PION-NUCLEAR INTERACTIONS AT THE SC AND BEYOND¹⁾

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Abstract

The motivations and intellectual impact of the CERN SC programme in π -nucleus physics are examined in perspective.

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1. Background

The SC at CERN pioneered most of the lines in nuclear pion physics that were later explored in depth at the meson factories at LAMPF, at SIN or PSI and at TRIUMF. The golden age for these investigations was the period 1965–75, while the later programme with a few exceptions was overwhelmed by the superior intensities and beams at the meson factories. This programme at CERN established most of the general ideas which now are routinely exploited although with a far higher degree of sophistication. The impact has been far-reaching well outside of nuclear physics using pion beams. The reason for this is that pions are the major nuclear constituent in addition to the neutron and the proton. In the early 1960s very little was known about the quantitative and even qualitative consequences of the pion for nuclear structure, except of course the one-pion-exchange nucleon–nucleon potential as a major explanation for the nuclear force. At the time, nuclear physics was mainly dominated by the recent break throughs in the understanding of nuclear shell structure and collective motion as well as by the intricate interplay of the two. There was no particular need for exploring those aspects using pions. At present the situation is very different. The pion degree of freedom is integrated in the mainstream of nuclear physics, solidly established as a principal nuclear feature, while nuclear quark physics now is the frontier that then was occupied by pion physics. Indeed, we have now reached a point at which a large part of modern nuclear pion physics is not even carried out by physical pion beams, but by virtual pions in many forms. All of this change is largely due to the pion programme at the SC. The origin of the programme, like the rest of the nuclear physics programme at the SC, was the crucial decision by Viki Weisskopf in 1963 to broaden the CERN programme by exploiting this machine for another field instead of shutting it down. His farsighted idea was that of a symbiosis between particle and nuclear physics with each fertilizing the other one. On the one hand one would exploit the properties of nuclei to learn more about elementary particles and their interactions, and on the other one would probe properties of nuclear structure using the high energy nucleons and mesons as probes. It is very interesting to examine the priorities and the perspectives at the time. In order to stimulate this idea Amos de Shalit and Viki Weisskopf made it known in the middle of 1962 that there would be a small conference at CERN in order to discuss these issues. This was enthusiastically received and, in fact, this meeting was the first in what has now become the PANIC conferences on High Energy Physics and Nuclear Structure of which the 12th was recently held in Cambridge, Mass., with over 700 participants. I had the luck as a rather fresh postdoc to be given the task of organizing this meeting at short notice, both scientifically and materially. Interestingly, it was easy to find logical main speakers on muonic atoms (Hans Sens), strange particle interactions and hypernuclei (Denys Wilkinson), electron scattering (Henry Kendall), proton interactions (A.B. Clegg), particle physics with nuclei (Val Telegdi) etc. There was one big problem: there was no logical speaker for pion-nuclear physics! Since we had some experience with this in the group from the analysis by my wife Magda Ericson of the scant data on pionic atoms, I sacrificed myself by taking on the task, much to my later advantage, though I was certainly no expert. It was clear at the meeting and in the next few years that there was only a very mild interest in using pions for nuclear physics. The good reasons for this

are clear from the following excerpts from my talk [1].

‘Typical intensities may be exemplified by some figures from the CERN SC: 10^5 pions in flight/sec with an energy definition of 7–8% or 10^4 stopped pions/sec.’

‘In preparing this talk it came as a surprise to me how small the effort has been, both experimentally and theoretically. — It is curious to notice that as much is known about strange particle interactions with nuclei as about pion ones, —’

I gave as the reason that *‘— nuclear information is no longer a by-product of elementary particle experiments for the exploratory period with weak beams is long gone’.*

‘In so far as pion experiments are mere repetitions of experiments with standard probes, the interest in the pion is very limited. Its radically different properties — make it a potentially powerful addition to the arsenal we dispose of for nuclear study.’

It is interesting that, at this point in time and in spite of the fact that this talk was particularly directed to pion physics, there is no particular emphasis on the importance of understanding the general behaviour of pions in nuclei as an essential starting point for the understanding of the pionic structure of nuclei and on the fact that the nuclear pion field is a major aspect of nuclear physics. In the motivations for the meson factories in the USA at the same time the priority given to pion physics is rather low. For instance, in the influential Bethe panel report in 1964 [2], which is the primary document giving the scientific motivation for LAMPF, pion–nuclear physics is mentioned as follows:

‘The most important experiments are those of stopped pions - including pion absorption.’

‘As third in line for nuclear structure we chose (pion) charge exchange scattering.’

Clearly, in the early 1960s there were some arguments, but not excessively strong ones, for investigating nuclei with pions.

2. Pionic Atoms

It was with this background that the investigations of nuclear interactions with pions started at the SC. The first steps in this programme had to face the lack of basic information. As is normal in such a situation a number of the experiments were exploratory ones in order to establish which lines of investigation were the most fruitful and practical ones for the future. In this respect, and quite apart from specific influential results, the SC has played a very important role in establishing the priorities for the later programmes at the meson factories. A major hurdle in any experiments trying to resolve nuclear energy levels with pions, or for that matter simply separating out the elastic scattering leaving the nucleus in the ground state, was the appalling energy resolution of about 10 MeV typical of the beams. It was essential to overcome this and get down to resolutions of a few MeV or better in order to have anything very interesting to contribute. It was in particular crucial to rapidly obtain an understanding of the elastic propagation of pions in the nuclear medium, since this influences nearly all reactions in nuclei in one form or other. This problem was solved in two different ways. The key point in both cases was that there were no pions to be wasted at the low intensities typical of the SC. The first way to obtain the resolution was to stop the pions in matter and in particular to study the properties of pionic atoms. At the price of working exactly at zero kinetic energy stopped pions could be efficiently investigated. This programme has just been described by Professor Backenstoss

[3] and he has given an excellent review in 1970 [4], so I will be brief and give only a sketch of the background as seen by a theoretical physicist. In 1963 there only existed some very crude measurements of the shifts in the $1s$ states of a few light pionic atoms measured with sodium iodide counters by Camac *et al.* [5] and by Stearns and Stearns [6] as well as a few absorption widths in the $1s$ state by West and Bradley [7]. By enormous luck it was possible to use some of the very first germanium solid-state detectors which had been brought here for the muonic x-ray programme also for pions. This made it possible to rapidly measure energy shifts, absorption widths and intensity attenuations in a whole series of elements throughout the periodic system and for a variety of transitions. This was just the kind of data that were desperately needed at the time. Magda Ericson had just shown that the existing data were incompatible with a usual local average potential and that new features were needed [8, 9]. The strong interactions shifts in the atomic states are equivalent to the measurement of the the real and imaginary part of the elastic threshold amplitudes for scattering states with the same angular momentum as the atomic states, so this provided an excellent short cut to a phase shift analysis: the pionic atom is, via the widths and shifts which give the generalized scattering lengths, a 'natural phase shift analyser'. The complex strong interaction level shift is simply proportional to the complex generalized scattering length A_l .

The success of such studies is seen in Fig. 1 taken from a review in 1974 [10], which clearly demonstrates the precision of the measurements, their systematic dependence with nucleon number A and the sensitivity to neutron number.

Figure 1: Real and imaginary parts of the s -wave pion-nucleus scattering lengths deduced from energy shifts and widths in pionic atoms [10].

Here I will describe the impact on later theoretical developments and thinking as well as the symbiosis with the theory group, for developments went hand in hand. The expected properties of the scattering on nuclei can be guessed from the structure of the πN

interaction at threshold:

$$\pi N \text{ average amplitude : } b + c\mathbf{q} \cdot \mathbf{q}',$$

which is dominated by s and p waves, i.e. by monopole and dipole scattering. In the impulse approximation this leads to a pion optical potential in (in)homogeneous nuclear matter of density ρ :

$$V \propto b_{\text{eff}}\rho - \nabla \cdot c_{\text{eff}}\rho\nabla.$$

The key observations of the experiments were the following:

I. The effective s wave strength parameter b_{eff} is *repulsive* and numerically much stronger than simple impulse approximation. This information comes from $1s$ states.

II. There are quite large isospin effects with increasing repulsion as neutrons are added as seen in Fig. 1. This information also comes from the $1s$ states.

III. The p wave strength parameter c_{eff} is strong and *attractive*, which reflects the importance of the Δ isobar. It dominates the $2p$, $3d$ and $4f$ states, which have attractive level shifts. In the case of the $2p$ states one sees with increasing A how the repulsion gradually takes over leading to a switch of the effective attraction in a $2p$ state to an effective repulsion [11] in the region of $A \simeq 80$.

The understanding of these features has deeply influenced nuclear physics and I will now qualitatively indicate how. The effective s wave scattering can first be understood on the basis of multiple scattering from pairs of correlated nucleons in the medium [12, 13]. Normally the potential from monopole scattering in a medium (examples are sound waves from bubbles in water, neutrons from nuclei in matter) is proportional to the average ‘elementary’ scattering length. But the scattering length for a pion averaged over neutrons and protons nearly vanishes as a consequence of chiral symmetry. This gives a chance to next order terms, which in fact dominate, so that two nucleons 1 and 2 in a distance r_{12} contribute a term

$$b_{\text{eff}} \approx b_1 < 1/r_{12} > b_2,$$

which accounts for the bulk of the repulsive s wave shifts. In this case there is an important second level of understanding associated with the nature of chiral symmetry in a nuclear environment. One can demonstrate [14], [15], [13] that this multiple scattering is the natural way to generate the leading chiral corrections in an extended medium. The effective p wave parameter has also an important modification as compared with the leading approximation. This is the important renormalization which goes under the name of the Lorenz–Lorentz effect and which is provoked by the local effective field experienced by a pion in the correlations and fluctuations nuclear medium [12, 13]. The effect is a consequence of the short-range anti-correlations between nucleons in the medium. This idea, largely established by the pionic atom work at the SC, has had a far-reaching influence on thinking in nuclear physics well outside of normal pion physics:

1. The Lorenz–Lorentz effect is crucial to nuclear many-body theory, since it prevents the collapse of nuclei into π condensates [16], [17], [18], [13].

2. The Lorenz–Lorentz effect leads to the quenching of nuclear Gamow–Teller strength in weak interactions as well as in np charge exchange scattering. This has been a topic

of major discussion since the experimental discovery of the Gamow–Teller resonance in 1980 [19], [20], [13].

3. The Lorenz–Lorentz effect has led to the understanding that axial physics and pion physics in nuclei are *equivalent* and that they are only kinematically different aspects of the same physics [13].

3. Pion–Nuclear Scattering

The indirect influence of the pionic atom experimental and theoretical programme at the SC in the 1960s and early 1970s has thus been a very major one. The second line of investigation of elastic interactions concerned scattering experiments in the 100–300 MeV region. This is the region at which the SC produced beams of the highest fluxes. Such experiments were very time-consuming and, typically, the investigation of a single nucleus took a month of data-taking. It was then not possible to explore sequences of nuclei systematically. In spite of this, the SC experiments in this energy region have played an essential role in the development of intermediate energy physics and they have paved the way to what is now called the Δ -isobar model in nuclei: indeed from the viewpoint of this model the Δ in the nucleus is just as good as a nucleon [21, 22]. The key developments in this direction were taken by Meunier, Stroot and Spighel (MSS). In order to establish a successful programme it was essential to overcome the hurdle of energy resolution without wasting pions. The novel feature was the construction of a double achromatic energy loss spectrometer. The idea of measuring the energy loss was not a standard one in nuclear physics at the time and was quite the opposite one to the way energy resolution was achieved via the primary beams of protons, alpha particles or ions in cyclotrons and tandems. The MSS spectrometer is however the forerunner to the high-resolution devices in intermediate energy physics like SUSY at SIN, EPICS at LAMPF and the Saclay SPES spectrometers. This spectrometer was proposed and accepted quite early in the programme although it took some time to get it operational. Figure 2 shows how it appeared on the floor in 1967. The characteristic resolution of the spectrometer is apparent from Fig. 3, which represents the measured spectrum of ^{12}C for 180 MeV pions. As you see, it was indeed capable of separating widely spaced states in nuclei. Starting from 1967 this spectrometer was applied to measurements of angular distributions in light nuclei as a function of energy. The first indication of the importance of the Δ isobar appeared in the elastic scattering data on ^{12}C published by Binon *et al.* in 1970 [23]. The data in Fig. 4 show a spectacular dip in the first minimum at the energy which corresponds to the isobar.

On reflecting on the interpretation of this deep minimum the group came to the conclusion that this must correspond to the very short mean free path of a pion in nuclear matter at resonance. Thus they concluded that black-disk scattering was the likely explanation. This caused an amusing episode which I happened to witness. When they presented this explanation to Professor Peter Preiswerk who was the division head, he became quite enraged and declared that it was not the business of Cern to investigate trivial phenomena. Investigations along these lines have later been further developed at LAMPF using far more efficient beams [24]. The results are much more detailed and convincing but the conclusion is essentially the same.

Figure 2: The MSS energy loss spectrometer as it appeared in 1967.

Figure 3: The typical resolution of the MSS energy loss spectrometer [23].

Figure 4: The $\pi^{-12}\text{C}$ elastic differential cross-sections versus $-t$ at incident pion energies between 120–280 MeV from the MSS experiment [23]. Note the deep first minimum at 180 MeV.

For example, the elastic angular distributions from medium-heavy and heavy elements as in Fig. 5 show splendid textbook examples of diffraction scattering with a large number of oscillations. They are described excellently as scattering from a disk with a diffuse edge. Once more the minima are extremely deep in the resonance region which is a clear signature of the isobar dominance even in heavy nuclei.

The MSS group found another interesting example of closely related character in the nuclear Coulomb interference experiment by Binon *et al.* [25], which appeared in 1971; the preliminary results circulated as early as 1968. In this case the experiment on ^{12}C demonstrates clearly that the forward scattering amplitude changes character at the Δ resonance energy, so that the interference of the strong amplitude is constructive below the resonance and destructive above. This result stimulated the development of nuclear forward dispersion relations [26]. Figure 6 gives the data compared with theory in this first experiment. The surprise was that the effect of the binding of the composite nuclear target was nearly negligible and this made it possible to use a dispersion technique to extract the effective π nuclear coupling constant. Modern data have greatly improved this result. Figure 7 shows the quality of modern data for the real and imaginary part of the 0° amplitude in the same reaction. The most remarkable feature of the real amplitude is

Figure 5: The angular distribution for elastic π^- scattering at 162 MeV from several medium-heavy and heavy nuclear targets as measured at LAMPF in 1978 by Zeidman *et al.* [24]. The theoretical solid curves correspond to diffractive scattering from a diffuse disk [13].

Figure 6. The difference between the measured differential cross-section and the calculated Coulomb cross-section for $\pi^-^{12}\text{C}$ elastic scattering at several energies versus the squared four-momentum transfer as measured in about 1970 by the MSS group [25]. Note the change of the constructive interference at 120 MeV to a destructive interference at 260 MeV.

that it crosses zero at almost exactly the same position as for free πN scattering, which is a clear indication of the importance of the isobar in the nuclear interactions of pions. While the original explanation of the diffraction-like character of the elastic pion–nuclear scattering is mostly correct, it is only part of the story. The blackness is due not to pion absorption but to the incoherent scattering of the pion in the medium.

Figure 7. Modern results for the anomalous dispersion of the real part of the pion–nuclear forward-scattering amplitude exemplified by ^{12}C . The solid curve is the result of forward dispersion relations [13].

The non-triviality of the phenomenon is best seen by a comparison of the total cross-section for photons and for pions on ^{12}C as given in Fig. 8 [13].

Compared with the pion, the photon cross-section is almost the sum of the individual cross-sections on the nuclear neutrons and protons with a strong and clean isobar dominance standing out nearly intact. The pion cross-section on the other hand is strongly damped in the isobar region. The reason for this difference is not that the photon interacts weakly but that the photon is *transverse*, which suppresses rescattering effects. In contrast the pion is *longitudinal*. The effect is therefore non-trivial. These scattering experiments of pions on nuclei have taken on new twists in the last couple of years. All the classical experiments with pion scattering were made with physical pions coming as a beam from an accelerator. Modern pion experiments are now also made with ‘virtual’ pion beams which exploit the fact that a ^3He nucleus, for example, surrounds itself with a virtual pion cloud as in Fig. 9 by the process $^3\text{He} \leftrightarrow ^3\text{H} + \pi^+$. Such virtual processes are particularly dominant in 0° charge exchange reactions like $(^3\text{He}, ^3\text{H})$ reactions. By this method it is possible to use pions with an energy-momentum relation different from that of free pions, so that $q_0^2 - \mathbf{q}^2 \neq m_\pi^2$. Figure 10 taken from a Saturne experiment in 1985 [27] compares such reactions using ^3He to ^3H charge exchange at 0° on a light and on a heavy target with the same reaction on a proton used as a scale. The remarkable result is that the two reactions give rise to curves which are strikingly similar in shape with

Figure 8. Comparison of the $\pi^{12}\text{C}$ and $\gamma^{12}\text{C}$ total cross-sections in the Δ isobar region as compared with A times the average elementary cross-section [13].

Figure 9. The virtual dissociation process ${}^3\text{He} \leftrightarrow {}^3\text{H} + \pi^+$.

a characteristic 75 MeV shift for the peak in the cross-section for the nuclear targets as compared with the proton one, which dominated by the Δ isobar excitation. This effect is interpreted as evidence for a new type of pionic collective mode in nuclear matter [28]. There is thus a direct line from the pioneering experiments at the SC which opened this field to the recent developments.

Figure 10. Evidence for the observation of the pionic mode in nuclei [28] from the forward (^3He , ^3H) charge exchange reaction [27] using properties of virtual pions.

4. Basic πN Data

While the topics concerned with elementary particle physics fall outside my talk here, nuclear physics needs accurate data on certain key elementary particle physics processes like πN scattering. Often the precision needed is superior to the one demanded by elementary particle physics and the crucial amplitudes are frequently different from the ones of main interest to particle physicists. The SC has in fact provided some important data of this type. In particular, in the early 1970s Bugg and his group undertook at the SC a series of classical studies of πN scattering and charge exchange to a previously unmatched precision [29], [30], [31]. These data have set the standard for later work up to this day. The special point about these studies was the enormous care that went into the control of systematics of various origins, a crucial point in experiments aimed at the absolute determination of cross-sections at a level of one to a few per cent. These experiments measured both total cross-section and angular distributions in the range of 100 MeV to 260 MeV. Figure 11 illustrates the progress this group achieved in the integrated cross-section for $\pi^+\text{p} \rightarrow \pi^+\text{p}$ charge exchange, while Fig. 12 gives the integrated cross-section for $\pi^-\text{p} \rightarrow \pi^0\text{n}$.

As you see, the increase in precision is spectacular. There are various important uses to which these experiments can be applied. In particular, they have played a central role

Figure 11. The total $\pi^+p \rightarrow \pi^+p$ total cross-section as measured by Carter *et al.* [29] compared to previous data.

Figure 12. The total charge-exchange cross section $\pi^-p \rightarrow \pi^0n$ of Bugg *et al.* [30] compared to previous data.

in the programme of the Karlsruhe group of Professor Höhler in which analyticity and dispersion relations have been used to analyse the scattering properties of the πN and $\pi\pi$ systems in great detail [32]. The group of Bugg analysed immediately their data in terms of the πN coupling constant and the πN scattering lengths, which are central to chiral symmetry. The result [33] was for the coupling constant $f^2 = 0.0790 \pm 0.0010$ compared with the earlier $f^2 \simeq 0.081$; $a_1 + a_3 = -0.014 \pm 0.005 \mu^{-1}$ compared with the earlier $+0.003 \pm 0.008 \mu^{-1}$ etc. The precision in these new values was such that the results were a significant constraint on charge symmetry and measured the mass splitting of the Δ isobar [34]. These improvements have been essential to many applications both in particle and in nuclear physics.

From the point of view of nuclear physics the deuteron plays also the role of a basic system and it is a very important testing ground for concepts that can then be applied in a more complex environment.

Certain pion-induced processes like pion absorption or production appear first for the deuteron, since the process $\pi N \leftrightarrow N$ cannot occur for the free nucleon. The deuteron process $\pi d \leftrightarrow NN$ has no such hindrance and is thus the simplest system for which absorption and production can be studied. The first good-quality data on this reaction covering the entire Δ region were provided by the well-known study at the SC by Richard-Serre *et al.* in 1969 [35]. This study confirmed quantitatively that the Δ isobar plays the major role in this reaction and that the main mechanism in sharing the momentum and energy between the two final nucleons involves a Δ in an intermediate rescattering as indicated in Fig. 13. The work was influential less for the individual experimental data than for the overall perspective it allowed on this reaction.

Figure 13. The total cross section for the reaction $pp \rightarrow \pi^+ d$ with the solid points given by the experiment of Richard-Serre *et al.*[35]. The curve is a theoretical calculation[36].

The elastic pion scattering from the deuteron was first explored at the SC by K. Gabathuler *et al.* in 1973 [37]. Figure 14 shows some of their data on elastic scattering which proved to be primarily dominated by single scattering with double scattering and higher terms appearing as corrections.

Figure 14. The elastic π^+d differential cross-section measured at 256 MeV by Gabathuler *et al.* in 1973 [37]. Note the dominant single scattering interfering with double scattering [38].

Figure 15. Charge symmetry breaking in the difference of the total π^+d and π^-d cross-sections versus pion energy as observed at SIN by Pedroni *et al.* [40].

The detailed analysis of more refined scattering experiments on the deuteron together with absorption data have played an essential role in elucidating the description of three-body systems using Faddeev-like equations when one of the particles was a boson.

Furthermore, the investigation at the SC of $\pi^\pm$ total cross-sections on various light elements by Wilkin *et al.* [39] was the immediate precursor of a very elegant continuation by the same group at SIN [40] applying their know-how to a study of the charge symmetry breaking as it manifests itself in the $\pi^\pm d$ total cross-section difference. Figure 15 shows how the charge symmetry breaking stands out very clearly and that it has its origin in the mass splittings within the Δ isobar.

From this experiment one concludes that the neutral and singly charged Δ 's have the same mass splitting as the neutron and the proton to considerable precision:

$$M_{\Delta^0} - M_{\Delta^+} = 1.38 \pm 0.06 \text{ MeV.}$$

This should be compared with the np splitting of 1.29 MeV.

5. Pion Double-Charge Exchange

I will now turn to a couple of topics where the role of the SC has been to focus attention on issues that later have been developed elsewhere. The first of these is the double-charge exchange reaction $\pi^+ \leftrightarrow \pi^-$ on nuclei. This process has, since the early 1960s, been a dream of nuclear physics [12], since it by necessity involves at least two nucleons in the nucleus. As a consequence it is much more directly sensitive to the two-body correlations in nuclei than any other process, for the single nucleon background is automatically suppressed. This process also opens possibilities to make exotic nuclear systems. One of the earliest experiments in pion-nuclear physics at the SC attempted to observe the tetraneutron via this process [41]. Later the double-charge exchange reaction was indeed observed, but with a very low count rate. For lack of intensity this line of research was therefore discontinued and it became the task of the meson factories with 10^3 times more pion intensity to pursue this line. Even there life was rough, but Fig. 16 shows how it reached fruition at TRIUMPH in 1984 [43], and at LAMPF in 1985 [44].

Figure 16. Differential cross-sections at 50 MeV for pion double-charge exchange on ^{14}C and ^{18}O leading to the isobaric analogue states [42, 13]. The measurements are from TRIUMPH [43] and LAMPF [44].

These two experiments proved that the process in this case is extremely sensitive to exotica such as quark bags, but that nucleons alone suffice for a parameter-free quantitative description although correlations are crucial.

6. Pion Production and Absorption

In nuclei the production and absorption of pions in various forms are reactions which correspond to a high fraction of the inelastic processes. Naturally various studies were undertaken of such processes at an early stage in the SC programme. A notable series of experiments were carried out by the group around Charpak on π^+ absorption in light nuclei starting in 1965, in particular on ${}^6\text{Li}$, with the detection of two coincident protons, the energy and angles of which were determined with considerable precision [45], [46], [47]. From the reconstructed energy loss various conclusions could be made about the mechanism of such reactions. Unfortunately, although technically this programme was quite successful in so far as resolution was concerned, and although results showed both interest and promise, the time consumed in attacking even a single nucleus was so large that a systematic programme of this type was unfeasible. The experiments were the first application of spark chamber techniques to nuclear physics. Figure 17 shows the nature and the quality of some of the data taken by the group.

Figure 17. The $\pi^+ {}^6\text{Li} \rightarrow pp + X$ reaction observed at the SC in 1965 [45]. This was the first nuclear physics experiment involving spark chambers.

A programme that had a much larger general influence was the study of exclusive processes of the type $A+B \leftrightarrow C+\pi$. These have a special significance to nuclear physicists, since momentum transfer in such processes is far higher than the Fermi momentum in nuclei. Such processes are often referred to as coherent pion production, meaning that the nucleus stays in its ground state or in a state of low excitation. Such reactions are

fundamentally sensitive to novel aspects of nuclei not explored by more conventional probes. The first of these to be observed at the SC was the proton-induced reaction $p + A \rightarrow \pi + X$. The Göteborg–Oxford group [48] explored this reaction using the 600 MeV incident protons in 1970 with the purpose of learning the main features of the continuum spectrum. They found that the endpoint of the spectrum had an unexpected structure as is seen in Fig. 18.

Figure 18. The endpoint spectrum of pions produced coherently at 0° from ^{12}C , ^{13}C and ^{14}N bombarded by 597 MeV protons as observed by Domingo *et al.* in 1970 [48].

In this case the momentum mismatch to a single nucleon reaction is 600 MeV/c, a large figure by nuclear standards. When they attempted a description in terms of single-particle wave functions these failed badly to describe the data by a factor 100. This was a clear indication of a cooperative effect by several nucleons. There was little possibility of pursuing detailed studies at the SC with sufficient resolution, but these observations stimulated immediately a couple of young Ph.D students to try out the process in a table top experiment with 185 MeV protons in Uppsala, that is, at a machine that had existed for two decades without any pion experiment. This led to intensive explorations of such processes near threshold [49], where excellent resolution could readily be achieved. A typical result is seen in Fig. 19. When the SC came under pressure in pion physics from the meson factories in the late 1970s, a variant of this reaction with complex projectiles provided a lot of excitement. In 1979 [51] Aslanides *et al.* used the 910 MeV ^3He beam to the reaction $^3\text{He} + ^6\text{Li} \rightarrow ^9\text{C} + \pi^-$. This was the first observation of a doubly coherent production process. The cross-section was very small, of the order of a little less than 1 pb/sr and the momentum transfer was even larger than in the proton-induced reactions. The spectrum of the first observations is shown in Fig. 20. Such processes were studied in more detail by them [52] as well as by several other groups using heavier projectiles [53, 54]. The

Figure 19. An energy spectrum of pions produced by 185 MeV protons incident on ^{12}C at Uppsala in 1978 [50]

Figure 20. The inclusive spectrum for $^3\text{He} + ^6\text{Li} \rightarrow \pi^- + X$ in the endpoint region as measured in 1979 by Aslanides *et al.* [51]. Note the evidence for doubly-coherent production of ^9C near the endpoint.

most notable advances occurred in relation to the observation of coherent π^0 production in reactions $C + C \rightarrow \pi + X$ below the free threshold, since the neutral production is unaffected by Coulomb distortions. This process was first observed at the SC at projectile energies down to 60 MeV/nucleon. Similar processes were rapidly explored at other accelerators with lower energy per nucleon. Figure 21 shows that now 35 MeV/nucleon has been reached, not far from the absolute threshold of 20 MeV/nucleon.

This means that there must be at least eight nucleons cooperating in this production process.

Figure 21. Cross-sections for neutral pion production in $^{12}\text{C} + ^{12}\text{C}$ collisions in the threshold region as measured at CERN [54] and at Michigan State [55]

7. Conclusion

The SC has thus been of central importance to the development of our present picture of pion-nuclear interactions. In the golden age in the 1960s and early 1970s the key features of the low energy interaction were tied down, the ground for the Δ isobar model was prepared, the modern parameters for πN scattering and π production in pp interaction were established. Further, a number of pioneering studies such as those of pion double-charge exchange, single exclusive pion production and coherent pion production were first observed and explored at the SC and have strongly influenced further developments at more appropriate accelerators. It is not too strong to say that as far as pion-nuclear physics is concerned the field was born at the SC.

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