# NEW EXPERIMENTAL EVIDENCES FOR OPTIMAL RESONANCES IN PION-NUCLEUS SCATTERING

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In this paper new experimental evidences, on the excitation of PMD-SQS-optimal resonances in pion-nucleus scattering in the $\Delta(1236)$-resonance region, are presented. The saturation of the optimal resonance limits is experimentally evidentiated with high accuracy the following pion-nucleus scatterings: $(\pi^{\pm}D, \pi^{\pm}He, \pi^{\pm}Li)$, $(\pi^{\pm}Be, \pi^{\pm}C, \pi^{\pm}O)$, $(\pi^{\pm}Al, \pi^{\pm}S, \pi^{\pm}Ca)$, $(\pi^{\pm}Fe, \pi^{\pm}Sn, \pi^{\pm}Pb)$. The masses and widths of the optimal resonances, obtained from the experimental data on total pion-nucleus cross sections, are given.

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## 1. INTRODUCTION

The mathematician Leonhard Euler (1707–1783) appears to have been a philosophical optimist having written:

"*Since the fabric of universe is the most perfect and is the work of the most wise Creator, nothing whatsoever take place in this universe in which some relation of maximum or minimum does not appear. Wherefore, there is absolutely no doubt that every effect in universe can be explained as satisfactory from final causes themselves the aid of the method of Maxima and Minima, as can from the effective causes".*

Having in mind this kind of optimism in the papers [1–16] from Ref. [1] we introduced and investigated the possibility to construct a predictive analytic theory of the elementary particle interaction based on the principle of minimum distance in the space of quantum states (PMD-SQS). So, choosing the partial transition amplitudes as the system variational variables and the *distance in the space of the quantum states* as a measure of the system effectiveness, we obtained the results [1–16] from Ref. [1]. These results proved that the principle of minimum distance in space of quantum states (PMD-SQS) can be chosen as variational principle by which we can find the analytic expressions of the partial transition amplitudes. In this paper we continue to present a description of hadron-nucleus scattering in the energy-region corresponding to the $\Delta(1236)$ resonance in the elementary pion-nucleon interaction, *via* principle of minimum distance PMD-SQS when the distance in space of states is minimized with the constraints: $d\sigma/d\Omega(+1) = fixed$. Special PMD-SQS-optimality investigations was dedicated dedicated to the development of a theory of the PMD-SQS-optimal resonances. Here, many important results are proved: (i) The *very high total widths* for the optimal resonance, where: $\Gamma_n^o = \Gamma_1 n$, $n = L_o + 1$, (ii) A definite correlation between "positions" and "widths" of "elementary" resonances which are constituents of the optimal resonances, (iii) A "diffractive" character of the angular distributions, (iv) A total intensity proportional with $(L_o+1)^2$. Moreover, our investigation was conducted to get from the available data the experimental evidences for the optimal resonances in hadron-hadron scattering as well as in hadron-nucleus scattering. We must underline that not only so called "diffractive (Morrison) resonances" ($A_1, A_2, etc.$) are candidates for to be optimal resonances, but also, the "dual diffractive resonances" discovered by us and published in the paper [2]. Some of results of these investigations was reported in the papers [3]–[4]. Therefore, as a continuation of our papers [2],[3],[4], new experimental evidences for PMD-SQS-optimal resonances are presented in Sect. 2. The masses of the PMD-SQS-optimal resonances are determined from the experimental data by fit in Sect. 3.

## 2. NEW EXPERIMENTAL EVIDENCES FOR PMD-SQS-OPTIMAL RESONANCES

It is well known that the essential results obtained from the experimental data on pion-nucleus scattering, in the region corresponding to the $\Delta(1236)$ resonance in the elementary pion-nucleon interaction, are characterized by the following *resonance-diffraction duality*:

I. *A resonant energy behaviour* manifested in the total, integrated elastic and inelastic cross sections (see refs. [3–11]), as well as, in each pion-nucleus partial wave.

II. *A typical diffraction pattern* observed in the pion-nucleus angular distributions [12–15] (see also Refs. [37, 38, 41–76] in ref. [1]).

III. The resonance width $\Gamma_A$ becomes broader as nuclear mass A increases. A behaviour of form: $\Gamma_A = \Gamma_\Delta A^{1/3}$ is verified experimentally with high accuracy (see ref. [2]).

IV. The *resonance peak shifts* downward with increasing A to lower kinetic energy.

In order to explain consistently all the above essential characteristic features of the pion-nucleus scattering, a new concept of nuclear collective resonance state was introduced in ref. [2]. According to their diffraction pattern observed in the angular distributions, these collective nuclear resonant states was called *dual diffractive resonances* (DDR).

In this paper, we continue to report the results of our investigations [3,4] for to get from the available data the experimental evidences for the optimal resonances especially in pion-nucleus scattering in the $\Delta(1236)$ region. So, in the papers [3,4], by using the Principle of Minimum Distance in Space of Quantum States (PMD-SQS) [1], we obtained not only the experimental evidences for a new kind of resonance, called optimal resonance, but also a new description of the pion-nucleus scattering in the $\Delta(3,3)$-resonance region. Hence, using the principle of minimum distance in space of quantum states (see Refs. [1])

$$\text{minim}\left\{\sum(2l+1)\,|\,f_l(E)\,|^2\right\} \text{ with } \frac{d\sigma}{d\Omega}(E,1)=|\sum(2l+1)f_l(E)\,|^2=\mathit{fixed} \quad (1)$$

we obtained:

$$f_N(E,x)=f(E,1)\frac{K_{L_o}(x,1)}{K_{L_o}(1,1)}, \quad (2)$$

$$2K(x,1)=\sum_{l=0}^{L_o}(2l+1)P_l(x)P_l(1)=\dot{P}_{L_o+1}(x)+\dot{P}_{L_o}(x), \quad (3)$$

where the *optimal angular momentum* is given by:

$$2K(1,1)=\Sigma_{l=0}^{L_o}(2l+1)=(L_o+1)^2=\frac{4\pi}{\sigma_{el}}\frac{d\sigma}{d\Omega}(E,1) \quad (4)$$

Then, all the essential characteristic features I–IV of the pion-nucleus in the optimal resonance limit are derived. All the optimal resonance predictions are found in a good agreement with the available experimental data. Hence, we proved that the "dual diffractive resonances" discovered by us in 1981 and published in the paper [2] are actually *genuine optimal resonances*.

Now, as a direct consequence of the PMD-SQS optimality conditions (1) from [3,4] we obtain that all $\pi A$-resonant states which are derived from a single $\pi N(\Delta)$-resonant state become degenerate. Hence, for the nuclear part of the forward pion-nucleus scattering, we obtain the following expression:

$$f_N(E,1)=\sum_{l=0}^{L_o}(2l+1)\frac{1}{2k}\frac{\Gamma_{el}}{E_0-E-\frac{i}{2}[\Gamma-\gamma_0(E_0-E)]}=\frac{1}{2k}\frac{\Gamma_{el}(L_o+1)^2}{E_0-E-\frac{i}{2}[\Gamma-\gamma_0(E_0-E)]} \quad (5)$$

where $E$ is the c.m. energy, $k$ is the c.m. momentum, $x\equiv\cos\theta$, $\theta$-c.m. scattering angle, $E_o,\Gamma,\Gamma_{el}$, and $\gamma_0$, are the effective optimal resonance parameters: mass, total width, elastic width and asymmetry parameter, respectively. We note that the asymmetry parameter $\gamma_0$ was introduced as in refs. [2] in a natural way starting with a Regge expression, $f_l(E)\propto[l-\alpha_l(E)]^{-1}$, for the pion-nucleus partial amplitude $f_l(E)$.

Therefore, in the optimal resonance limit, the pion-nucleus scattering is characterized by the following essential features:

(i) The energy behavior of the total hadron-nucleus cross section is of the asymmetric Breit-Wigner form given by

$$\sigma_T = \pi \lambda\!\!\!^{-2} (L_o+1)^2 \frac{\Gamma_{el}[\Gamma-\gamma_0(E_0-E)]}{(E_0-E)^2+\frac{1}{4}[\Gamma-\gamma_0(E_0-E)]^2} \tag{6}$$

$$\sigma_{el} = \pi \lambda\!\!\!^{-2} (L_o+1)^2 \frac{\Gamma_{el}^2}{(E_0-E)^2+\frac{1}{4}[\Gamma-\gamma_0(E_0-E)]^2} \tag{7}$$

(ii) The real part of the forward hadron-nucleus scattering amplitude has a resonant behavior described by

$$\mathrm{Re} f_{\pi A}(E,0°) = \frac{\lambda\!\!\!^{-}(L_o+1)^2}{2} \frac{\Gamma_{el}(E_0-E)}{(E_0-E)^2+\frac{1}{4}[\Gamma-\gamma_0(E_0-E)]^2} \tag{8}$$

(iii) The angular distributions of the optimal resonances are typical diffractive patterns, very sensitive to the values of optimal angular momentum $L_o$. They are described by

$$\frac{d\sigma}{d\Omega}(E,x) = \frac{d\sigma}{d\Omega}(E,1)\left[\frac{K_{L_o}(x,1)}{K_{L_o}(1,1)}\right]^2 \approx \frac{d\sigma}{d\Omega}(E,1)\left[\frac{2J_1(\tau)}{\tau}\right]^2, \quad \mathrm{L_o} >> 1 \tag{9}$$

for $\mathrm{L_o} >> 1$, where $J_1(\tau)$ is the Bessel function of the first order and $\tau \equiv 2L_o \sin\frac{\theta}{2}$. The number of the diffractive maxima and minima in the entire $[-1,+1]$-interval are given by $N_{\max} = L_o+1$ and $N_{\min} = L_o$.

(iv) The optimal resonances saturate the “axiomatic” bounds:

$$\sigma_T^2(E) \le 4\pi \lambda\!\!\!^{-2} (L_o+1)^2 \sigma_{el}(E) \tag{10}$$

In Refs. [2–4], in fitting Eq. (6) to the experimental data we have considered the $E_0$ fixed by the relation

$$E_o = M_A + 1236 MeV - m_N, \ \Gamma_{el} = k\gamma_1, \ L_o \approx kR$$

and the geometric radius R fixed as in the Tables 1 of Ref. [3], for each nucleus. The other parameters $\gamma_0, \gamma_1$ and $\Gamma$ from Eq. (6) are allowed to vary for each nucleus in order to obtain the best $\chi^2$-fit of the total cross sections. The optimal resonance parameters are presented in Fig. 2 (see also Table 1 in Ref. [3]).

Next, the experimental data on the total pion-nucleus cross sections in the $\Delta(1236)$ – energy region are analyzed in terms of optimal resonance predictions (6)–(7). The saturation of the axiomatic optimal bound (10) is experimentally evidentiated in Figs. (1a)–(1c) with high accuracy in the following pion-nucleus scatterings: $(\pi^{\pm}D, \pi^{\pm}He, \pi^{\pm}Li)$, $(\pi^{\pm}Be, \pi^{\pm}C, \pi^{\pm}O)$, $(\pi^{\pm}Al, \pi^{\pm}S, \pi^{\pm}Ca)$, $(\pi^{\pm}Fe, \pi^{\pm}Sn, \pi^{\pm}Pb)$, respectively.

*Table 1*

The parameters $\gamma_0$, $\gamma_1$, and $E_0$ of Eq. (6) obtained by minimum $\chi^2$-fits to the total pion-nucleus cross sections when the total widths are fixed by $\Gamma_A = \Gamma_\Delta A^{1/3}$.
The experimental data are from Refs [5–17]

| $\pi^+ A$ | Mass A (MeV) | R (fm) | $\Gamma = 120\, A^{1/3}$ (MeV) | $\gamma_0^{(+)}$ | $\gamma_1^{(+)}$ | $E_0$-$M_A$+$m_N$ (MeV) | $\chi^2/n_{dof}$ |
|---|---|---|---|---|---|---|---|
| $\pi^{+2}$D | 1876.12 | 2.8 | 151.2 | 0.61 ± 0.09 | 0.081 ± 0.001 | 1240.5 ± 1.1 | 24.8 |
| $\pi^{+4}$He | 3728.40 | 2.21 | 190.5 | 0.57 ± 0.49 | 0.229 ± 0.005 | 1240.1 ± 8.9 | 39.9 |
| $\pi^{+6}$Li | 5603.05 | 3.23 | 218.1 | 0.60 ± 0.17 | 0.197 ± 0.003 | 1240.5 ± 3.4 | 1.44 |
| $\pi^{+7}$Li | 6535.37 | 3.15 | 229.6 | 0.76 ± 0.11 | 0.229 ± 0.001 | 1244.6 ± 2.1 | 5.67 |
| $\pi^{+9}$Be | 8394.79 | 3.12 | 249.6 | 0.63 ± 0.33 | 0.295 ± 0.004 | 1239.2 ± 8.0 | 14.2 |
| $\pi^{+12}$C | 11177.9 | 3.19 | 274.7 | 0.85 ± 0.09 | 0.373 ± 0.002 | 1235.7 ± 2.3 | 4.31 |
| $\pi^{+16}$O | 14899.2 | 3.55 | 302.4 | 0.69 ± 0.47 | 0.418 ± 0.012 | 1222.1 ± 17.1 | 0.49 |
| $\pi^{+27}$Al | 25133.1 | 3.76 | 360.0 | 1.33 ± 0.07 | 0.638 ± 0.04 | 1227.4 ± 2.3 | 0.35 |
| $\pi^{+32}$S | 29781.8 | 4.03 | 381.0 | 1.07 ± 0.23 | 0.72 ± 0.02 | 1211.7 ± 12.2 | 7.14 |
| $\pi^{+40}$Ca | 37224.9 | 3.48 | 410.4 | 1.72 ± 0.17 | 0.97 ± 0.01 | 1255.0 ± 3.6 | 2.25 |
| $\pi^{+56}$Fe | 52103.1 | 4.97 | 459.1 | 2.03 ± 0.06 | 0.88 ± 0.01 | 1210.6 ± 4.5 | 0.18 |
| $\pi^{+93}$Nb | 865213 | 5.7 | 543.7 | 2.43 ± 0.09 | 1.06 ± 0.05 | 1224.8 ± 11.2 | 0.07 |
| $\pi^{+119}$Sn | 110758 | 5.99 | 590.2 | 2.68 ± 0.12 | 1.28 ± 0.07 | 1213.9 ± 12.7 | 0.12 |
| $\pi^{+207}$Pb | 192797 | 6.98 | 709.9 | 3.18 ± 0.38 | 1.69 ± 0.24 | 1199.9 ± 30.5 | 0.23 |
| $\pi^{+209}$Bi | 194623 | 6.98 | 712.1 | 3.35 ± 0.56 | 1.77 ± 0.31 | 1191.8 ± 36.3 | 0.08 |
| $\pi^- A$ | Mass A (MeV) | R (fm) | $\Gamma = 120\, A^{1/3}$ (MeV) | $\gamma_0^{(-)}$ | $\gamma_1^{(-)}$ | $E_0$-$M_A$+$m_N$ (MeV) | $\chi^2/n_{dof}$ |
| $\pi^{-2}$D | 1876.12 | 2.8 | 151.2 | 0.52 ± 0.06 | 0.082 ± 0.001 | 1241.6 ± 0.7 | 11.6 |
| $\pi^{-4}$He | 3728.40 | 2.21 | 190.5 | 0.68 ± 0.12 | 0.225 ± 0.004 | 1244.6 ± 1.6 | 36.7 |
| $\pi^{-6}$Li | 5603.05 | 3.23 | 218.1 | 0.59 ± 0.11 | 0.204 ± 0.001 | 1238.1 ± 1.9 | 1.08 |
| $\pi^{-7}$Li | 6535.37 | 3.15 | 229.6 | 0.77 ± 0.08 | 0.270 ± 0.001 | 1234.6 ± 1.9 | 1.49 |
| $\pi^{-9}$Be | 8394.79 | 3.12 | 249.6 | 0.73 ± 0.30 | 0.34 ± 0.01 | 1232.4 ± 7.6 | 12.6 |
| $\pi^{-12}$C | 11177.9 | 3.19 | 274.7 | 0.76 ± 0.18 | 0.40 ± 0.004 | 1223.3 ± 5.0 | 8.95 |
| $\pi^{-16}$O | 14899.2 | 3.55 | 302.4 | 0.64 ± 1.88 | 0.49 ± 0.07 | 1194.9 ± 75.5 | 1.00 |
| $\pi^{-27}$Al | 25133.1 | 3.76 | 360.0 | 0.76 ± 0.50 | 0.67 ± 0.02 | 1202.9 ± 21.6 | 0.33 |
| $\pi^{-32}$S | 29781.8 | 4.03 | 381.0 | 0.43 ± 0.04 | 0.91 ± 0.01 | 1143.9 ± 1.8 | 0.57 |
| $\pi^{-40}$Ca | 37224.9 | 3.48 | 410.4 | 1.47 ± 0.10 | 1.26 ± 0.02 | 1204.3 ± 5.4 | 0.28 |
| $\pi^{-56}$Fe | 52103.1 | 4.97 | 459.1 | 1.83 ± 0.08 | 0.93 ± 0.03 | 1204.8 ± 7.8 | 0.09 |
| $\pi^{-119}$Sn | 110758 | 5.99 | 590.2 | 2.22 ± 0.09 | 1.37 ± 0.08 | 1216.6 ± 16.0 | 0.04 |
| $\pi^{-207}$Pb | 192797 | 6.98 | 709.9 | 4.01 ± 0.44 | 1.90 ± 0.26 | 1220.6 ± 25.3 | 0.15 |

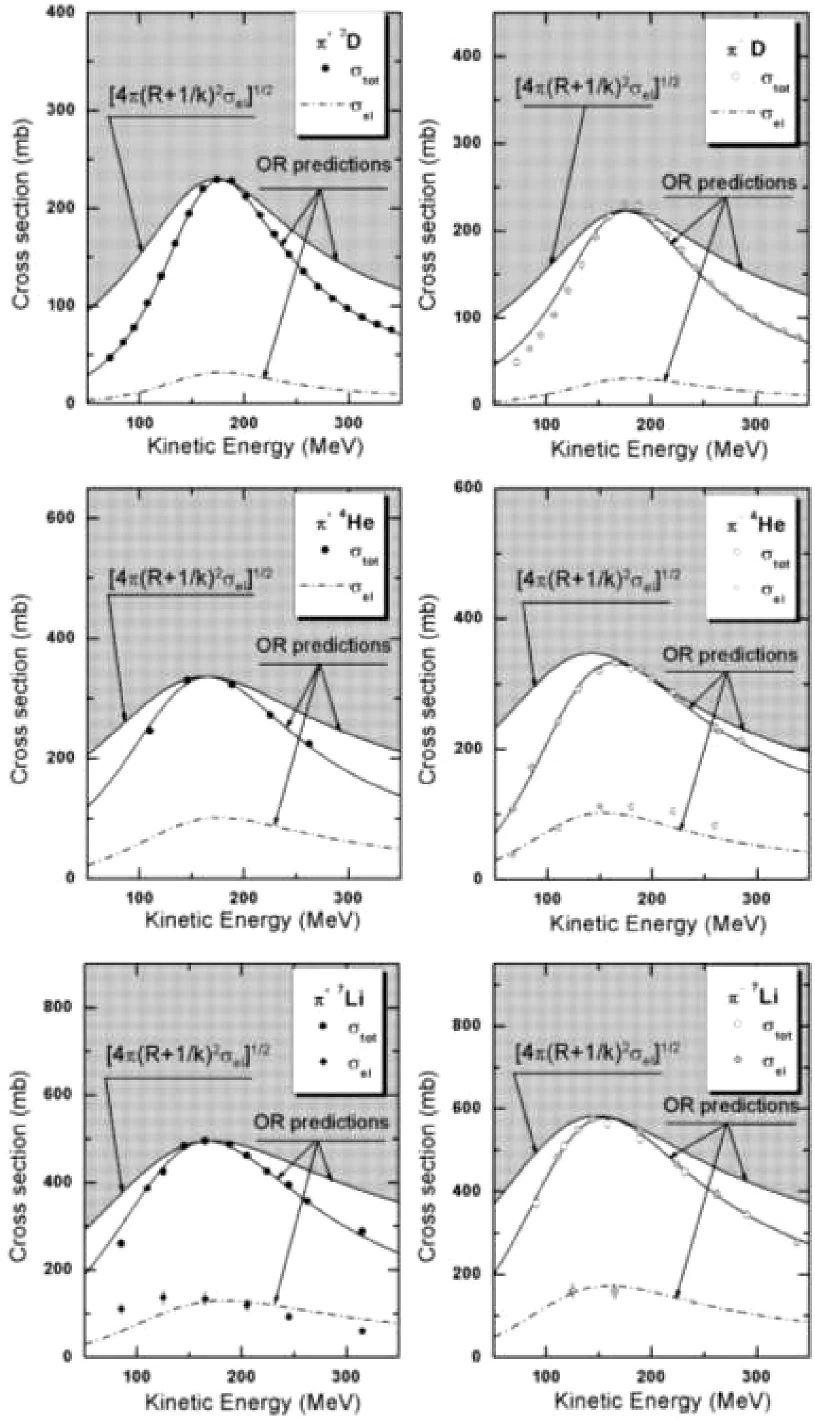


Fig. 1a – The experimental data on the total pion-nucleus cross sections in the $\Delta(1236)$ – energy Region are compared with the optimal resonance predictions. The saturation of the axiomatic optimal bound: $\sigma_T^2(E) \le 4\pi \lambda\!\!\!^{-2}(L_o+1)^2\sigma_{el}(E)$ , is experimentally evidentiated with high accuracy for

$(\pi^{\pm}D,\ \pi^{\pm}He,\ \pi^{\pm}Li)$.

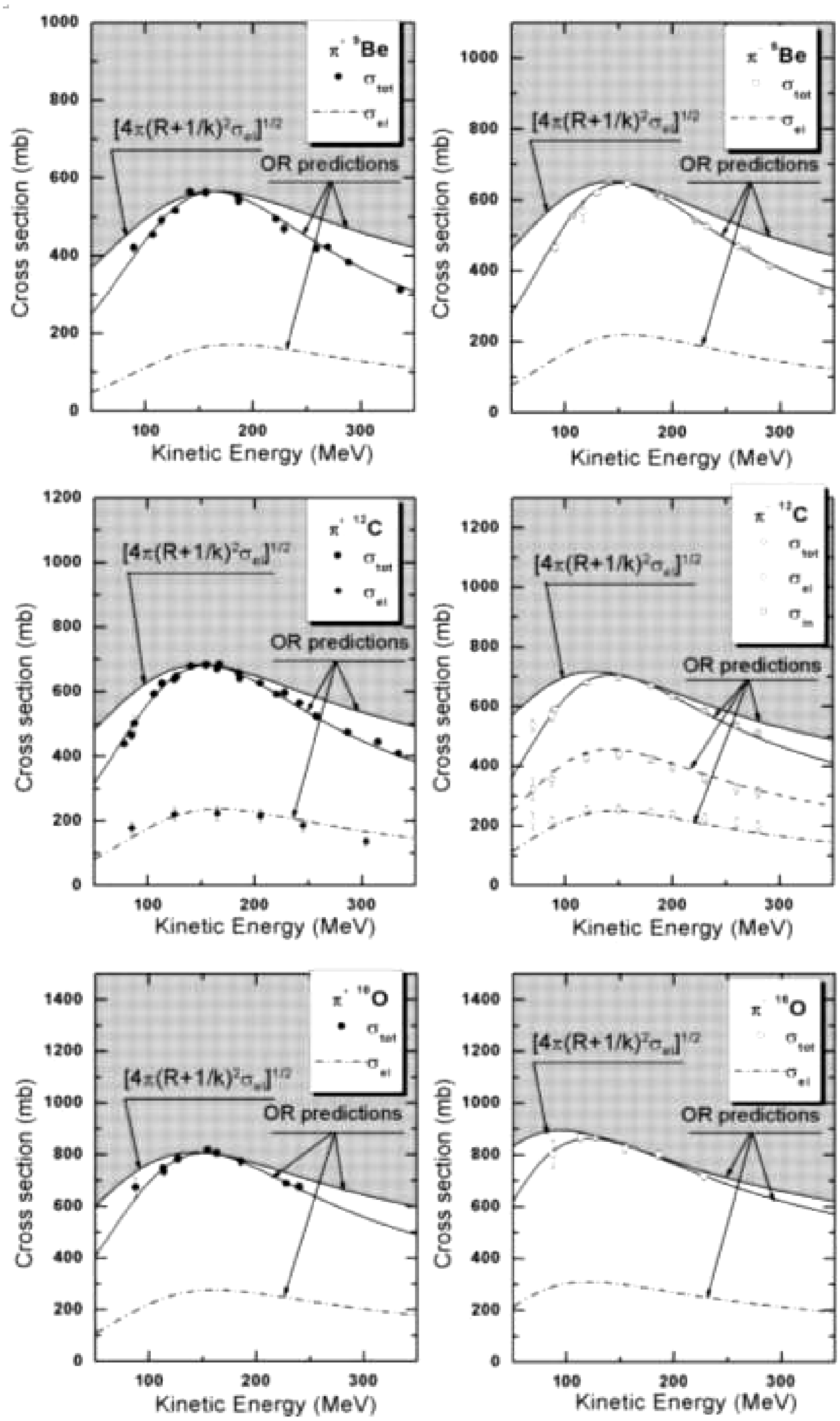


Fig. 1b – The experimental data on the total pion-nucleus cross sections in the $\Delta(1236)$ – energy Region are compared with the optimal resonance predictions. The saturation of the axiomatic optimal bound: $\sigma_T^2(E) \le 4\pi\bar{\lambda}^2(L_o+1)^2\sigma_{el}(E)$ , is experimentally evidentiated with high accuracy for

$(\pi^{\pm}Be,\ \pi^{\pm}C,\ \pi^{\pm}O)$.

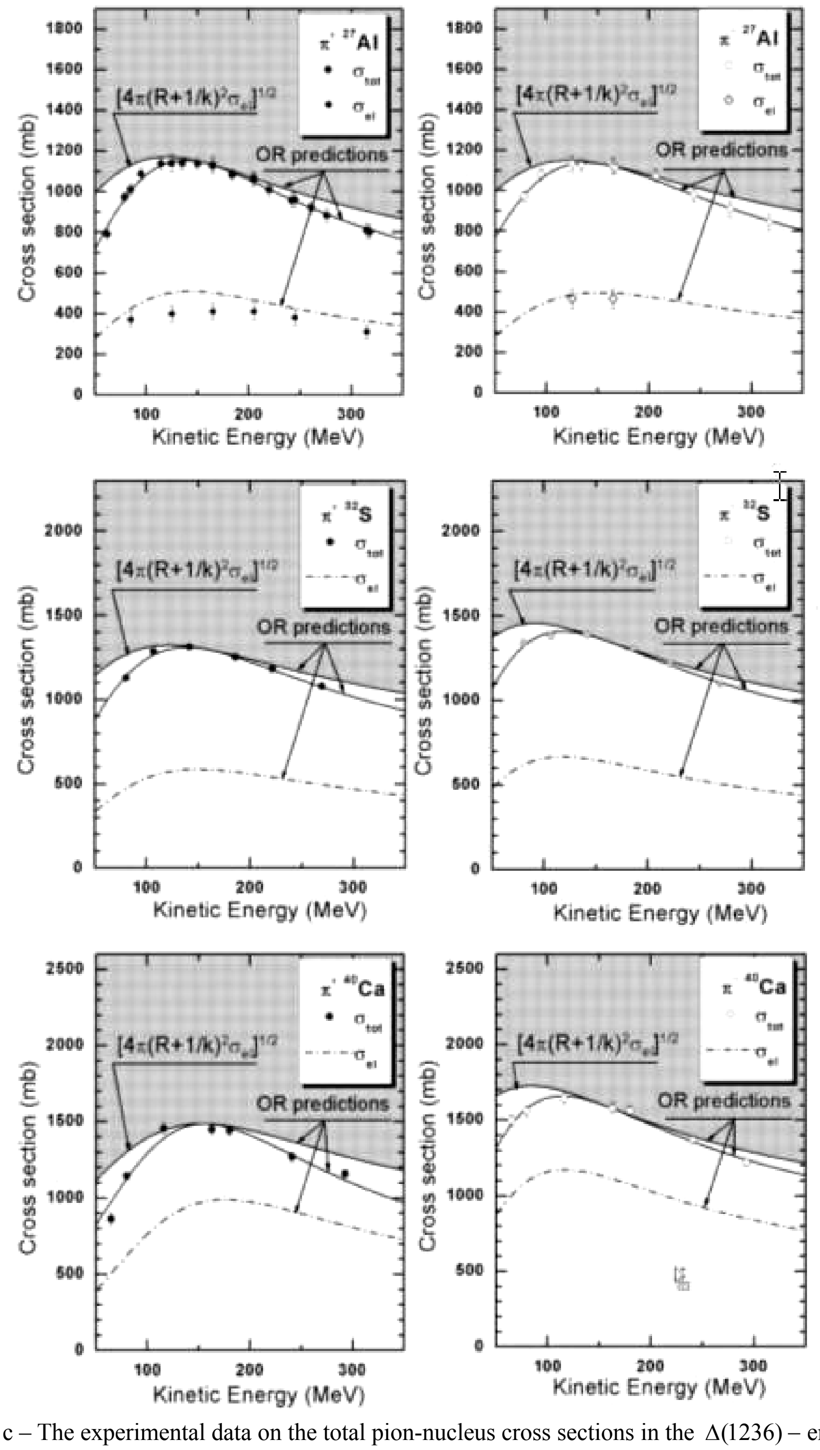


Fig. 1c – The experimental data on the total pion-nucleus cross sections in the $\Delta(1236)$ – energy Region are compared with the optimal resonance predictions. The saturation of the axiomatic optimal bound: $\sigma_T^2(E) \le 4\pi\lambda\!\!\!^{-2}(L_o+1)^2\sigma_{el}(E)$ , is experimentally evidentiated with high accuracy for

$(\ \pi^{\pm}Al,\ \pi^{\pm}S,\ \pi^{\pm}Ca)$ .

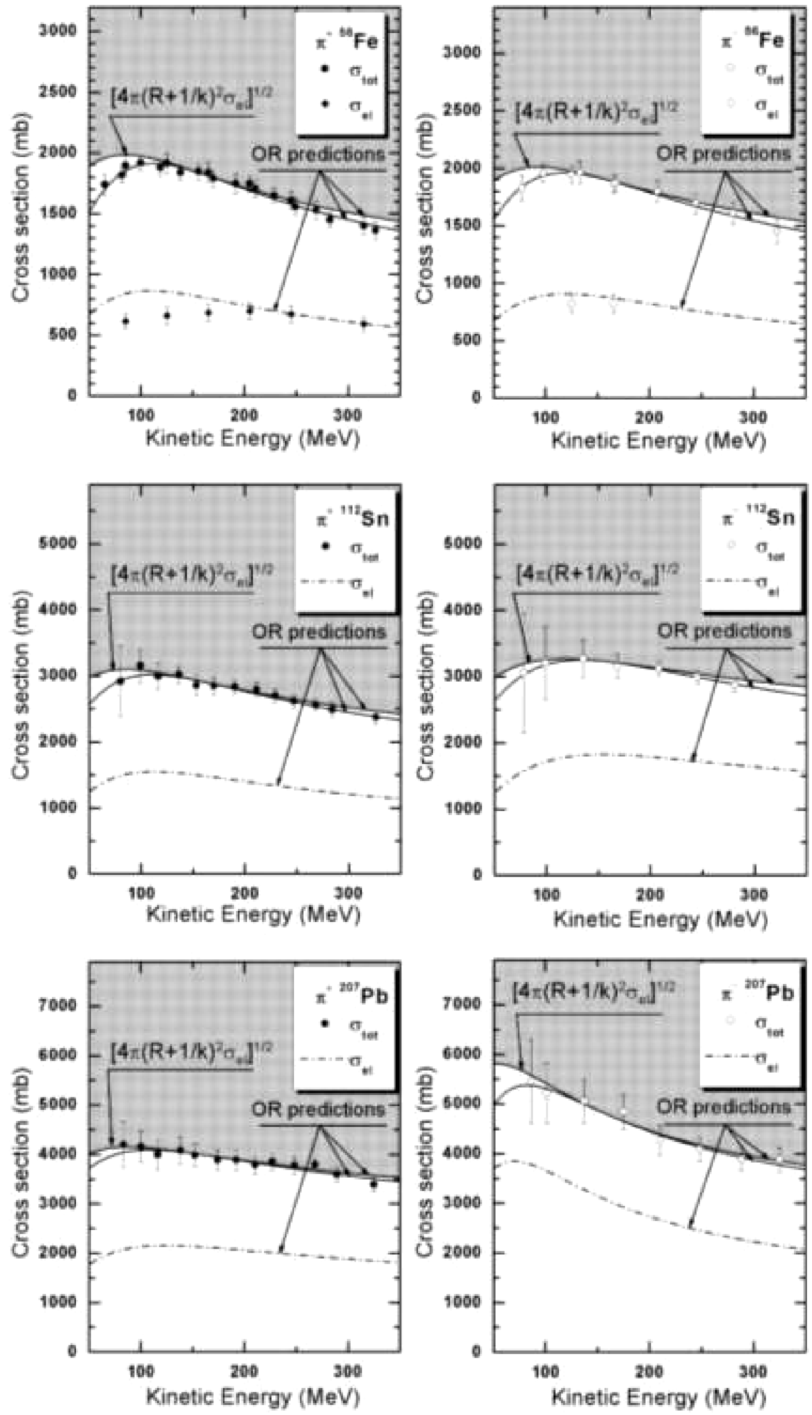


Fig. 1d – The experimental data on the total pion-nucleus cross sections in the $\Delta(1236)$ – energy Region are compared with the optimal resonance predictions. The saturation of the axiomatic optimal bound: $\sigma_T^2(E) \leq 4\pi\lambda\!\!\!^{-}{}^2(L_o+1)^2\sigma_{el}(E)$ , is experimentally evidentiated with high accuracy for

$(\pi^{\pm}Fe,\ \pi^{\pm}Sn,\ \pi^{\pm}Pb)$.

Therefore, from the results presented in Figs. (1a–1d) we see that all experimental data on the pion-nucleus total cross sections are well described by Eq. (6). Moreover, by using the fitted parameters of the total cross sections we obtain numerical predictions (see Fig. 1) for $\sigma_{el}, \sigma_{in}$ as well as for the upper bound $\left[4\pi(R+\lambda\!\!\!^{-})^2\sigma_{el}\right]^{1/2}$ which is saturated at the optimal resonance energy $E = E_0$. Then, we see that all optimal resonance predictions are in excellent agreement with the experimental data [5–17].

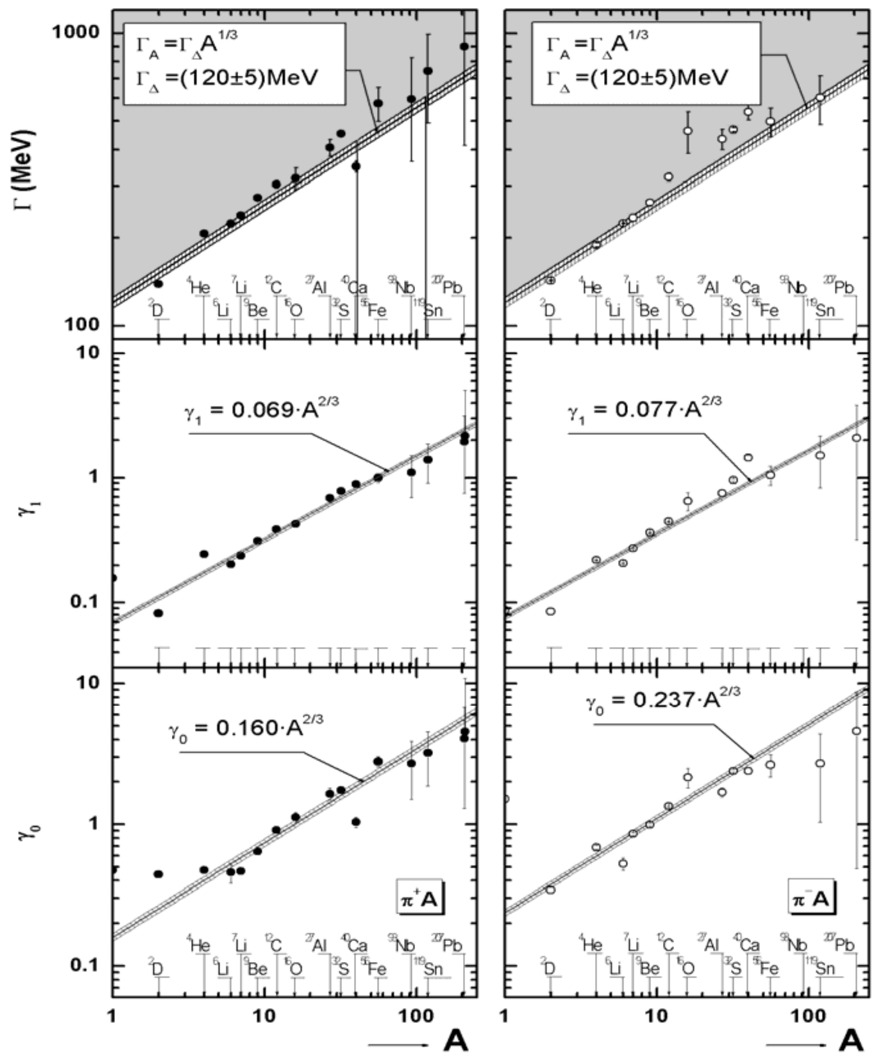


Fig. 2 – The parameters $\gamma_0$, $\gamma_1$, and of Eq. (1) obtained by minimum $\chi^2$-fits to the total pion-nucleus cross sections. The solid circles are obtained from the fits to $\pi^+ - nucleus$ data, while the open circles are from fits to $\pi^- - nucleus$ data. The solid lines represent the smooth A-dependence of the corresponding parameter.

## 3. THE MASSES OF OPTIMAL RESONANCES

The masses of the optimal resonances $E_0$ are determined by the $\chi^2$-fit of the parameters $\gamma_0$, $\gamma_1$, and $E_0$ of Eq. (6) to the total pion-nucleus cross sections when the total widths are fixed by $\Gamma_A = \Gamma_\Delta A^{1/3}$. Hece, the mass of delta resonance in nucleus can be approximated with $M^*_\Delta = E_0 - M_A + m_N$.

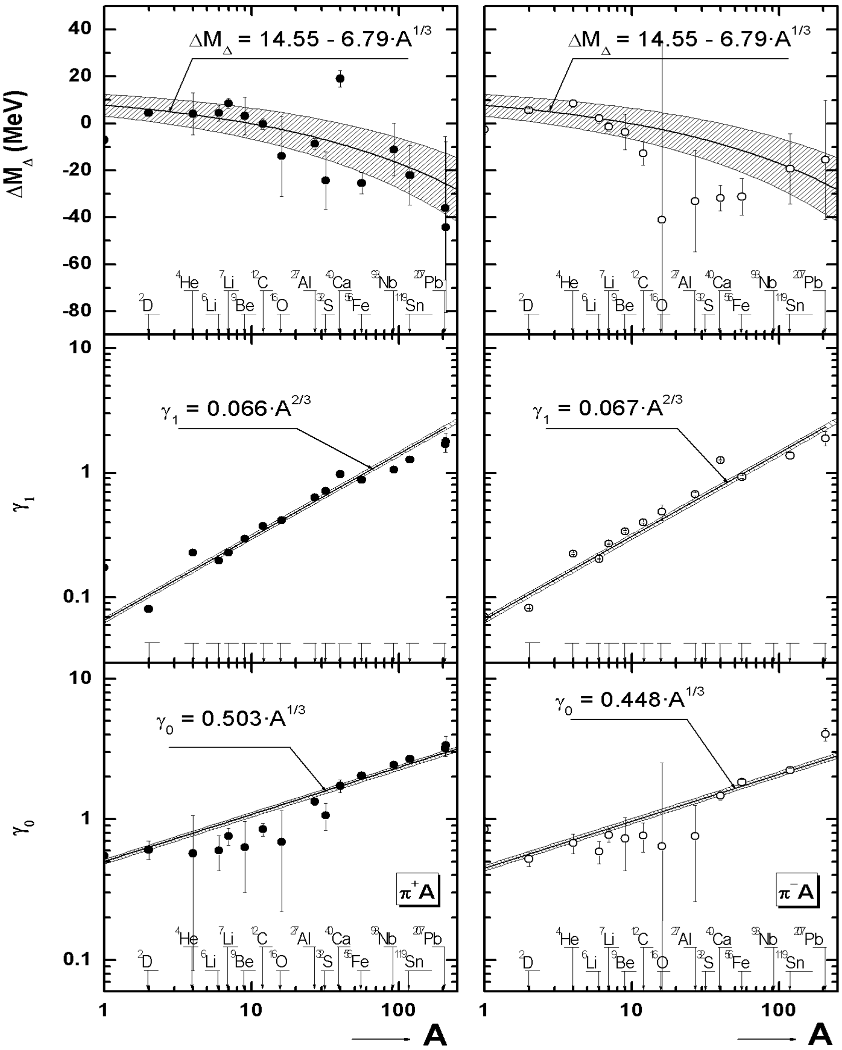


Fig. 3 – The parameters $\gamma_0$, $\gamma_1$, and $E_0$ of Eq. (6) obtained by minimum $\chi^2$-fits to the total pion-nucleus cross sections [5–17] when the total widths are fixed by $\Gamma_A = \Gamma_\Delta A^{1/3}$. The solid circles are obtained from the fits to $\pi^+ - nucleus$ data, while the open circles are from fits to $\pi^- - nucleus$ data.

The solid lines represent the smooth A-dependence of the corresponding OR-parameters. $\Delta M_\Delta = M_\Delta^* - 1236\text{MeV}$ where the $\Delta(3,3)$ -mass in nucleus is given by: $M_\Delta^* = E_0 - M_A + m_N$ and the c.m. parameter pion-nucleus resonance position $E_0$ is that obtained by fit of Eq. (6).

## 4. CONCLUSIONS

In this paper new experimental evidences, on the excitation of PMD-SQS-optimal resonances in pion-nucleus scattering in the $\Delta(1236)$ -resonance region, are presented. The main results and conclusions can be summarized as follows:

(i) The pion-nucleus total cross sections, in the energy region corresponding to $\Delta(1236)$ resonance in the elementary pion-nucleon interaction, are well described by optimal resonance predictions and obey the axiomatic bound $\sigma_T^2(E) \leq 4\pi\lambda\!\!\!^{-2}(L_o+1)^2\sigma_{el}(E)$ and (see Fig. 1a, b, c, d);

(ii) The saturation of the optimal resonance limits is experimentally evidentiated with high accuracy the following pion-nucleus scatterings: $(\pi^\pm D, \pi^\pm He, \pi^\pm Li)$, $(\pi^\pm Be, \pi^\pm C, \pi^\pm O)$ , $(\pi^\pm Al, \pi^\pm S, \pi^\pm Ca)$, and $(\pi^\pm Fe, \pi^\pm Sn, \pi^\pm Pb)$.

(iii) The total widths of optimal resonances, obtained by fit of the total cross sections in the $\Delta(1236)$ energy region, are consistent with the optimal resonances predictions $\Gamma_{\pi A} = \Gamma_\Delta A^{1/3}$ for $\Gamma_\Delta = (120 \pm 5)$ MeV (see Fig. 2);

(iv) The masses and widths of the optimal resonances, obtained from the experimental data on total pion-nucleus cross sections, are given in Table 1 and Figs. 2–3;

(v) The available experimental data on $\sigma_{el}, \sigma_{in}$ , are also in good agreement with the predictions of the PMD-SQS-resonance mechanism (see Fig. 1) but more experimental data are required.

Finally, we note that, a detailed quantitative analysis of the experimental data on the angular distributions is also necessary since the general diffractive behaviour is also experimentally verified with high accuracy especially for the number of maxima and minima as function of optimal angular momenta.

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