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NEW DEVELOPMENTS IN PION NUCLEAR PHYSICS BELOW AND ABOVE THE Δ REGION*

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A brief review and discussion is made of a few topics concerning the pion nucleus interaction at low energies and above the delta region. A many body description of the pion nuclear optical potential at low energies is presented by means of which one obtains a fair reproduction of the data of pionic atoms, including the former "anomalous atoms", and of the scattering data at low energies in all different reaction channels: elastic, quasielastic and absorption. A connection between the second order optical potential and the "absorption contribution" to the double charge exchange process is made and results are shown for this latter reaction. Of particular interest is the application made of pionic atom data to extract information on neutron distributions in nuclei. At high energies we show some small but systematic discrepancies between theory and experiment which call for some explanation. On the other hand the former and large discrepancies between theory and experiment in single and double charge exchange find a natural explanation by means of the core polarization which renormalizes the isovector πN scattering amplitude.

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1. Microscopic description of the optical potential

The background for a microscopic description of the pion nucleus optical potential at low energies was set in the early work of Ericson and Ericson [1]. The lowest order optical potential was given in terms of the elementary πN scattering amplitude, while the higher order terms were skilfully

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parametrized and fitted to the pionic atoms data. The microscopic determination of these higher order terms has been the subject of intense and fruitful work (see [2] and [3] for reviews of the work done). A systematic study of the second order corrections has been done in [3] for the s-wave part of the potential and in [4] for the p-wave part. The approach of [3, 4] can be represented diagrammatically in Fig. 1, where the full dot stands for the s-wave part of the πN interaction while the square represents the p-wave part. The s-wave part is taken from experiment on shell and different all shell extrapolations in the Literature are used. For the p-wave part a standard model [5] accounting for nucleon and delta pole terms, direct and crossed, as shown in Fig. 2, is used. Higher order corrections coming from the interaction of the ph or Δh in the diagrams of Fig. 1 are also included. Correlation corrections which come from interaction of all p-wave pieces linked by the Landau–Migdal interaction are also considered (this accounts for the traditional Lorentz–Lorenz effect but with a value of ξ of the order of 2 in our case).

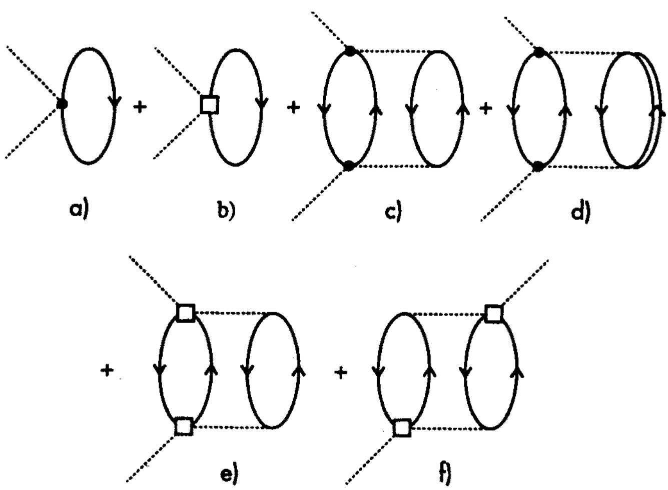

Fig. 1. Diagrams used in the evaluation of the pion-nucleus optical potential. (a) lowest-order s-wave part; (b) lowest-order p-wave part; (c), (d) second-order p-wave parts; (e), (f) second-order p-wave parts. The full dot stands for the πN s-wave t-matrix and the square for the p-wave t-matrix.

For the s-wave of a π^- one obtains a typical potential (Π = selfenergy = $2\omega V_{\rm opt}$) $(\varepsilon = \omega/M)$

$$\Pi^{(1,S)} = -4\pi(1+\varepsilon)\{b_o\rho + b_1(\rho_n - \rho_p)\}\,, \quad (1)$$

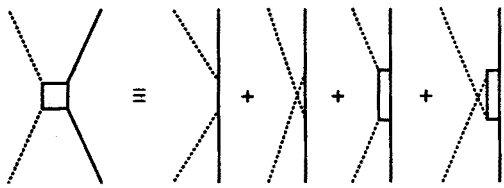

Fig. 2. Model used for the p-wave *t*-matrix containing nucleon and delta direct and crossed pole terms.

from the lowest order piece in the density (Fig. 1.a), while the higher order pieces Fig. 1.c, 1.d provide

$$\Pi^{2,S} = -4\pi\left(1+\frac{\varepsilon}{2}\right)B_0 2(\rho_p\rho_p + \rho_p\rho_n)\,. \tag{2}$$

In addition the second order Pauli corrected rescattering term of [1], deduced in the many body framework in [3] with the same results, is also included. It can be incorporated by means of Eq. (1) with an extra Δb_0 term with

$$\Delta b_0 = -\frac{3k_F}{2\pi}(1+\varepsilon)[b_0^2 + 2b_1^2]\,. \tag{3}$$

The p-wave part of the potential is a non-local function of the type

$$\begin{aligned}\Pi^{(p)}(\vec{r}) &= 4\pi\frac{1}{(1+\varepsilon)^2}\vec{\nabla}\frac{P(\vec{r})}{1+4\pi g' P(\vec{r})}\vec{\nabla}\\ &- 4\pi\frac{\varepsilon}{2}\frac{1}{(1+\varepsilon)^2}\vec{\nabla}^2\left(\frac{P(\vec{r})}{1+4\pi g' P(\vec{r})}\right)\end{aligned} \tag{4}$$

with $P(\vec{r})$ a local function of ρ_n, ρ_p.

The novelties of the present potential are that it provides an explicit isospin dependence (ρ_n, ρ_p dependence) and that it also provides a ρ dependence beyond the traditional ρ and ρ^2 terms. While Eqs (1)–(3) reproduce fairly well the s-wave part in terms of ρ and ρ^2 functionals, the p-wave behaves differently. There are saturation effects which make $\operatorname{Im} P(r)/\rho$ to be a function which tends to a constant as $\rho \to \rho_0$, rather than being a linear function in ρ as in the traditional potentials [1] or even in our s-wave part. The medium polarization due to the iterated ph-Δh excitations in Figs 1(e), 1(f) is responsible for it.

The isospin dependence of the p-wave is interesting. For small values of ρ where $\operatorname{Im}\Pi$ is quadratic in ρ one obtains

$$\mathrm{Im}\, P(r) \approx C(4\rho_n\rho_p + \rho_p\rho_p)\,. \tag{5}$$

Given the weight of s- and p-waves in the π^- absorption we get ratios of π^- absorption by pn pairs to pp pairs of the order of 3. This value is compatible with the recent value of 3.5 ± 1.5 from Gornov quoted by Mashnik in the present Workshop.

The widths and shifts of the pionic atom data over the periodic table are fairly well reproduced with this potential within 10-15 %, including the previous "anomalous atoms". The saturation effects, the Lorentz–Lorenz corrections and the isospin dependence collaborate together to improve the results for these "anomalous data".

One can also add a small phenomenological potential to the theoretical one in [4] the parameters of which are fitted to the data. By means of this new potential one obtains a better reproduction of the data. This extra fit serves to show that the magnitude of this additional potential is of the order of 10-15 % of the theoretical ones.

One shortcoming is some "missing repulsion" in the s-wave part. We have

$$\begin{aligned}
&b_0 = -0.013 m_\pi^{-1};\ \Delta b_0 = -0.014 m_\pi^{-1}\,,\\
&\text{“}\delta b_0\text{”(missing)} = -0.0053 m_\pi^{-1},\ \text{if } \mathrm{Re}\, B_0 = 0\,,\\
&\text{“}\delta b_0\text{”(missing)} = -0.013 m_\pi^{-1}\,,\ \text{if } \mathrm{Re}\, B_0 = 0.032 m_\pi^{-4}.
\end{aligned}$$

(This latter result for $\mathrm{Re}\, B_0$ was obtained in [3]).

Hence there is a missing repulsion of the order of magnitude of the existing one from the isoscalar amplitude or the second order Pauli corrected rescattering term.

2. The search for the "missing repulsion"

The "missing repulsion" has stimulated much work looking for sources of extra repulsion. I shall make a critical review of some recent ideas about this topic. Some of the work has moved around relativistic effects. In Ref. [6] the authors start with a πN p-wave amplitude of the type

$$t^{(p)} \sim c_0 \vec{k}'\vec{k} + i d_0 \vec{\sigma}(\vec{k}' \times \vec{k})\,, \tag{6}$$

where the spin flip, d_0, term does not contribute to the optical potential in non-relativistic calculations with spin saturated nuclei. By casting this amplitude in a relativistic form of the type

$$t^{(p)} \sim \bar{u}(p')[A + B(k_\mu + k'_\mu)\gamma^\mu]u(p) \tag{7}$$

and averaging over the Fermi sea, the authors obtain a contribution from the d_0 term only if they assume effective masses m^* for the external spinors $u(p), \bar{u}(p')$. These corrections have proved to be ambiguous in [7] and the results depend strongly on the form of the relativistic expression used. However, in Ref. [8] one proves that the corrections come from the inconsistent use of effective masses in the hole part and free masses in the particle part of the ph excitation piece in the pion selfenergy, leaving apart the fact that accounting for the nucleon selfenergy in a nuclear medium is something more complex than just changing the nucleon mass by an effective mass. The work in [8] has the value of showing that in an exact relativistic impulse approximation there are no new relativistic corrections which had not been considered before.

In [9] a different source of relativistic corrections is exploited. A mixture of pseudoscalar and pseudovector coupling for the πNN vertex is used together with the exchange of a σ field. The pseudoscalar coupling requires a σ field to produce a small s-wave isoscalar amplitude. The s-wave repulsion in the pion nucleus optical potential has nothing to do with relativistic corrections in that scheme. Some transformation properties of the fields are imposed in such a way that, together with the $\pi\pi\sigma$ vertex, a $\pi\pi\sigma\sigma$ vertex is generated. This vertex gives rise immediately to a second order piece when a nucleon loop is attached to each one of the σ fields in the $\pi\pi\sigma\sigma$ vertex. Although the piece is genuine within the model, the way to generate it is not unique, it is also tied to the amount of pseudoscalar coupling assumed and hence remains as an ambiguous piece.

Another interesting source of repulsion was investigated in [10] and is tied to chiral contributions involving $\pi\pi$ scattering and the $\pi N \to \pi\pi N$ amplitude. These corrections are genuine since the models used can be contrasted with experimental $\pi N \to \pi\pi N$ amplitudes. One obtains from this source a repulsion which can be of the order of magnitude of what is missing in [3, 4].

3. Low energy pion nucleus reactions

The model used in [3, 4] for pionic atoms has been extended to finite energies of the pions and for π^+ or π^- scattering [11, 12]. In addition to the pieces in Fig. 1, extended to finite pion energies, one must add diagrams involving pions in the intermediate states, as shown in Fig. 3, so that one can obtain the contribution to the imaginary part of the optical potential coming from quasielastic scattering. Indeed, the imaginary part of the potential appears when in the integration over the variables of the intermediate states these are placed on shell. Thus in the diagrams of Fig. 1(c), 1(e) ... if the 2ph are placed on shell we get an imaginary part of Π, which is related to

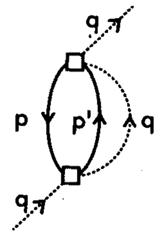

Fig. 3. Feynman diagrams which provide the quasielastic contributions in the lowest order in the number of ph excitations. The square stands for the πN t-matrix.

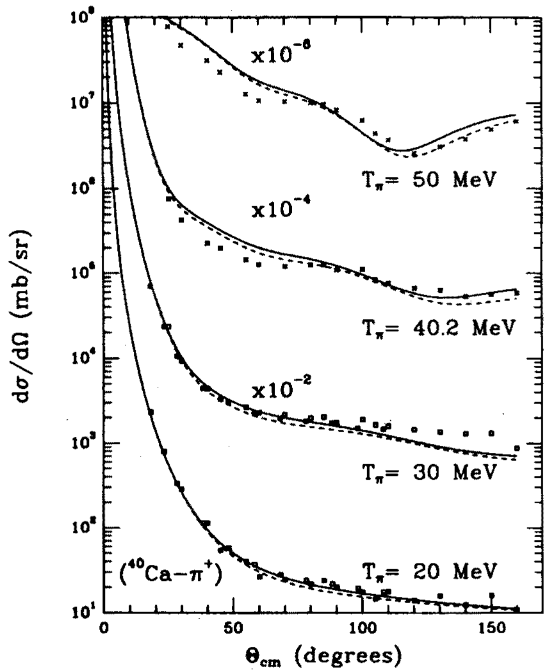

Fig. 4. Center-of-mass differential cross section for elastic scattering of 20, 30, 40.2 and 50 MeV π^+ from ^{40}Ca. The data at 50 and 40.2 MeV are from Refs [14] and [15], respectively. At 30 MeV the white squares are from Ref. [15] and the black ones from [17]. At 20 MeV the black squares are from Ref. [16] and the white ones from [17]. The solid line is the result of using all terms for the optical potential. The results that we obtain by using the theoretical potential alone(excluding the semiphenomenological terms) are represented by the dashed line.

a specific reaction channel: in this case pion absorption. However, when in Fig. 3 we place the ph and the pion on shell we get another source of Im Π which is related to quasielastic pion scattering and which occurs above pion threshold.

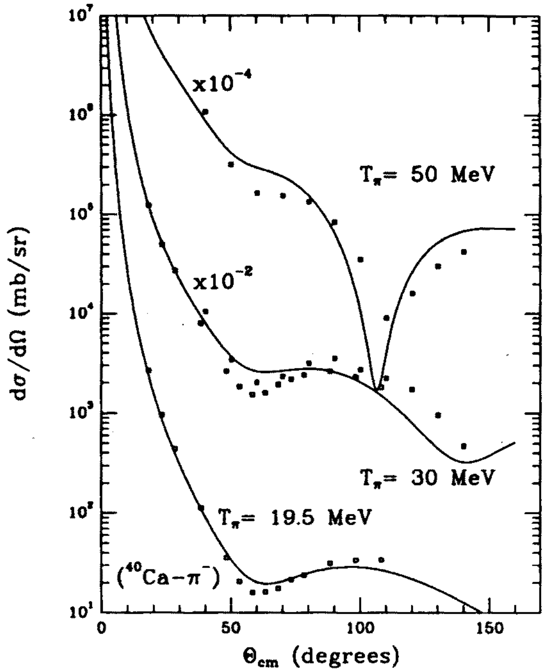

Fig. 5. Center-of-mass differential cross section for elastic scattering of 50, 30 and 19.5 MeV π^- from ^{40}Ca. The data at 50 and 19.5 MeV are from Ref. [18] and Ref. [17], respectively. At 30 MeV the black squares are from Ref. [18] and the white ones from Ref. [17].

This separation in the absorption and quasielastic contributions of Im Π is an important asset of the approach of [11, 12] which allows one to obtain separately the differential elastic cross sections, the total and reaction cross sections and the absorption or quasielastic cross sections. The agreement of the results with experiment is quite good in the different channels, for different nuclei and the range of energies up to almost 70 MeV. At higher energies the approach matches the Δh model of [13]. In Figs 4 and 5, I show results for π^+ and π^- elastic scattering on ^{40}Ca.

In Fig. 6, I show the results obtained for the reaction cross section, the absorption and quasielastic cross sections for π^- scattering from ^{63}Cu.

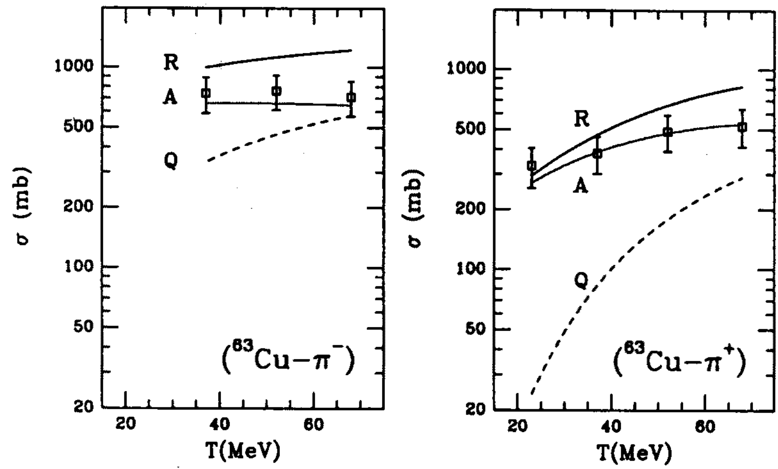

Fig. 6. Reaction (R), Absorption (A) and Quasielastic (Q) cross sections of π^+ and π^- on ^{63}Cu. The experimental data are for pion absorption from Ref. [19].

4.Neutron distribution from pionic atoms

The problem of determining neutron radii of nuclei from the data of pionic atoms is an old one [20]. The traditional procedure has been to take a πA optical potential with parameters fixed to some data and carry a fit to the data of some specific nucleus by taking the neutron radius as a free parameter. The procedure has only had mixed success proving the sensitivity of the results to the neutron radii but has been unable to provide precise values. One of the problem is that the fixed potential induces systematic errors of the same magnitude as those caused by the small changes in the neutron radii. This is, however, a common feature of all methods discussed in [20]. In [21], however, a modified approach was used. A global fit to the data of many nuclei over the periodic table was conducted by leaving all the parameters of the potential plus all the neutron radii as free parameters. In order to determine the systematic uncertainties due to assumptions made in the form of the potential, three different potentials were used, the one in [4] and those of Refs [22, 23]. The agreement of the results for R_n obtained with the three potentials is remarkable and the differences obtained give us an idea of the systematic uncertainties which are of the order of 0.05 fm. Altogether, systematic and statistical uncertainties are about 0.1 fm in heavy nuclei. In table I we give the results obtained for the neutron mean square radius of the neutron matter distribution for different nuclei with the three potentials, together with the Hartree Fock value and the proton radius for reference.

TABLE I

$\langle r_n^2\rangle^{1/2}$ [fm]

	[21]	[22]	[23]	HF	$\langle r_p^2\rangle^{1/2}$
^{147}Au	5.64 ± 0.07	5.61 ± 0.04	5.58 ± 0.04	5.61	5.43
^{208}Pb	5.74 ± 0.07	5.71 ± 0.04	5.68 ± 0.05	5.71	5.52
^{209}Bi	5.69 ± 0.07	5.71 ± 0.04	5.65 ± 0.05	5.69	5.52

This novel method, which minimizes and puts some control in the systematic uncertainties, is in my understanding probably the most reliable and efficient method to obtain neutron distributions in nuclei of all those exposed in [20].

5. Absorption contribution to double charge exchange

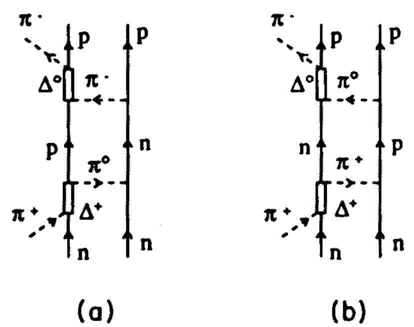

Fig. 7. Different isospin combinations in $\pi^+ nn \to \pi^- pp$.

There was a shared believe that absorption contribution would be relevant in double charge exchange reaction [24, 25]. By this I mean the contribution of diagrams like those shown in Fig. 7. The evaluation of these contributions has only been done recently [26]. This was done by considering the second order diagrams in Fig. 1 of the optical potential, opening the hole lines and changing the charges such as to make them suitable for the pion double charge exchange process. The result of this calculation is that around resonance the effects are moderate but they help to shift at lower angles, the minimum of the differential cross section of $\pi^+\ ^{16}\text{O} \to \pi^-\ ^{16}\text{Ne}$ at $T_\pi = 164$ MeV, which is still a puzzling problem. On the other hand at low energies it increases the DCX cross section in about a factor of two, indicating that any serious calculation attempting to be accurate must take these effects into account.

6. Pion reactions above the Δ region

Elastic scattering at higher energies is becoming an interesting topic of research with new results coming particularly from KEK. The different theoretical approaches include the use of optical potentials [27] and Glauber Theory [28–30]. However, all the results coincide in that the differential cross section from $p_\pi = 800$ MeV/C are about 20 % lower than experiment. This discrepancy persists in spite of medium renormalization corrections done to the resonances [31]. The problem bears much resemblance to the discrepancies found in K^+ scattering from nuclei. This latter problem has been the object of discussions and suggestions about the origin of discrepancies pointing at swollen nucleons in the nucleus or effects of the pion cloud. I believe that the problem requires a serious analysis and new efforts are being done [32]. But it looks to me that the fate of this problem is most probably linked to the one of the discrepancies in the pion scattering and it would be worth to consider the two problems together.

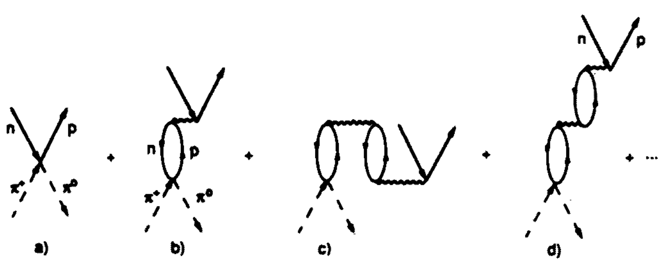

Fig. 8. Schematic representation of renormalization of the πN amplitude

On the other hand there has been recent work on single and double charge exchange reactions [33–37], which proves that the discrepancies with the data [34, 38] are quite significative. Indeed in [35] it was found that the theoretical cross sections overcounts the SCX cross section by about 50 % while the discrepancies, with the DCX cross section are about a factor three. While many considerations failed to reduce minimally the discrepancies, the recent idea of the core polarization and subsequent renormalization of the isovector πN scattering amplitude, has proved very fruitful in [36, 37]. The idea is expressed diagrammatically in Fig. 8. The core polarization, produces ph components in the t-channel with zero excitation energy and can be easily accounted for in the Glauber formalism. One needs an effective ph interaction which we take of the Landau Migdal type

$$f = (f_0 + f_0'\vec{\tau}_1\vec{\tau}_2 + g_0\vec{\sigma}_1\vec{\sigma}_2 + g_0'\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2)\delta(\vec{r}_1 - \vec{r}_2)\,. \tag{8}$$

Since the $\vec{\tau}\vec{\tau}$ operator is needed in the charge exchange reaction, only the f_0' and g_0' parameters are relevant here, but the spin flip contribution (which would require the g_0' part) is negligible for the isobar and double isobar analog transitions which one studies in the quoted works. Hence the f_0' parameter is the only one relevant for the renormalization of their charge exchange amplitude. In [36, 37] this parameter is taken from [39] which carries out a fit to electromagnetic transitions. The agreement obtained with both the SCX and DCX reactions, different nuclei, different energies and the measured range of angles is quite remarkable. In table II we give the results for DCX for two nuclei and several energies with and without the isovector polarization and compare the results to the experiment of [38].

TABLE II

The center-of-mass differential cross section in $\mu b/sr$ at $5°$ for the (π^+, π^-) reaction leading to the ground state of the resultant nucleus. The experimental results are from Williams *et al.* [38]. The columns labeled TH are the results of theory without polarization and those labeled THP include the isovector polarization.

T_π		^{14}C			^{18}O	
(MeV)	Experiment	*TH*	*THP*	Experiment	*TH*	*THP*
300	3.84 ± 0.54	11.9	3.0	2.68 ± 0.37	8.9	3.0
350	4.15 ± 0.42	14.8	3.6	3.00 ± 0.27	9.4	3.0
400	3.14 ± 0.39	15.1	3.8	3.06 ± 0.29	8.9	2.8
450		14.2	3.7	2.94 ± 0.33	8.1	2.6
500	3.62 ± 0.65	13.7	3.8	2.69 ± 0.35	7.7	2.6
525		13.5	3.7	2.65 ± 0.80	7.5	2.6

7. Concluding results

The recompilation of work done here indicates that much progress has been done in the microscopical description of pion nuclear processes.

On the other hand the relative transparency of the nucleus to high energy pions and the richness in the selection of charge exchange channels shows that pions at these energies are excellent tools to investigate details of nuclear structure and excitation mechanisms of the nucleus.

We have also seen that the theoretical models have become precise enough to provide information on neutron radii if skilfully combined with phenomenology.

Many problems remain open, on the s-wave repulsion in pionic atoms, DCX, the small discrepancies of pion elastic scattering at high energies, *etc.*

In any case the field of pion physics is reaching a maturity which should be welcome in other areas of intermediate energy physics: photonuclear and electronuclear reactions, scattering with nucleons and light ions, weak interactions in nuclei, $\bar{p}$ annihilation, heavy ions, *etc.*, where the information of pion physics is much needed.

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