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PION INELASTIC SCATTERING, PION PHOTOPRODUCTION, AND INELASTIC ELECTRON SCATTERING ON LIGHT NUCLEI

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1. Introduction

Extensive programmes of investigations of partial nuclear transitions in pion scattering and in pion photoproduction performed up to now provided a lot of experimental data. This holds especially true for the 1p-shell nuclei. One should now try to understand these reactions simultaneously, taking as an input the fixed nuclear structure information and a unified description of the reaction mechanisms.

To describe these reactions, phenomenological as well as microscopical approaches have been used. In this report we mainly concentrate on the microscopical one based on the multiple scattering theory (MST). The approach was described at the first Workshop /1/ and subsequently applied to ^{12}C /2/. Since we have observed a satisfactory agreement of the theoretical and experimental results, we expect that the main physical content of the reactions analysed is correctly described by our approach, and shall here continue the analysis of new data and further effects.

II. Basic Elements of Microscopical Theory of (π, π')- and (γ, π)- reactions

2.1. When the pion is scattered on a free nucleon $\pi(K_1) + N(P_1) \to \pi'(K_2) + N'(P_2)$ the corresponding amplitude in the (πN) c.m. system reads:

$$f = f_0 + f_T \vec{\tau}\cdot\vec{t}_\pi + i\,\vec{\sigma}\cdot[\vec{\eta}_1\times\vec{\eta}_2]\left(f_S + f_{ST}\,\vec{\tau}\cdot\vec{t}_\pi\right), \qquad (1)$$

where $\vec{\eta}_{1(2)}$ - are unit vectors along the momentum of an incoming (outgoing) pion. Scalar functions f_i depend on two variables: $S = -(K_1 + P_1)^2$ and $t = -(K_1 - K_2)^2$. They are determined from the phase shift analyses. Salomon parameterization /3/ was used for the calculations of f_i.

For pion photoproduction $\gamma(k_1) + N(P_1) \to \pi(K_2) + N'(P_2)$ the elementary amplitude in the (πN) - c.m. system reads

$$f_\gamma = i f_1 \vec{\sigma}\cdot\vec{\varepsilon} + f_2[\vec{\eta}_1\times\vec{\varepsilon}]\cdot\vec{\eta}_2 + i f_3 \vec{\sigma}\cdot\vec{\eta}_1\,\vec{\eta}_2\cdot\vec{\varepsilon} + i f_4 \vec{\sigma}\cdot\vec{\eta}_2\,\vec{\eta}_2\cdot\vec{\varepsilon}, \qquad (2)$$

where f_i are linear combinations of three independent scalar functions - $f_i^{(\pm,0)}$

$$f_i = [\, f_i^{(+)}\delta_{\alpha 3} + f_i^{(-)}\frac{1}{2}[\tau_\alpha, \tau_3] + f_i^{(0)}\tau_\alpha \,]\, \varphi_\pi^\alpha \; . \qquad (3)$$

Here φ_π^α is the isospin part of the pionic wave function. To determine these scalar functions, one has to use one of the models-either the dispersion relations, or the phenomenological Lagrangians. Two versions of the amplitude, called CGLN and BDW, have been derived by using the first method, and the third, EL, by using the second one. For details see ref. /4/ .

2.2. To get the amplitude of pion scattering and of pion photoproduction on nuclei, one may start with the amplitude of the elementary process and to use the MST. According to the MST one can consider pion-nuclear interaction as a subsequent rescattering of a pion on the nucleons in the nucleus. The corresponding T-matrix reads

$$T = \sum_{j=1}^{A}\tau_j + \sum_{i\neq j}^{A}\sum_{j=1}^{A}\tau_i G \tau_j + \sum_{k\neq i}^{A}\sum_{i\neq j}^{A}\sum_{j=1}^{A}\tau_k G \tau_i G \tau_j + \cdots \qquad (4)$$

where G is the Green function for a free πA system, τ_j is the scattering matrix on a bound nucleon. It is connected with t -matrix (scattering matrix on a free nucleon) by the relation

$$\tau_j = t_j + t_j\,(G - g)\,\tau_j \; . \qquad (5)$$

In (5) g is the Green function for a free πN system.

In pion photoproduction on nuclei when the pion rescattering in the framework of MST is taken into account for T^γ matrix one has:

$$T^\gamma = \sum_{j=1}^{A}\tau_j^\gamma + \sum_{i\neq j}^{A}\sum_{j=1}^{A}\tau_i G \tau_j^\gamma + \sum_{k\neq i}^{A}\sum_{i\neq j}^{A}\sum_{j=1}^{A}\tau_k G \tau_i G \tau_j^\gamma + \cdots \qquad (6)$$

In (6) τ_j^γ is the pion photoproduction matrix on a bound nucleon. One can rewrite both expressions for T and T^γ in the form of a system of integral equations:

$$\begin{aligned} T' &= U' + U' G T' \\ T^\gamma &= U^\gamma + T' G U^\gamma , \end{aligned} \qquad (7)$$

where

$$T' = \frac{A-1}{A}T \; , \quad U' = \frac{A-1}{A}\sum_{j=1}^{A}\tau_j \; , \quad U^\gamma = \sum_{j=1}^{A}\tau_j^\gamma \; . \qquad (8)$$

Following ref. /5,1,2/ one can rewrite the system of equations (7) in the total-momentum $\vec{j}$ representation. Then for a nuclear transition from the ground $|0\rangle$ to an excited state $|n\rangle$ one gets:

i) for the pion scattering

$$\mathcal{F}_{no}^{\prime j}(\pi';\pi) = U_{no}^{\prime j}(\pi';\pi) - \frac{1}{\pi}\sum_{\tilde{n}\tilde{L}_n}\int\frac{\tilde{k}^2 d\tilde{k}}{\mathcal{M}_{\tilde{n}}(\tilde{k})}\,\frac{U_{n\tilde{n}}^{\prime j}(\pi';\tilde{\pi})\,\mathcal{F}_{\tilde{n}o}^{\prime j}(\tilde{\pi};\pi)}{\mathcal{E}_o(k) - \mathcal{E}_{\tilde{n}}(\tilde{k}) + i\varepsilon} \; , \qquad (9)$$

ii) for pion photoproduction

$$\mathcal{F}_{no}^{\gamma j}(\pi';\gamma) = U_{no}^{\gamma j}(\pi';\gamma) - \frac{1}{\pi}\sum_{\tilde{n}\tilde{L}_\pi}\int\frac{\tilde{k}^2 d\tilde{k}}{\mathcal{M}_{\tilde{n}}(\tilde{k})}\,\frac{\mathcal{F}_{n\tilde{n}}^{\prime j}(\pi';\tilde{\pi})\,U_{\tilde{n}o}^{\gamma j}(\tilde{\pi};\gamma)}{\mathcal{E}_n(k) - \mathcal{E}_{\tilde{n}}(\tilde{k}) + i\varepsilon} \; , \qquad (10)$$

where

$$(\pi';\gamma) \equiv (L_\pi, k'; L_\gamma, E_\gamma, \lambda) \quad , \quad (\pi';\pi) \equiv (L_\pi', k'; L_\pi, k) \, .$$

2.3. To solve (9) and (10), the following approximations are usually used:

i) the many-body operators τ_j and τ_j^γ are replaced by two-body operators t_j and t_j^γ ;

ii) only few intermediate nuclear states are taken into account in the sum over $\tilde{n}$ (coupled channel method);

iii) in particular, only two channels - $(\tilde{n}\,,\,0) = (0,0)$ and $(n\,,\,0)$ are used very often; putting $n = \tilde{n}$, one arrives at the DWIA equations;

iv) factorization approximation - πN amplitude is evaluated at effective nucleon momenta.

2.4. Nuclear matrix elements for 1p-shell nuclei in equations (9) and (10) are calculated either in the shell model or in some phenomenological model. In all the cases the model must reproduce the electromagnetic form factors for the levels which are of interest. At this point some problems, however, arise. Firstly, one needs some estimate of the mesonic exchange currents. Their quantitative contribution is somewhat uncertain. To calculate mesonic exchange currents unambiguously, one needs to extend the space of the wave functions and to take into account the nucleonic correlations including $2\hbar\omega$ -excitations. However, the inclusion of $2\hbar\omega$ -configurations on a rigorous ground is not realised. Therefore, the situation remains uncertain.

In this situation it is interesting to consider such transitions, where the mesonic exchange currents contribute only slightly. A magnetic transition of a high multipolarity is a good example of this type. One can consider, e.g., ^{10}B, where two isovector M3 transitions are known.

Very interesting is ^{6}Li nucleus since here one can construct the wave functions more realistic than the shell model ones. Considering ^{6}Li as an αNN system and using realistic αN and NN potentials, one can solve the Schrödinger equation using, for example, the procedure described in ref. /6/ .

The last part of the report will be devoted to the spin-isospin dipole resonance in p-shell nuclei and its manifestation in pion photoproduction reactions.

III. Partial Transitions in Pion Photoproduction Reactions on Light Nuclei

3.1. The partial $J^{\pi}T = 0^{+}0 \rightarrow 1^{+}1$ transition in ^{12}C. In the shell model based only on the $1s^4 1p^8$ configurations (Cohen and Kurath (CK) as an example) for this transition a strong contribution of the second maximum to reproduce the experimental data - Fig. 1a. When a model space is enlarged by means of some $2\hbar\omega$ - configurations, the region of the second maximum is described almost without exchange currents. However, as has been mentioned, this procedure itself is somewhat ambiguous. One may parametrize the nuclear matrix elements in the framework of the Helm model (HM) or parametrize the nuclear wave function (like Dubach and Haxton (DH)) to reproduce the M1 form factor in ^{12}C (see fig. 1a).

The M1-form factor in ^{12}C is described by two matrix elements: [101] , which is due to the operator $\vec{\sigma} j_0(qr)$ and [121], which is due to the operator $j_2(qr)[\vec{\sigma}\otimes Y_2]_1$. Fig. 1b shows that different approaches give different values for these matrix elements.

In fig. 2 the results of calculations of differential cross-sections in transition $^{12}C(\pi', \pi)^{12}C$ $(1^{+}, 1;\ E^{*} = 15.1$ MeV) are given. The CK version, which has not reproduced the M1 form factor, fails to reproduce the measured /7/ (π, π') cross-section. From this one concludes that the second maximum in the M1-form factor is hardly due to exchange currents. At the same time it becomes clear that $2\hbar\omega$ - configurations are very important for the region of the second maximum.

Let us discuss now the pion photoproduction (fig. 3a). In none of the versions it is possible to reproduce the experimental data starting from $\theta_{\pi} = 90°$ when $T_{\pi} = 70$ MeV /8/. On the other hand,

as it is pointed out in ref. /9/ , one of the phase equivalent pion-nuclear potentials brings the results in coincidence with the experimental data (Fig. 3b). To realize what is the matter, let us consi-

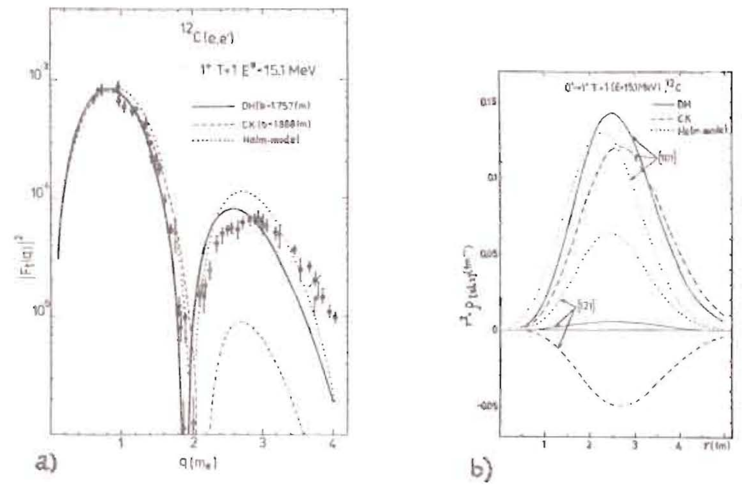


Fig.1. a -M1 form factor in ^{12}C in different models, b - the transition densities $r^2\rho_{SLJ}(r)$ for M1-transition.

der a simple qualitative example. Taking into account only pionic S - and P -waves, we get for the differential cross-section (in the one-shell approximation /2/)

$$d\sigma/d\Omega \sim |F_{\pi\gamma}|^2 = |F_S + F_P \cos\theta_{\pi}|^2 , \qquad (11)$$

where $F_{S(P)} = V_{S(P)}\eta_{S(P)}$, $V_{S(P)}$ - is the plane-wave part of the partial amplitude for $S(P)$ -pion wave and $\eta_{S(P)}$ - distortion factor. Let us consider, as given in Fig.4, two different situation for F_S and F_P . Because F_S and F_P interfere destructively, the cross section at large angles becomes very sensitive to the different values of $\eta_{L_{\pi}}$. It becomes important to calculate also inelastic pion scattering /2/ and coherent photoproduction of neutral pion /10/.

3.2. The partial transitions in ^{6}Li. The wave functions of ^{12}C have been constructed within the shell model. The contruction of the ^{12}C wave functions on a more rigorous ground is a very difficult problem, and one does not expect a substantial progress in this aspect

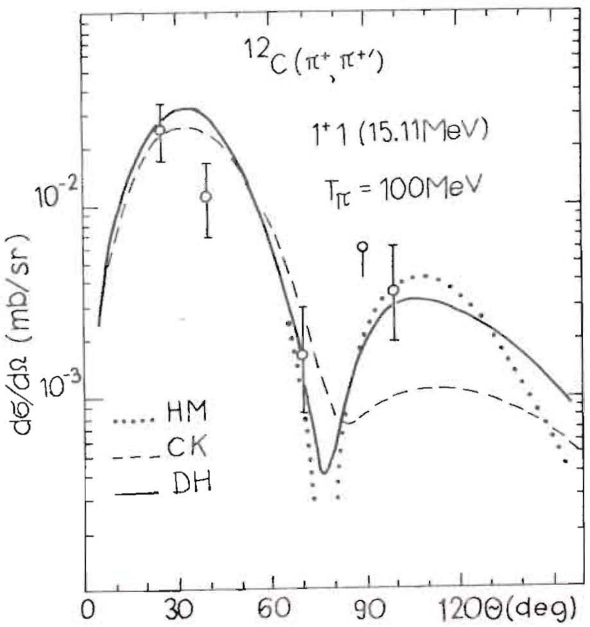
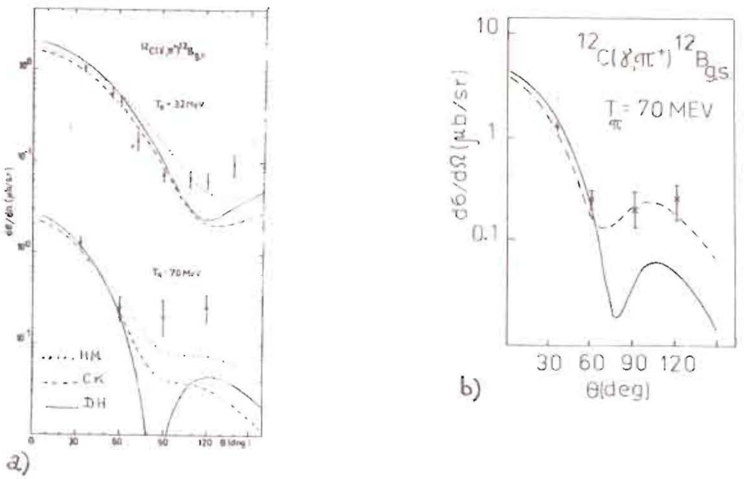


Fig.2. Differential cross-section for $^{12}C\ (\pi^+, \pi^{+\prime})^{12}C$ (1^+1, $E^* = 15.1$ MeV) reaction [2]. The experimental data are from ref. [7] .

in the nearest future. On the other hand, ^{6}Li due to its specific features has allowed a definite progress. The wave functions of ^{6}Li can be constructed within the 3-body model mentioned in the introduction with the realistic potentials. This method, however, describes the M1 form factor satisfactory only up to $q \sim 0.5\ fm^{-1}$ and does not reproduce it at larger q -values. It turns out that the distribution of magnetization current in the ground state is described only roughly in this three-body model. The same problem will arise in pion photoproduction, too (see fig. 4a).

Let us consider pion photoproduction with transition to 2^+1 ($E^* = 1.8$ MeV) state of ^{6}He (see fig.4b). In this case the discrepancy between the theory and experiment [12] in forward direction of outgoing pions is very important. Since the contribution of M1



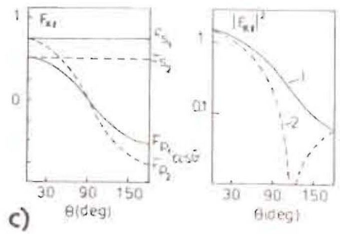


Fig.3. $d\sigma/d\Omega$ for $^{12}C(\gamma,\pi^+)^{12}B_{g.s.}$ reaction. The results of calculation are (a)-ref. [8] and (b) - from ref. [9] . (c) -qualitative interpretation.

multipole is small, the cross-section cannot be so large at small angles. As for this point, we would like to call attention of the experimentalists to it.

3.3. Pion photoproduction in ^{10}B . M3-transitions.

In ^{10}B there are well-known examples of M3-transitions. They arise when $J^\pi T = 0^+1$ and the first $J^\pi T = 2^+1$ levels are excited. The corresponding electromagnetic form factors are given in Fig.5a. Only the operator $j_2(qr)[\vec{\sigma}\otimes Y_2]_3$, contributes to the transition, when $1s^4 1p^6$ configurations are used. The results given in fig.5a are obtained with Boyarkina wave functions [11]. The experimental data exist up to $q \sim 2.0\ fm^{-1}$ and are well reproduced by this model. For pion photoproduction the data exist for a wide region of energies of incoming γ -quanta up to $E_\gamma = 340$ MeV at two angles: $\theta_\pi = 45^0$ and $\theta_\pi = 90^0$.

Four versions of calculations are shown in Fig.5b,c. At $\theta_\pi = 90^0$ all the versions give the same cross section, which overestimates the

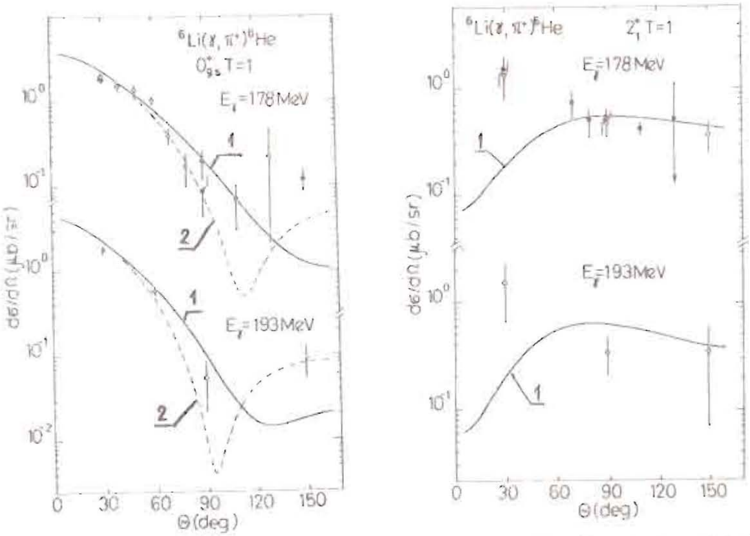


Fig.4. The differential cross-section for the ^{6}Li(γ, π^+)^{6}He reaction. Our results obtained: 1- in αNN -model, 2 - with Donnelly and Walecka parametrization for nuclear transition density /20/ .

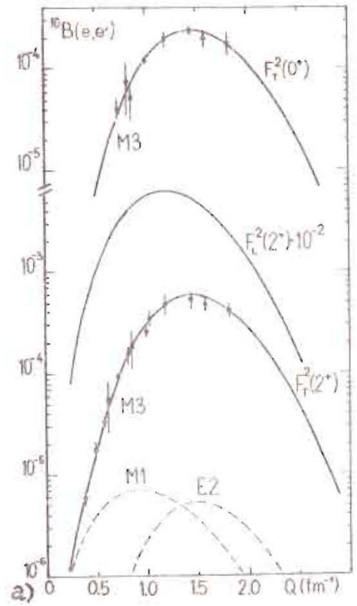
data at lower energies and agrees with experiment for $E_\gamma \geqslant 230$ MeV. The agreement of different calculations is apparently connected with the S -wave character of πN interaction: the P -wave contribution vanishes at $\Theta_\pi = 90^0$.

The situation changes completely when $\Theta_\pi = 45^0$. Various theoretical versions give different results. This may be due to the P -wave contribution which is different in the four versions used.

It seems to be important to continue the consideration of this problem and to discuss simultaneously inelastic pion scattering, where the same problem appears.

3.4. Partial transitions in inelastic pion scattering. The interference between spin-dependent and spin-independent matrix elements.

Let us now consider (π , π')-reaction with transitions on 2^+0(E^*= 4.4 MeV), 2^+ 1 (E^*= 16.1 MeV) levels in ^{12}C and 3^+0(E^* = = 2.18 MeV) in ^{6}Li. In all these three cases in the Δ -resonance region the differential cross-section has two humps (see fig.6 and fig.7). The humps are more pronounced in ^{12}C for the isoscalar transition.



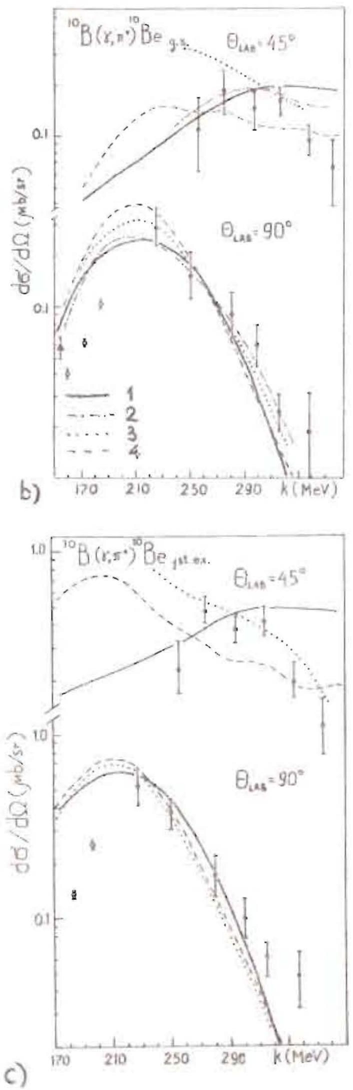


Fig.5. The electromagnetic form factors in ^{10}B (a), and the $d\sigma/d\Omega$ for ^{10}B(γ , π^+)^{10}Be-reaction at Θ_π = 45^0 and Θ_π = 90^0 (b,c). Curves 1,2,3,4 are from refs. /1,4,13,14/, respectively.

The relative intensity of the humps depends on the energy of incoming pions. When T_π is small, the hump at backward angles gets higher. At larger T_π the hump at forward angles becomes more intensive.

Such a gross-structure of differential cross section results from a specific behaviour of the elementary amplitude in the Δ -resonance region. Indeed, in this region in the elementary amplitude (1) the $P_{3/2}$ -wave dominates. Neglecting the other waves, one gets for :

$$f_{0(T)} \approx 3 f_{P_{3/2}} \cos \theta_{\pi} . \qquad (12a)$$

$$f_{S(ST)} \approx - f_{P_{3/2}} . \qquad (12b)$$

At $\theta_{\pi} = 90^{0}$, $f_{0(T)} = 0$. $f_{0(T)}$ differs in sign in forward and backward hemisphere. This results in a two-hump structure of differential cross-sections.

The most pronounced humps appear when the contribution of (12b) is small due to the smallness of the corresponding nuclear matrix elements. Such a situation holds in ^{12}C for the isoscalar transition. For two other transitions considered the minimum is partly filled by $f_{S(ST)}$ part of the amplitude.

Both the position of minimum and the magnitude of humps depend on the energy T_{π} of incoming pions. The reason is as follows: a different momentum transferred is realized at $\theta_{\pi} = 90^{0}$ when T_{π} is varying. This means that $f_{0(T)}$ becomes equal to zero at different values of q . The nuclear form factor amplifies this difference in elementary amplitude, giving rise to the gross-structure of differential cross-sections.

3.5. Partial transition in inelastic pion scattering on ^{18}O and the difference in spatial distributions of neutron and proton densities.

In the vicinity of the (3,3) resonance the elementary π^- -neutron (or π^+ -proton) amplitude is about 3 times as large as the π^- -proton (or π^+ -neutron) one. Long time ago it has therefore been suggested that comparison of the scattering of positive and negative pions may provide detailed information on the difference of neutron and proton distributions in nuclei.

Let us assume the case of a completely inert nuclear core and a transition fully due to the valence neutrons. In such a case $R = \sigma(\pi^-)/\sigma(\pi^+) = 9$ should be expected. The transition $^{14}C_{g.s.} \longrightarrow {}^{14}C$ (2_2^+ , 8.32 MeV) seems to provide a dramatic example: the 2_2^+ excitation, though well pronounced in π^+ -scattering, is practically invisible in the π^- – ^{14}C reaction.

In a sense much more interesting – though more complicated – examples are those, where core degrees of freedom take part in the

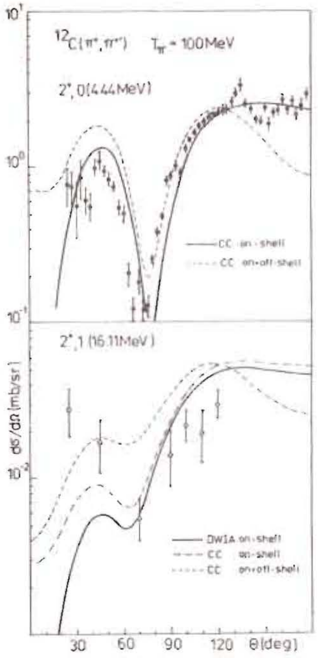


Fig.6. $d\sigma/d\Omega$ for $^{12}C(\pi^+,\pi^{+'})^{12}C$-reaction calculated in the CC (coupled channel) method and DWIA, using Cohen-Kurath transition densities with the renormalisation needed to reproduce (e, e') data.

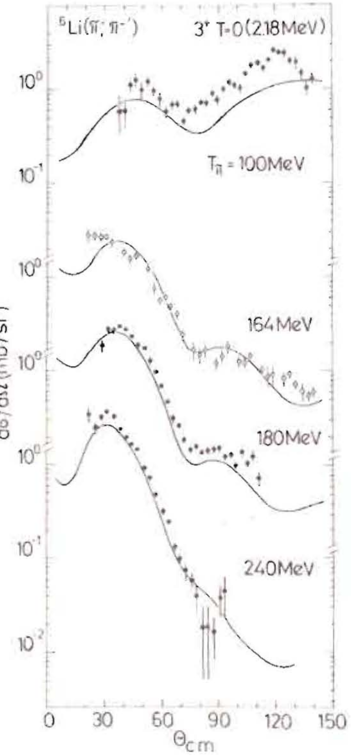


Fig.7. $d\sigma/d\Omega$ for $^{6}Li(\pi^-,\pi^{-'})^{6}Li$-reaction using DWIA (on + off-shell) and αNN-model wave functions. Experimental data are from ref./21/ (♦) and ref./22/ (◊).

transition. E.g., for the $^{18}O_{g.s.} \rightarrow {}^{18}O$ (2_1^+ , 1.98 MeV) transition, the ratio $R = \sigma(\pi^-)/\sigma(\pi^+)$ has been observed as 1.86, 1.58, and 1.66 at T_{π} = 164, 180 and 230 MeV, respectively. It is clear that collective excitations which destroy the inert ^{16}O core play an important role in damping the above estimate of R = 9.

The standard approach to interpreting these results is to fit the parameters $(\beta R)_n$ and $(\beta R)_p$ of the macroscopic nuclear model so that the DWIA calculations describe the pion scattering data. In fig.8 we show the first results obtained by using a microscopic nuclear model /15/. The wave functions of the $0^+_{g.s.}$ and 2^+_1 excited states of ^{18}O were calculated within the generalized hyperspherical function method developed by Filippov and collaborators.

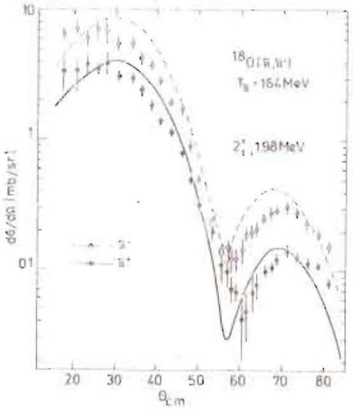


Fig.8. The differential cross-sections of ($\pi^\pm$, $\pi^\pm$) reaction in ^{18}O /15/.

In this approach the collective nucleonic motions in the nucleus are dynamically described in terms of the A-body Schrödinger equation with a fixed NN interaction. Besides the realistic case $\rho_n \neq \rho_p$ shown in fig.8, a calculation has also been performed by using our coupled-channel scattering program MESON for the case $\rho_n = \rho_p$. The results (not shown) for π^- and π^+ scattering are then very close to each other in strong disagreement with experiment.

IV. Excitation of Spin-Isospin Dipole Resonance in p-Shell Nuclei

In p-shell nuclei a concentration of spin-isospin dipole transitions takes place. Such a concentration has been manifested in radiative pion capture from mesoatomic orbits. Typical examples of such a concentration are given in fig.9a (theory) and fig.9b (experiment) /16/. $^{12}C(\pi^-,\gamma)$ reaction is calculated in the continuum shell model /17/, two others - in the bound shell model. In photoproduction, when pions are emitted in forward direction, the same levels as in (π^-,γ) reaction are excited in p-shell nuclei. When pions are emitted in backward direction, the transition of higher multipolarity dominates in (γ,π^+)-reaction on light nuclei.

The spin-isospin dipole resonance has also been observed in ^6Li. The observation has been made in different reactions: (π^-,γ), (γ,π) and (n,p) - fig.10. For the giant resonance in ^6Li its configurational splitting is very typical. The gross-structure of the nuclear response is a result of such a splitting. For a detailed discussion see ref./19/ .

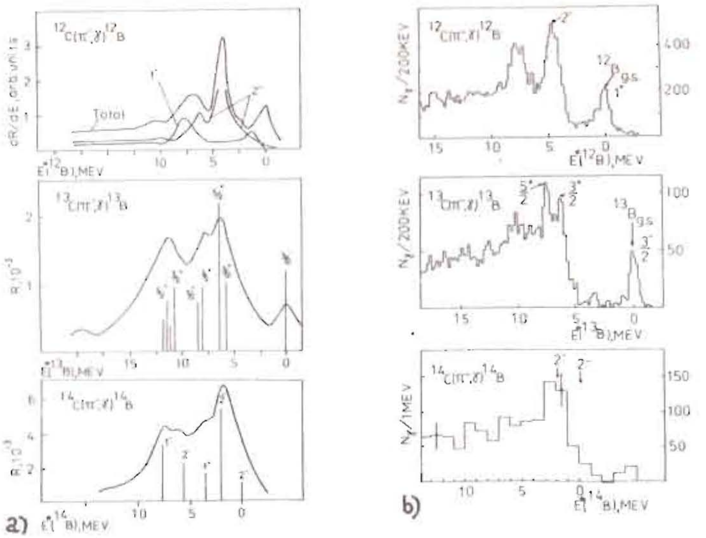


Fig.9. Spin-isospin dipole resonance in carbon isotopes as seen in (π^-,γ)-reaction: a - theory; b - experiment/16,17/ .

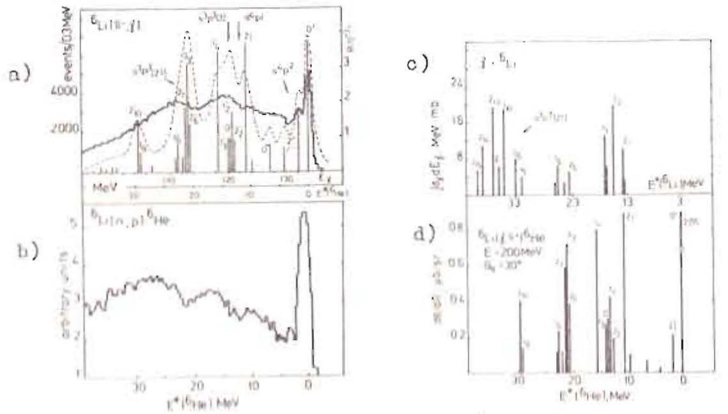


Fig.10. Spin-isospin dipole resonance in ^6Li excited in the reactions a - (π^-,γ)/16/ , b) - (n,p) 18 c - (γ,π) and dipole photonuclear resonance - d /19/ .

V. Conclusion

We have discussed some aspects of pion photoproduction and inelastic pion scattering processes on p-shell nuclei. These reactions together with electron scattering have become an important tool for nuclear structure studies. The formalism developed made it possible to describe a large number of experimental data from a general point of view on the nuclear structure. At the same time some contradictions between theory and experiment have been found. The reason is not yet clear . Additional studies, both theoretical and experimental, are needed to make clear these points. Some of them have been discussed in this report.

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Эрамжян Р.А. и др. E4-85-523

Рассеяние электронов и пионов и фоторождение пи-мезонов на легких ядрах

Рассматриваются парциальные переходы в реакции фоторождения пионов на ядрах ^6Li, ^{10}B и ^{12}C. Особое внимание уделено необходимости совместного анализа как (γ,π) так и (e,e') и (π,π')-реакций. Приведены конкретные примеры такого анализа, при использовании как феноменологического, так и микроскопического подходов. Показано, что микроскопический подход дает правильные представления о механизме (γ,π), (e,e') и (π,π') реакций при промежуточных энергиях. Рассматриваются спин-изоспиновые дипольные резонансы в ядрах 1p -оболочки. Показано, что гросс-структура спектра возбуждения ядерной системы обусловлена конфигурационным расщеплением резонанса.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1985

Eramzhyan R.A. et al. E4-85-523

Pion Inelastic Scattering, Pion Photoproduction, and Inelastic Electron Scattering on Light Nuclei

Partial transitions in pion photoproduction and in elastic pion scattering are analysed together with inelastic electron scattering on 1p -shell nuclei (^6Li, ^{10}B, ^{12}C). The dependence of differential cross-sections on the p-wave part of pion-nuclear interaction is discussed. The role of spin-independent and spin-dependent matrix elements in formation of differential cross-sections in (π,π')-reaction is established. Spin-isospin dipole resonance excitations in 1p -shell nuclei are considered.

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

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