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FERMI MOTION IN HYPERNUCLEAR PRODUCTION

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Abstract

The effects of target nucleon motion in the (K, π) reaction are studied. The distortion of meson waves and full transition amplitude is taken into account. The renormalization of the A-body transition matrix due to Fermi motion does not reduce theoretical cross-sections substantially.

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1. Introduction

The reaction (K^-, π) has been mainly used for producing hypernuclei either in collinear geometry ($\theta_\pi = 0^\circ$)¹⁾ or also taking angular distributions of outgoing mesons²⁾. Theoretical analyses of this process are reviewed in ref. ³⁾ and extensive models for detailed calculations of excitation functions and angular distributions are described in refs. ⁴⁾ and ⁵⁾ for light and heavier p-shell hypernuclei, respectively.

The reaction mechanism was usually treated in the impulse approximation with distorted waves of mesons and the static transition operator was employed. The elementary t-matrix on a free nucleon $N(K, \pi)A(Z)$ is used to describe the process on a nucleon, bound in a nucleus and bearing thus information on the structure of this target nucleus. The usual procedure was to fix a priori the momentum of the nucleon on which the reaction takes place. This procedure factors out the elementary t-matrix, introduces an effective number of nucleons for the studied reaction, simplifies calculations, but resulting theoretical cross sections and thus corresponding line (or uniform widths) excitation functions are overestimated by a factor of 2-3 as compared to the experiment and differ in shape slightly. A more realistic static approximation is to Fermi average the elementary amplitude over the momentum distribution in the target nucleus⁵⁾ to make the energy dependence of it smoother.

The problem of the actual inclusion into the (K, π) reaction mechanism of the motion of target nucleons was studied in a simplified form in ref. ⁶⁾ for $^{12}C(K^-, \pi^-)^{12}C$. It was conjectured there that a correct treatment of Fermi motion reduces theoretical cross sections

substantially, bringing them down to experimental ones. Moreover, a pronounced angular dependence of the reduction factor in 1^- (ground state) and $2^+(p^{-1}p_\Lambda)$ states of resulting hypernucleus was found there.

Such a strong effect of Fermi motion in the (K, π) reaction is unexpected in view of the smaller one in analogous reactions⁷⁾. Also, there should be room for a further mechanism of cross section reduction, namely inclusion of realistic widths of hypernuclear resonances^{4, 8)}.

It is the aim of this study to remove approximations of ref. 6)

(plane waves for K^- and π -mesons and transition amplitude in the s-wave resonant form) and to reexamine the Fermi motion influence in a more complete context. Necessary theory is reviewed briefly in sect. 2, the numerical results for the ^{12}C case are displayed and discussed in sect. 3, followed by concluding sect. 4. Some of the present results using plane waves were preliminarily reported in ref. 9).

2. Formalism

The differential cross section for the reaction $A(K^-, \pi^-)H$ is proportional to the properly summed and averaged square of T-matrix and in the laboratory system it is¹⁰⁾:

$$\frac{d\sigma}{d\Omega \text{ lab}} = \frac{(2\pi)^4 p_\pi^2}{p_K} \frac{|T_{if}^{\text{lab}}|^2 E_K E_\pi}{(E_H - E_\pi - p_K \cos \theta_\pi)}, \quad (1)$$

where $E(p)$ are laboratory energies (momenta) and θ_π is the laboratory angle of outgoing pions. In an impulse approximation, the T-matrix is expressed in terms of the elementary t-matrix for a reaction on a single nucleon where, however, exclusion of center-of-mass motion and use of Jacobi coordinates $\vec{\xi}_1$ for both nucleus and hypernucleus

introduces further correlations. The wave function of initial state (K, A) reads:

$$\langle \vec{r}_K, \vec{r}_1 \dots \vec{r}_A | \phi_K(\vec{p}_K) \psi_A(\vec{p}_A) \rangle = \frac{1}{(2\pi)^3} \exp(i\vec{p}_K \vec{r}_K) \exp(i\vec{p}_A \vec{r}_A) F_{KA}(\vec{r}_K, \vec{r}_A) \cdot \psi_A(\vec{\xi}_1 \dots \vec{\xi}_{A-1}) \quad (2)$$

and similarly for final channel (π, H) . In (2), $\vec{R}_A(\vec{R}_H)$ is the nucleus (hypernucleus) center-of-mass coordinate and F depends on relative K - A (π - H) momentum and describes distortion of the meson wave (it will be treated here in eikonal approximation). Using (2), the T-matrix may be rewritten as follows:

$$T_{if}^{\text{lab}} = \frac{\sqrt{A}}{(2\pi)^3} \sum_{(A,H)} \int \exp(i(\vec{p}_N + \vec{q} \cdot \vec{B}) \vec{\xi}_\Lambda) F_{\pi H}(\vec{p}_\pi, \vec{B} \vec{\xi}_\Lambda) \psi_H^*(\vec{\xi}_\Lambda, \vec{\xi}_2 \dots \vec{\xi}_{A-1}) \times \\ \times \langle \vec{p}_N, \vec{p}_\Lambda | t | \vec{p}_K, \vec{p}_N \rangle \exp(-i\vec{p}_N \vec{\xi}_1) F_{KA}(\vec{p}_K, \vec{\xi}_1 - \frac{1}{A} \vec{\xi}_1 \psi_A(\vec{\xi}_1 \dots \vec{\xi}_{A-1}) \times \\ \times d\vec{p}_N d\vec{\xi}_\Lambda d\vec{\xi}_1 \prod_{i=2}^{A-1} d\vec{\xi}_i. \quad (3)$$

There, $\vec{q}$ is the transferred momenta $\vec{q} = \vec{p}_K - \vec{p}_\pi$ and $B = (A-1)/(A-1 + (m_\Lambda/m_N))$ and summations (A, H) include corresponding summed variables in ψ, ψ^* . As a first simplifying approximation, terms $1/A$ and the

difference between m_Λ and m_N may be neglected. Their influence for nuclei with $A \gtrsim 9$ is small and will be studied with plane waves here. Expression (3) is often simplified by introducing further approximations into it. They may be best displayed with wave functions ψ specified. For the sake of simplicity, we shall work with independent particles, $J=0$ targets and adopt a Λ particle $(j_{\Lambda\Lambda}^{\ell m})$ - N hole $(j_{N^N}^{\ell m})$ description of hypernuclear resonances. Then for matrix elements in $|T_{if}|^2 = \sum_M |\langle JM | \hat{T} | 00 \rangle|^2$, it holds:

$$\langle JM | \hat{T} | 00 \rangle = C \sum_{\mu, \mu_\Lambda} \langle \ell - \mu, \ell, \mu_\Lambda | JM \rangle (-)^{J+j_\Lambda+\mu+1/2} \langle \phi_{\ell\mu} | \hat{T} | \phi_{\ell\mu_\Lambda} \rangle, \quad (4)$$

where $\phi_{\ell m}$ are single particle (harmonic oscillator) wave functions,

$$G = \frac{1}{\sqrt{A}} \sqrt{(2j_N+1)(2j_A+1)} \left\{ \begin{matrix} j_N & j_A & j \\ j_A & j_N & 1/2 \end{matrix} \right\}$$

and $\langle \phi | T | \phi \rangle$ stands for:

$$\int d\vec{p}_N d\vec{\xi}_1 d\vec{\xi}_A \phi_{q, m_A}(\vec{\xi}_A) e^{i\vec{\xi}_A \vec{p}_A} \exp(-i\vec{p}_N \int_0^\infty \rho(|\vec{\xi}_A + \vec{p}_N t|) dt - \beta_K \times \\ \times \int_0^\infty \rho(|\vec{\xi}_A - \vec{p}_N t|) dt) \langle \vec{p}_N \vec{p}_A | t | \vec{p}_K \vec{p}_N \rangle e^{-i\vec{p}_N \vec{\xi}_1} \phi_{q, m_N}(\vec{\xi}_1) \cdot \quad (5)$$

In (5), $\vec{p}_A = \vec{p}_N + \vec{q}$, $1/A$ terms are already omitted (approximation I) and the density distribution of target nucleus was introduced through eikonal approximation for F. Further possible approximations are:

II. Static approximation: The dependence of elementary t-matrix on target nucleon momentum $\vec{p}_N$ is neglected, $\vec{p}_N$ is replaced by some effective momentum^{3,4,7)} and (5) reduces to

$$\langle \vec{p}_N \vec{p}_A | t | \vec{p}_K \vec{p}_N \rangle \int d\vec{\xi}_A e^{i\vec{\xi}_A \vec{q}} \phi_{q, m_A}(\vec{\xi}_A) \phi_{q, m_N}(\vec{\xi}_A) \exp(-i\vec{p}_N \int_0^\infty \rho(|\vec{\xi}_A + \vec{p}_N t|) \times \\ \times dt - \beta_K \int_0^\infty \rho(|\vec{\xi}_A - \vec{p}_N t|) dt) ; \quad (6)$$

III. Plane wave approximation: All F's in (5) are put equal to 1 and (5) is again reduced to 3-dimensional integration

$$d\vec{p}_N \phi_{q, m_A}(\vec{p}_N + \vec{q}) \langle \vec{p}_N \vec{p}_A | t | \vec{p}_K \vec{p}_N \rangle \phi_{q, m_N}(\vec{p}_N) \cdot \quad (7)$$

$1/A$ terms in the above approximations would renormalize transferred momentum:

$$\vec{q} + \frac{A-1}{A-1+(m_A/m_N)} (\vec{p}_K - \vec{p}_N) \cdot$$

IV. Elementary t-matrix is replaced by some simple function of energy, $\sqrt{s}$, e.g. in effective s-wave parametrization⁶⁾.

V. The excitations of final hypernuclear states E^* and their influence on $\vec{q}$ are neglected ($m_H = m_H^* - E^*$).

In addition to the above approximations, a non-uniqueness arises due to the use of the elementary t-matrix off-mass-shell. We work in laboratory system with $\vec{q} = (\vec{p}_K - \vec{p}_N) \parallel z$ (it simplifies ϕ dependence of integrand in (5), as for azimuthal angles ϕ , it holds then $\phi_N = \phi_A$),

$$s = (E_K + E_N)^2 - (\vec{p}_K + \vec{p}_N)^2 \cdot$$

The elementary 2CM amplitude f of ref. 11) is related to the laboratory t-matrix by

$$\langle \vec{p}_N \vec{p}_A | t | \vec{p}_K \vec{p}_N \rangle = \sqrt{\frac{(E_A + m_A)(E_N + m_N)}{(E + m_A)(E + m_N)}} \cdot \frac{1}{\sqrt{(E + m_A)(E + m_N)}} \cdot \frac{f(s, \theta_{K\pi})}{16\pi^2} \cdot \\ \cdot \left\{ 2\sqrt{s+2m_A m_N} + E_K + E_N - \frac{p_K^2 - p_\pi^2}{E_A + m_A} + \frac{E_K + E_N - 2\sqrt{s-2m_A m_N}}{(E_A + m_A)(E_N + m_N)} \cdot \vec{p}_N \vec{p}_A - \right. \\ \left. - \left[(E_N + m_N)^{-1} + (E_A + m_A)^{-1} \right] (\vec{p}_K + \vec{p}_N) \vec{p}_N \right\}, \quad (8)$$

where $E(\epsilon)$ are lab (2CM) energies, $\bar{m} = (m_A + m_N)/2$, $\vec{p}_A = \vec{p}_N + \vec{q}$. The spin-flip terms in the t-matrices were found to contribute by approximately 3 orders of magnitude less to strongly populated resonances in p-shell hypernuclei and are thus neglected here. The elementary 2CM angle $\theta_{K\pi}$ in f and laboratory angle $\theta_{K\pi}^L$ are related by

$$\cos \theta_{K\pi} = \frac{p_K p_\pi \cos \theta_{K\pi}^L + \epsilon_K \epsilon_\pi - E_K E_\pi}{k_1^{2CM} \cdot k_f^{2CM}} \cdot \quad (9)$$

For small angles needed here ($\theta_\pi < 20^\circ$), the off-shell extension (8+9) is well behaved⁷⁾ and may be used here.

3. Results and discussion

In order to illustrate qualitatively the influence of Fermi motion of target nucleons, the formulae (5)-(9) have been applied to the $^{12}\text{C}(K^-, \pi^-)^{12}\text{C}$ reaction. It was previously studied often both experimentally¹²⁻¹⁴⁾ and theoretically^{5,6,15)} and accumulated data may be well compared and analysed. The influence of approximations I to V,

made in theoretical studies will be disentangled here successively.

Specification to ^{12}C target implies for the density distribution⁽¹⁶⁾

$$\rho(r) = \left(\frac{\alpha^2}{\pi} \cdot \frac{A}{A-1} \right)^{3/2} e^{-\alpha^2 A / (A-1) r^2} \cdot \frac{A}{A-1} \cdot \left\{ 3 + \frac{2}{3} (A-4) \frac{A}{A-1} \alpha^2 r^2 \right\} \quad (10)$$

with $A = 12$ and $\alpha_N = 1/1.68 \text{ fm}^{-1}$ is the nucleon harmonic oscillator

(HO) constant, also entering the single particle HO wave functions.

Hyperon wave function has $\alpha_\Lambda = \alpha_N \sqrt{m_N/m_\Lambda}$. Constants β_i in the definition of eikonal distorting factors F are

$$\beta_i = a_i \alpha_i^2 (1 - i\alpha_i)/2$$

and the following values have been adopted here (in fm^2):

$$\text{at } p_K = 450 \text{ MeV}/c: \beta_K = 1.75 - i0.70, \quad \beta_\pi = 1.82 + i1.93,$$

$$\text{at } p_K = 800 \text{ MeV}/c: \beta_K = 1.70 - i1.23, \quad \beta_\pi = 1.32 + i0.39.$$

All n -dimensional integrations ($n = 3; 6$) have been performed with the use of a very efficient code of ref.⁽¹⁷⁾. As there are two regions of K -meson momenta, produced from different machines^(1,2) and differing also in physical input and results, both were included in the present study. Results are displayed in the form of the ratio R of the cross sections with full Fermi motion treatment to the static one, where $\vec{p}_N = 0$:

$$R = \frac{|\int F' \Psi_A^* \Psi_H \langle p_\pi p_\Lambda | t | p_K p_N \rangle e^{i\vec{p}_N(\vec{\xi}_\Lambda - \vec{\xi}_1) + i\vec{B}\vec{q}\vec{\xi}_\Lambda} d\vec{p}_N d\vec{\xi}_1 d\vec{\xi}_\Lambda|^2}{|\langle p_\pi p_\Lambda | t | p_K 0 \rangle \int F' \Psi_A^* \Psi_H e^{i\vec{p}_N(\vec{\xi}_\Lambda - \vec{\xi}_1) + i\vec{B}\vec{q}\vec{\xi}_\Lambda} d\vec{p}_N d\vec{\xi}_1 d\vec{\xi}_\Lambda|^2} \quad (11)$$

The ^{12}C nucleus is considered to consist of $s_{1/2}$ and $p_{3/2}$ nucleons⁽⁶⁾ and thus, four hypernuclear resonances $(p_N^{-1} s_\Lambda)^{-}$ (ground state), $(p_N^{-1} p_\Lambda)^{-}$ 0^+ 1^+ 2^+ and $(s_N^{-1} s_\Lambda)^{-}$ 0^+ 1^+ 2^+ are studied here. Their excitations, if needed, are assumed to be 0, 10 and 20 MeV, respectively.

Table 1 displays a small influence of terms $1/A$ in T -matrix as resulted in PWIA. Larger sensitivity encountered for $\theta_\pi \sim 20^\circ$ in the 0^+ state and $\theta_\pi \sim 0^\circ$ in 2^+ is non-physical and is due to a deficiency

of HO functions in PWIA in those regions (overlaps $\langle \Psi_H / \Psi_A \rangle$ exhibit dips). It should not be present when distortion is introduced. The $1/A$ terms become even less important for the lower region of momenta of incoming K -mesons and at fixed p_K for increased transferred momenta (or increased θ_π). In the following discussion, $1/A$ terms in eq. (3) are thus neglected.

To facilitate the DWIA calculations, the average excitation energy of p -h states is introduced. The influence of this approximation (No. V) is illustrated in table 2 as it results in PWIA. The changes in excitation energies influence ratio R appreciably for geometry close to collinear ($\theta_\pi < 5^\circ$) and in hypernuclear states with $J \neq 0$ only.

Otherwise, variations in energy of states by as much as 10 MeV is not felt by R . The excitation energies of p -h states should thus appear notably in kinematics (precise calculations of smaller peaks in excitation function for collinear geometry). For the exploration of the influence of Fermi motion on the π^- -angular distributions, the averaged excitation energy (10 MeV for ^{12}C) is sufficient. It should be remembered, however, that negligible influence on R does not necessarily mean negligible change in cross sections themselves. In fact, they change by up to 10% due to the above changes in such a way that R remains the same.

Before discussing DWIA results, the influence of changes in nuclear structure input on cross sections and R should be mentioned. The use of HO single-particle wave functions for nucleons and Λ -hyperon is well established and yields reasonable structure of both nuclei and hypernuclei. For certain J_H , q_{tr} and HO constants α , it may, however, produce "spurious" resonant-like behaviour (due to variations of an

overlap integral $\int \phi_N(\vec{p}_N) \phi_A(\vec{p}_N + \vec{q}_{tr}) d\vec{p}_N$. This may appear not only in PWIA (see e.g. tables 1 and 2, $j = 0^+$, $\theta_\pi = 20^\circ$), but also in static DWIA treatment. This is an important aspect of a correct treatment of the Fermi motion. Outside of those "spurious" regions, changes of α do not change cross sections or R appreciably.

The results of the full distorted wave calculations are shown in table 3 and fig. 1. The ratios R , characterizing the influence of Fermi motion inclusion for both PWIA and DWIA are roughly similar and differ by less than 50% from unity (except in the above "spurious" regions). Also, the angular dependence of reductions R is not strong. Both those results differ from those of ref. 6) and the difference may be mainly ascribed to approximate treatment of the scattering amplitude used there. The ratio DW/PW is a measure of the cross section reduction due to distortion of meson waves for cases, when Fermi motion is treated fully. It is seen that the distortion reduction factor is of the order of 0.1 in most cases, but varies appreciably as opposed to the static case, where the ratio DW/PW is more uniform. For smaller transferred momenta ($p_K = 450$ MeV/c) the influence of Fermi motion is much smaller as values of R are closer to unity.

A corroboration of the influence of Fermi motion and correctness of its present treatment comes from comparison with experiment¹²⁻¹⁴) on ^{12}C for $p_K = 800$ MeV/c. The state $0^+_1(S^{-1}_N S_A)$ has a large width and is not well suited for detailed considerations (which is typical for $s^{-1}_N s_A$ states in the second half of p -shell). Ground state 1^- and $0^+_1, 2^+$ ($p^{-1}_N p_A$) excited states in ^{12}C are, however, well seen and of comparable widths, thus the reduction of calculated cross sections in line

excitation function is similar. In the experiment, only one summed peak¹⁴) is seen and not three separate peaks $0^+(p^{-1}_3 p^{-1}_2 p_{3/2})$, $2^+(p^{-1}_3 p_{1/2})$, $2^+(p^{-1}_3 p_{3/2})$. The collinear experiment¹³) suggests for the ratio of main peaks $P = (d\sigma/d\Omega)^{0^+, 2^+} / (d\sigma/d\Omega)^{1^-}$ a value $P_0 \sim 10$. A static (no Fermi motion) calculation with distorted waves has yielded $P_0 \sim 22.6$, inclusion of Fermi motion decreases P (for our choice of parameters, it gives $P_0 \approx 13.8$). π^- -angular distribution measurements¹⁴) also suggest a similar width of 1^- and $(0^+, 2^+)$ states and comparable cross sections at $\theta_\pi = 10^\circ$, namely $P_{10}(\text{exp}) \sim 0.7$; static DWIA gives $P_{10} \approx 2.3$, whereas DWIA with Fermi motion included $P_{10} \approx 1.9$. The influence of Fermi motion is illustrated in more detail in fig. 1, where static and full DWIA results are compared with experimental data¹⁴). Those results cannot be reproduced obviously in PWIA even if Fermi motion is included.

In order to understand the origin of large reduction of cross sections due to Fermi motion, obtained in ref. 6), we performed PWIA and DWIA calculations, where we replaced the t -matrix (8) by the s -wave resonance approximation $t \sim 1/(\sqrt{s} - M_T + i\Gamma/2)$ with $M_T = 1700$ MeV and $\Gamma = 100$ MeV [ref. 6)]. The results are shown in table 4 and it is seen there that a great reduction found in ref. 6) may be indeed ascribed mainly to neglecting contributions of full s^- and of higher partial waves into the t -matrix. The small differences between reduction factors R reported in ref. 6) and PWIA results of table 4 are due to small differences in kinematics and excitation energies of hypernuclear states. For $p_K = 450$ MeV/c, the PWIA with approximate t -matrix suggests that Fermi motion inclusion increases cross sections slightly and this result persists even if distortion of meson waves is included.

4. Conclusion

The influence of the Fermi motion of target nucleons on the reaction (K, π) producing hypernuclei has been studied in detail. Also, the role of various approximations in the description of this reaction has been analyzed. The formalism has been quantitatively illustrated on the $^{12}\text{C}(K^-, \pi^-)^{12}\text{C}_\Lambda$ reaction which was often studied before, both experimentally and theoretically.

The $1/\Lambda$ and $(1-m_\Lambda/m_N)$ terms in transition operators and variations of nuclear and hypernuclear structure input have only very limited influence on Fermi motion effects. The inclusion of Fermi motion becomes physically plausible when distortion of meson waves (DWIA) is incorporated, as well. If the elementary transition amplitude of the reaction $n(K^-, \pi^-)\Lambda$ is taken fully into account, DWIA results suggest a reduction of a few tens of percent in cross sections and no pronounced angular dependence. This reduction cannot thus explain the discrepancy between static DWIA cross sections and experimental ones, being as much as 100-200%. A mechanism for substantial (and non-uniform) reduction of DWIA cross sections would then be to use more involved hypernuclear wave functions (with configuration mixing and not mere particle-hole scheme).

The inclusion of Fermi motion of target nucleons complicates the usual DWIA conclusion substantially. It should then appear in analysis of experimental data at least phenomenologically and its interference with nuclear structure and reaction mechanism should be discussed. Experimental verification of the Fermi motion influence would come from a comparison with data for very low transferred momenta (p_K close to

530 MeV), where the enhancement instead of decrease of static DWIA cross sections should be encountered.

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Table 1

Influence of neglecting the 1/A terms on R in PWIA for two K-meson momenta and various angles of outgoing π -mesons. Heading TI denotes full treatment with 1/A terms included.

P_K	State	$1(p^{-1}s_A)$		$0^+(p^{-1}p_A)$		$2^+(p^{-1}p_A)$		$0^+_2(s^{-1}s_A)$	
	$\theta_{K\pi}$	TI		TI		TI		TI	
800	0°	1.79	1.59	0.68	0.67	18.1	13.7	0.80	0.80
	10°	0.92	0.88	0.65	0.64	0.80	1.01	0.80	0.81
	20°	0.80	0.78	0.50	0.28	0.79	0.84	0.83	0.82
450	0°	2.61	2.45	0.91	0.91	11.0	5.30	0.94	0.94
	10°	0.98	0.98	0.91	0.91	0.87	0.95	0.94	0.94
	20°	0.94	0.94	0.91	0.90	0.92	0.95	0.94	0.95

Table 2

Influence of variations of excitation energies (MeV) of hypernuclear states on ratios R , as obtained in PWIA.

P_K	State	1^-	0_1^+	2^+	0_2^+		
	$\theta_{K\pi}$	0	10	0	10	20	
800	0°	1.59	1.98	0.67	0.67	0.80	0.80
	10°	0.88	0.90	0.63	0.64	0.80	0.81
	20°	0.78	0.80	0.26	0.28	0.81	0.82
450	0°	2.29	1.33	0.91	0.91	0.94	0.94
	10°	0.97	0.97	0.91	0.91	0.94	0.95
	20°	0.94	0.95	0.90	0.90	0.94	0.95

Table 3

Full distorted wave calculation of ratios R_{DW} , compared to PWIA values R_{PW} . The average excitation of 10 MeV is adopted. DW/PW stands for reduction due to distortion in the non-static case.

P_K	$\theta_{K\pi}$	1^-	0_1^+	2^+	0_2^+
800	0°	2.0	0.67	13.2	0.80
	10°	0.90	0.64	0.78	0.80
	20°	0.80	0.28	0.78	0.81
	0°	1.33	0.91	8.51	0.94
450	10°	0.95	0.90	0.96	0.94
	20°	0.94	0.91	0.89	0.94

Table 4

Influence of approximating f_{tot} by s-wave t-matrix only; for both DWIA and PWIA and $P_K = 450$ and 800 MeV/c , average excitation energy 10 MeV is adopted.

θ_π	States	1^-	0_1^+	2^+	0_2^+
0°	R_{PM}^{450}	0.30	1.12	5.37	1.06
	R_{PM}^{800}	2.04	0.37	21.7	0.50
	R_{DM}^{800}	0.85	0.39	1.14	0.46
	R_{PM}^{450}	1.13	1.15	1.23	1.08
10°	R_{PM}^{800}	0.63	0.34	0.58	0.49
	R_{DM}^{800}	0.49	0.34	0.54	0.44
	R_{PM}^{450}	1.24	1.23	1.19	1.13
	R_{PM}^{800}	0.47	0.09	0.45	0.46
20°	R_{DM}^{800}	0.38	0.49	0.41	0.26

Figure Caption

Fig. 1 Angular distributions of π -mesons for the ground state 1^- and excited state (at excitation of $\sim 10 \text{ MeV}$) $0_1^+(2^+, 2^+)$ as resulted from DWIA (dashed line) and from DWIA with Fermi motion included (full line), compared to experiment (I).