde{E}$ enables us to take into account a good deal of true pion absorption (of course, in a phenomenological way).

Needless to say that new precise experiments on $\pi\,^4He$ elastic scattering and total cross sections at energies lower than say 40 MeV would be of great significance for investigation of both the nuclear excitation effects and the true pion absorption on ^{4}He.

4.2. Pion Elastic Scattering on ^{3}He - Optical Model

The experimental situation is less favourable than that in the case of ^{4}He nucleus, however, much progress has been made in the past years. Till recently, only data from Dubna-Torino group /57/ were available in the energy region 70 - 210 MeV. New measurements including π^3H elastic scattering have been reported at Zürich conference /58/.

The π^3He scattering obeys several attractive features one of them being connected with nonzero spin and isospin (J=T=1/2) of the target nucleus. Spin-isospin formalism was introduced into the optical model /59/ and an important cancellation was established /60/ between various parts of the optical potential in the case of π^3He scattering. The potential has the form

$$V\Phi = \{(B_0+2\frac{\vec{t}.\vec{T}}{A}B_1)\rho(r)-(C_0+2\frac{\vec{t}.\vec{T}}{A}C_1)\,\vec{\nabla}\cdot\rho(r)\vec{\nabla} +$$

$$+2\frac{\vec{J}.\vec{I}}{A}(D_0-2\vec{t}.\vec{T}D_1)\frac{1}{r}\frac{\partial\rho(r)}{\partial r}\}\Phi, \qquad (2)$$

where the coefficients B_i , C_i and D_i (i=0,1) are expressed in terms of πN phase shifts and $\vec{t}$ is the pion isospin operator. Since $2(\vec{t}.\vec{T})=-2$ holds in the I=1/2 channel ($\vec{I}=\vec{t}+\vec{T}$) , the isospin-flip and isospin-non-flip parts of the potential will interfere destructively. However, an opposite situation occurs for the spin-orbit ($\vec{J}.\vec{I}$) terms. In the I=3/2 channel, $2(\vec{t}.\vec{T})=1$ holds, the constructive interference among isospin-non-flip and isospin-flip terms takes place, while the spin-orbit terms almost cancel out. The consequence is, as can be seen from Fig. 6, that minima of $\pi^+ \, ^3He$ angular distribution are deeper than those of the $\pi^- \, ^3He$ reaction. Greater sensitivity to nuclear structure details can further be expected in $\pi^- \, ^3He$ reaction as opposed to $\pi^+ \, ^3He$ one.

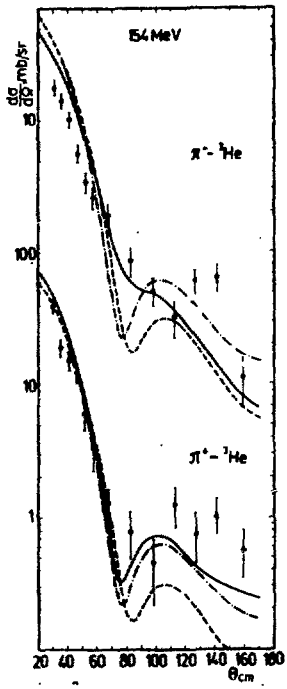

Fig. 6. Comparison of optical model calculations with Dubna data. - - - - - full calculations, -·-·- spin and isospin terms neglected.

The aim of the more detailed calculations performed by Landau[48] in momentum space and by Mach[61] in coordinate space was to investigate the sensitivity of elastic scattering to some details of 3N wave function. Landau characterized the ^3He nucleus by four formfactors derived from electron scattering experiments on ^3He and ^3H, while Mach used a semimicroscopic nuclear wave function with a reasonable admixtures of the S′- and D-states. It is evident that these two approaches differ by the different treatment of meson exchange currents. Within the formfactor method one assumes that the meson currents are the same as in the electron-nucleus scattering, in the second approach they are neglected completely. In became clear that the $\pi^- \, ^3He$ reaction is more sensitive to the spin distribution in the nucleus (especially in the dip region) than the $\pi^+ {}^3He$ one. Nevertheless, all attempts to extract quantitative information are somewhat premature at the present level of accuracy of both the theory and experiment.

4.3. Pion Elastic Scattering on ^3He and ^4He – Other Approaches

There are no a priori reasons, why the Glauber model should work well for energies less than ~ 500 MeV. Nevertheless, the model provides usually a better description of the small angle part ($\theta \lesssim 70^{\circ}$) of differential cross sections than more ambitious calculations even in the region of the (3,3) resonance. Several Glauber model calculations have been performed [62,63] for pion scattering on ^3He and ^4He at energies $E \gtrsim 100$ MeV. The Glauber model π-nucleus amplitude contains information on nuclear correlations and also about nucleon spin- and isospin-flip processes in the intermediate states (even for $J=T=0$ nuclei) which are completely or almost completely disregarded in the optical model.

Spin- and isospin-flip effects and especially the nuclear recoil correlation tend to lower the cross sections particularly for the low energy tail of the resonance. Recent calculations based on the second order optical potential [64] exhibit similar trends and sensitivities of the cross sections to nuclear recoil correlation as the Glauber model (spin and isospin-flip effects were not included in ref. [64]). It can be concluded that the Glauber model can give qualitative information about the significance of such effect, which are too complex to be treated otherwise.

The Glauber model as well as the optical one permit to calculate the total pion-nucleus cross section, too. However, the agreement between calculated and experimental results is slightly worse than in the case of elastic scattering. More careful treatment will be necessary of both the pion true absorp-

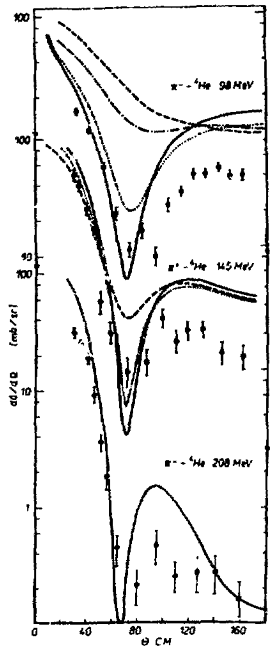

Fig. 7. Comparison of Dubna data with Glauber model results.[63] — · — full calculations, · · · · · spin and isospin neglected, - - - - - correlation also neglected.

tion and its escape from elastic channel, in order the total cross sections could be calculated reliably.

Several π^3He and π^4He calculations have been done[65,66] via direct summation of the multiple scattering series in the fixed scatterer approximation. Taking into account the "angle transformation" and some binding effects, Gibbs et al. [65] were able to reproduce rather well the π^4He elastic scattering in the energy interval 24 - 190 MeV. Interesting calculations based on approximate Faddeev-Yakubovskij equations for π^3He and π^4He scattering are being continued by Belyaev and Wrzecionko[67]. The most attractive feature of the model is possibility to avoid the impulse approximation in a very consequent way.

5. PION INELASTIC REACTIONS WITH A = 3 AND A = 4 SYSTEM

Although the elastic scattering is probably of principal significance for our understanding of the pion-nucleus reaction mechanisms, other processes have also been comprehensively studied in the past few years. The two topics discussed here reflect author's taste rather than a representative sample of work done.

5.1. Single Charge Exchange on A = 3 System

The reaction $^3H(\pi^+,\pi^o)^3He$ going to the analogous state of the initial nucleus has many common features with elastic scattering. In spite of this fact, the similar reaction on ^{13}C represents one of the most puzzling pion-nucleus process. The total cross section of $^{13}C(\pi^+,\pi^o)^{13}N$ reaction calculated using DWIA /58/ or optical model /69/, exhibits a deep minimum in the (3,3) resonance region, while the experimental data lie one order of magnitude higher. As was pointed out by Eisenberg /70/ the reaction goes predominantly via excited intermediate nuclear states. Recent calculations of $^3H(\pi^+,\pi^o)^3He$ reaction performed either in optical /48,61/ or Glauber /71/ models show a broad maximum shifted considerably downwards in energy. It will be interesting to see, whether future experiments will confirm these calculations. In any case, experiments around 180 MeV would shed a light on the role of incoherent virtual processes in reaction with A = 3 system. It should be noted in this context that the first experimental differential cross sections of $^3H(\pi^+,\pi^o)^3He$ reaction have been reported at the Zürich Conference /72/.

5.2. Pion-Induced Knock-Out Reactions on ^4He

The study of the $(\pi,\pi N)$ reactions in the region of (3,3) resonance has a long history. Experimentally best known are the excitation functions for the reactions $^{12}C(\pi^{\pm},\pi N)^{11}C$ (bound), which invoked a considerable theoretical activity /73/. It is well established that the ratio $R_c = \sigma(^{12}C(\pi^-,\pi^-n)^{11}C)/(\sigma(^{12}C(\pi^+,\pi^+n)^{11}C)+\sigma(^{12}C(\pi^+,\pi^o p)^{11}C))$ depends rather strongly on energy, reaching the value $R_c \sim 1.5$ near the resonance position, whereas a value near 3 is expected on the basis of PWIA.

This apparent conflict indicates a remarkable role of initial and/or final state interaction in pion-induced knock-out reactions on carbon. Recently, new experimental data of Torino-Frascati group have been published [74] on the differential and total cross sections of the reactions $^4He(\pi^+\pi^-p)^3H(I)$, $^4He(\pi^+,\pi^+n)^3He(II)$ and $^4He(\pi^+,\pi^0p)^3He(III)$ at $E_\pi = 110$ and 160 MeV. The ratio $R_{He} = \sigma(I)/(\sigma(II) + \sigma(III))$ turned out to be not more than one half of the PWIA estimate. The subsequent calculations [75] have shown, that PWIA fails to reproduce also differential cross sections of the reactions I, II and III. Therefore, the distortion is very important in knock-out reactions even on such a light nuclei as ^4He. Much better results can be obtained, if the 3N exchange mechanism is considered in addition to the usual PWIA. In other words, an antisymmetric final state wave function was used in ref. [75] in evaluating the differential and total cross sections. Unlike the PWIA, the model containing the Pauli principle terms predicts correctly the dip position, as well as it explains the existence of the secondary maximum (Fig. 8). The curves calculated for reactions I and II were scalled in Fig. 8 by the factor $\sigma(exp)/\sigma(th) \simeq 3-5$. Although the ratio R_{He} yielded by the model lies much closer to experiment than the PWIA value, ratios of the type $\sigma(I)/\sigma(II)$ or $\sigma(I)/\sigma(III)$ are predicted incorrectly. We can conclude that the ratios R_C or R_{He} being frequently studied in the literature are not very sensitive to the reaction dynamics.

6. SUMMARY

At present, the elastic scattering appears to be the most important tool in studying the pion reactions with very light nuclei. There exist, or will exist very soon, both the good quality experimental data and refined calculations. Inelastic and pion production or absorption reactions are investigated to an

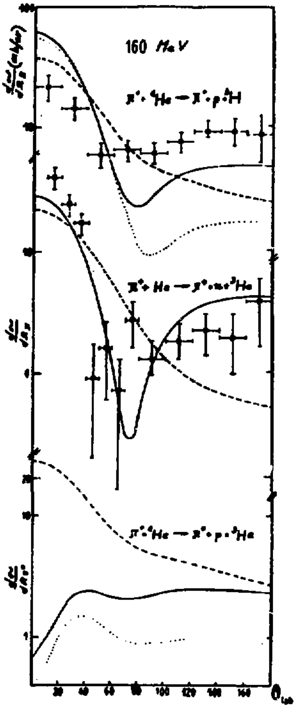

Fig. 8. Comparison of Torino-Frascati data with calculations. ----- PWIA, ——— PWIA+Pauli principle terms.

increasing extent. The main task of theory seems to be a more reliable description of relativistic effects as well as a more explicit treatment of the nuclear side of the problem in the case of A = 3 and A = 4 nuclei. When this program will be accomplished, the pion reactions with very light nuclei will become surely an important source of quantitative information on the nuclear structure and pion-nucleon dynamics.

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REFERENCES

1. Tabakin F. Proceedings of Conference on Meson-Nuclear Physics, Pittsburgh, 1976 (eds. P.D.Barnes et al.).
2. Thomas A.W. Carnegie-Mellon Conference (see ref./1/), 375.
3. Thomas A.W. Invited talk, Conference on High Energy Physics and Nuclear Structure, Zürich, 1977.
4. Aaron R., Amado R.D., Young J.E. Phys.Rev., 1968, 174, p. 2022.
5. Alessandrini V.A., Omnes R.L. Phys.Rev., 1965, 139, p. 139.
6. Celenza L.S., Liou M.K., Liu L.C., Shakin C.M. Phys.Rev., 1974, C10, p. 435.
7. Logunov A.A., Tavkhelidze A.N. Nuovo Cim., 1963, 29, p. 380.
8. Landau R.H., Phatak S.C., Tabakin F. Ann. of Phys., 1973, 78, p. 299.
   Heller L., Bohannon G.R., Tabakin F. Phys.Rev., 1976, C13, p. 742.
9. Denonder J.P. Nucl.Phys., 1971, A174, p. 251.
10. Mach R. Nucl.Phys., 1973, A205, p. 56.
11. Cammarata J.B., Banerjee M.K. Phys.Rev., 1976, C13, p. 299.
12. Partovi M.H., Lomon E.L. Phys.Rev., 1970, D2, p. 1999.
13. Schmit C., Denonder J.P., Maillet J.P. Nucl.Phys., 1975, A239, p. 445.
14. Rivera J.M., Garcilazo H. Nucl.Phys., 1977, A285, p. 505.
15. Rinat A.S., Thomas A.W. Nucl.Phys., 1977, A282, p. 365.
16. Thies M. Phys.Lett., 1976, 63B, p. 43.
    Liu L.C., Shakin C.M. Phys.Rev., 1977, C16, p. 333.
17. Bunatyan G.G., Pol Yu.S. Sov.Nucl.Phys., 1977, 25, p. 535.

18. Landau R.H., Thomas A.W. TRIUMF, May, 1977.
19. Dollard H. et al. Phys.Lett., 1976, 63B, p. 416.
20. Mandelzweig V.B., Garcilazo H., Eisenberg J.M. Nucl.Phys., 1976, A256, p. 461. Erratum in Nucl.Phys., 1976, A264, p. 531, and see ref./4/
21. Woloshyn R.M., Moniz E.J. Phys.Rev., 1976, C13, p. 286.
22. Rockmore R., Good P., Manus H.Mc. Phys.Rev. Lett., 1976, 37, p. 1720.
23. Myhrer F., Koltun D.S. Nucl.Phys., 1975, B86, p. 441.
24. Pewitt E.G. et al. Phys.Rev., 1963, 131, p. 1826.
25. Norem J.H. Nucl.Phys., 1971, B33, p. 512.
26. Gabathuler K. et al. Nucl.Phys., 1973, B55, p. 397.
27. Minehart R.C. et al. Zürich Conference (see ref. /3/).
28. Namyslowski J.M. Nuovo Cim., 1968, 57A, p. 355.
Weiss U. Nucl.Phys., 1972, B44, p. 573.
Weber H.J. Nucl.Phys., 1976, A264, p. 365.
29. Carlson C. Phys.Rev., 1970, C2, p. 1224.
Hoenig M., Rinat A.S. Phys.Rev., 1974, C10, p. 2102.
30. Gabathuler K., Wilkin C. Nucl.Phys., 1974, B70, p. 215.
31. Bayukov Yu.A. et al. Nucl.Phys., 1977, A282, p. 389.
32. Axen D. et al. Nucl.Phys., 1976, A256, p. 387.
33. Thomas A.W. Nucl.Phys., 1976, A258, p. 417.
34. Petrov N.M., Peresypkin V.V. Phys.Lett., 1973, 44B, p. 437.
Myhrer F. Nucl.Phys., 1974, B80, p. 491.
35. Afnan I.R., Thomas A.W. Phys.Rev., 1974, A 10, p. 109.
36. Kopaleishvili T.I. et al. JINR, E4-9951, Dubna, 1976.
37. Hüfner J. Phys.Rev., 1975, 21C, p. 1.
38. Brockmann R., Dilling M. Phys.Rev., 1977, C15, p. 361.

39. Preedom B.M. et al. Phys.Lett., 1976, 65B, p. 31.
Richard-Serre C. et al. Nucl.Phys., 1970, B20, p. 413.
40. Jones G. In: Proceedings of the Second International Conf. on the N-NInteract., Vancouver, 1977.
41. Green A.M., Niskanen J.A. Nucl.Phys., 1976, A271, p. 503.
42. Brayshaw D.D., Ferreira E. Phys.Lett., 1977, 68B, p. 139, and refs. cited therein.
43. Gibbs V.R., Hess A.T. Phys.Lett., 1977, 68B, p. 205.
44. Fearing H.W. Phys.Rev., 1977, C16, p. 313.
45. Kallne J. et al. Zürich Conference (see ref. /3/).
46. Shcherbakov Yu.A. et al. Nuovo Cim., 1976, 31A, p. 249.
47. Binon F. et al. Phys.Rev.Lett., 1975, 35, p. 145.
48. Landau R.H. Ann. of Phys., 1975, 92, p. 205. and Phys.Rev., 1977, C15, p. 2127.
49. Revai J. Nucl.Phys., 1973, A205, p. 20.
50. Celenza L.S., Liu L.C., Shakin C.M. Phys.Rev., 1976, C13, p. 2451.
51. Salomon M. TRIUMF Report TRI-74-2, 1974.
52. Almehed S., Lovelace C. CERN Report TH 1408 (1971).
53. Crowe K.M. et al. Nucl.Phys., 1970, B17, p. 168.
54. Landau R.H., Thomas A.W. TRIUMF Report TRI-PP-77-4, 1977.
55. Goldberger M.L. Phys.Rev., 1948, 74, p. 1269.
56. Mach R. Carnegie-Mellon Conrefence (see ref. /1/), p. 638.
57. Shcherbakov Yu.A. et al. Nuovo Cim., 1976, 31A, p. 262.
58. Nefkens B. et al. Zürich Conference (see ref. /3/).
59. Ericson M., Ericson T.E.O. Ann. of Phys., 1966, 46, p. 323.
60. Mach R., Nichitiu F., Shcherbakov Yu.A. Phys. Lett., 1974, 53B, p. 133.
61. Mach R. Nucl.Phys., 1976, A258, p. 513.
62. Franco V. Phys.Rev., 1974, C9, p. 1690.
Sparrow D.A. Phys.Lett., 1975, 58B, p. 309.

63. Mach R., Sapozhnikov M.G., Shcherbakov Yu.A. Czech. J. Phys., 1976, B29, p. 1248.
64. Lee T.-S.H., Chakravarti S. Phys.Rev., 1977, C16, p. 273.
65. Gibbs W.R. et al. Phys.Rev., 1976, C13, p.2433.
66. Galimzyanov R.M., Isaev V.P., Musachanov M.M., will be published in Sov. Nucl.Phys., 1978, 27.
67. Belyaev V.B., Wrzecionko J. JINR, E2-10668, Dubna, 1977.
68. Gibbs W.R., Gibson B.F. Phys.Rev.Lett., 1976, 36, p. 85.
69. Auerbach N., Warszawski J. Phys.Lett., 1973, 45B, p. 171.
70. Eisenberg J.M., Gall A. Phys.Lett., 1975, 58B, p. 390.
71. Lohs K.P., Mandelzweig V.B. Z.Physik, 1977, A283, p. 51.
72. Glodis P. et al. Zürich Conference (see ref. [3]). Kalne J. et al. Zürich Conference (see ref. [3]).
73. Sternheim M., Silbar R. Phys.Rev.Lett., 1975, 34, p. 824. Hüfner J., Pirner H., Thies M. Phys.Lett., 1975, 59B, p. 215.
74. Balestra F. et al. Lett.Nuovo Cim., 1976, 15, p.535, and 1976, 15, p. 542.
75. Guaraldo C. et al. will be published in Nuovo Cim. Mach R. et al. Zürich Conference (see ref. [3]).

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