Meson Production in Coherent Antiproton-Nucleus Annihilation

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Abstract. The study of a fully quantum mechanical description of coherent meson production in antinucleon annihilation on nuclei is presented. Two different reaction mechanisms are presented including initial and final state interactions, which are both derived from a folding approach. The underlying fundamental antinucleon-nucleon \( \bar{N}N \) and pion-nucleon \( \pi N \) interactions enter into the optical potentials, which are folded with Hartree-Fock-Bogoliubov nuclear densities. Existing approaches to pion nucleus interactions have been extended to higher energies beyond the \( \Delta \)-resonance. Cross sections are shown.

1. Introduction
Meson and hadron production by antinucleon-nucleus annihilation reactions is well suited to explore a broad spectrum of final particle configurations and physics phenomena. Varying the incident energy, the whole spectrum of flavour states can be scanned through. Annihilation of an incoming antiproton on both protons and neutrons of the target nucleus allows to study the dependence of production dynamics on the initial charge state. The upcoming FAIR@GSI facility with its large variety of envisioned experiments will provide ideal experimental conditions for such investigations. Corresponding efforts are being made on the theoretical side. Of highest interest is to identifying physics cases of general relevance. Here, we are investigating meson production in antiproton-nucleus reactions [1], intended as exploratory studies for the PANDA [2] experiment and, if realized at a later stage of FAIR, also for the nuclear structure-oriented use of high energy antiprotons aimed for within the AIC proposal [3]. Meson production in hadronic reactions can be obtained by different reaction scenarios. A well studied case is meson production out of high energy collisions of two heavy ions, see for example [4]. Here, our point of view is different: We consider coherent \( pA \) reactions, leaving the residual nucleus \( B \) intact and leading otherwise to few-body exit channels with a limited number of emerging hadrons. As a concrete and typical example we treat explicitly the case of two pion production. Coherent reactions have the distinct advantage that the full quantum mechanical structure of the production process is accessible, including the details of the interactions of the projectile and the ejectiles with the initial and final nuclei, respectively. Hence, different to heavy ion collisions, determined by reaction probabilities, in coherent reactions one is dealing with quantum mechanical amplitudes, including information on modulus and phase. The reaction scenarios for the coherent meson production are discussed in section 2. For their treatment \( pA \) initial and \( mB \) final state interactions are required. Our approach to these interactions is briefly
summarized in section 3 and section 4, respectively. In both cases, we use a description in terms of microscopically determined optical potentials. Both the \( \bar{p}A \) and the \( \pi A \) interactions are expressed in terms of state-of-the-art HFB nuclear structure input for ground state densities and binding energies, also far off stability. The reaction amplitudes by themselves had to be extended into energy regions hitherto not studied, neither experimentally nor theoretically. The paper closes with a summary and an outlook in section 5.

2. Reaction Mechanisms and Production Vertices

Two-meson production is inherently leading to a 3-body exit channel. This 3-body problem is not – or cannot be – solved exactly. In order to find reliable approximations, it is worthwhile to consider the reaction in more detail. A closer inspection shows that we can distinguish two meaningful reaction scenarios:

2.1. Peripheral In-Flight Reactions

In this reaction mechanism the antinucleon in flight picks up a nucleon of the target nucleus and forms an intermediate \( \bar{N}N \) correlated state, subsequently decaying into mesons in free space. The in-flight scenario resembles in the first step a traditional pick-up reaction as long known in \((p,d)\) or \((p,2p)\) reactions, but with the presence of a nucleus, there are more nucleons available to take care of the recoil momentum. The therefore low-momentum transfer character of this reaction is reflected in clearly visible nuclear structure effects indicated by the diffraction pattern of the angular distributions shown in in figure 1. As a first step we calculated the production of a hadron cloud. In figure 1 is shown the pick-up of valence neutrons of \( ^{48}\text{Ni} \), stable \( ^{58}\text{Ni} \) and neutron-rich \( ^{78}\text{Ni} \) target nuclei.

2.2. In-Situ Reactions

In contrast to the in-flight reaction mechanism the antinucleon in this reaction is stopped inside the target nucleus, similarly as in former experiments at LEAR. The annihilation and production of mesons takes place in-medium. The nucleus must absorb a large part of the incoming momentum. Hence, short range correlations and nuclear form factor effects will play a dominant role. As a first step we consider the production of a \( \rho \)-meson, which then decays into two pions. The relative motion of those pions has been integrated out. In figure 2 the cross

![Figure 1.](FAIRNESS 2012: FAIR NExt Generation of ScientistS 2012 IOP Publishing Journal of Physics: Conference Series 426 (2013) 012005 doi:10.1088/1742-6596/426/1/012005)
As a first step we calculate the cross section of one meson production, namely $\rho^-$, which then decays into two pions. The relative motion of the two pions has been integrated out. The differential cross sections are shown for meson production on a $^{78}$Ni target and $T_{\text{lab}} = 800$ MeV.

Figure 2. As a first step we calculate the cross section of one meson production, namely $\rho^-$, which then decays into two pions. The relative motion of the two pions has been integrated out. The differential cross sections are shown for meson production on a $^{78}$Ni target and $T_{\text{lab}} = 800$ MeV.

section is shown for the valence neutrons of $^{78}$Ni target.

As has been discussed above the two scenarios are different in their energy-momentum balance, but in a general description, both can be expressed in terms of cross section:

$$d^0 \sigma_{\alpha\beta} = N_{\alpha\beta} \left( \frac{\hbar c}{2\pi} \right)^9 \frac{d^3k_1}{E_1} \frac{d^3k_2}{E_2} \frac{d^3k_B}{E_B} |M_{\alpha\beta}(k_1^-,k_2^-,k_B^-;k_\alpha^-)|^2$$

$$\times \delta \left( k_1 + k_2 + k_B \right) \delta \left( E_1 + E_2 + E_B - \sqrt{s} \right)$$

where $N_{\alpha\beta}$ is a normalization constant and the subscripts 1 and 2 stand for each pion, while $B$ denotes the residual nucleus, $\alpha$ corresponds to the initial state and $\sqrt{s}$ is the total centre of mass energy, while the deltas account for energy and momentum conservation. Studying the production mechanism one finds a separation of scales. The influence of the nuclear matter proceeds on the scale of the Fermi-momentum ($\approx 250$ MeV/c), while the production involves baryon exchange ($\approx 1$ GeV/c), this allows to factorize the production amplitude into overlap wave function $\varphi_B$ and the production amplitude $t_{NN \rightarrow 2\pi}$ in the matrix element:

$$M_{\alpha\beta} \approx t_{NN \rightarrow 2\pi}(s) \langle \chi_{\alpha}(-) \chi_{\beta}(-) | \varphi_B | \chi_{\alpha}(+) \rangle.$$  

The outgoing wave functions $\chi_{\alpha}(\cdot)$ may be of mesonic or baryonic character, depending on the scenario, discussed above. The antiproton and meson self-energies are entering into the scattering wave functions of the incoming and outgoing particles. The wave functions are calculated in eikonal approximation.

3. Initial State Interaction

The prevailing reaction mechanism of the initial state $\bar{N}A$ interaction is annihilation. Due to the strong absorption the antinucleon penetrates only a little into the nucleus. In principle, the $NN$ interaction is modified by in-medium self-energies and Pauli-blocking of the target nucleons, but the importance of the low-density surface region justifies, as an approximation, to separate nuclear properties from the $NN$ dynamics. This is done within a folding approach, where the $T_{NN}^{(A)} \times T_{NN}^{(N)}$ is folded over the nuclear density $\rho_N$, taken from self-consistent Hartree-Fock-Bogoliubov calculations. This leads to a good approximation of the optical potential

$$U_{\text{opt}}(r) = V - iW = \sum_{N=p,n} \int \frac{d^3q}{(2\pi)^3} \rho_N(q)t_{\bar{p}N}(T_{\text{Lab}},q^2)e^{i\mathbf{q} \cdot \mathbf{r}}.$$
At those energies where theoretical results are available, the $NN$ interactions are taken from microscopic models, as for example Paris \[5\] and Jülich/Bonn \[6\]. Those models derive the $NN$ potential by $G$-parity transformation of their $NN$ potential. In a meson-exchange picture, that means a change of the sign of the contribution of $\pi$, $\omega$ and $\delta$ mesons. From the analysis of data one finds a rather shallow real part, indicating that the dispersive contributions are effectively reducing the otherwise very deep static potential obtained by $G$-parity, e.g. \[7\]. However, the dominating imaginary part strongly suppresses the incoming antiproton flux already in the surface region, thus inhibiting direct access to the nuclear interior. Considering the Jülich model in more detail, we find as a typical structure that a few annihilation channels are treated explicitly while the majority of states is treated schematically by a purely phenomenological $NN$ optical potential. This optical potential is fitted to describe the data up to 300 MeV incident kinetic energy. At higher energies where theoretical results are missing, we are depending presently on a phenomenological approach using a $T$-matrix where the on-shell strength is derived from the $NN$ cross section by means of the optical theorem. Finally, we mention that for central $pA$ collisions transport theory is the appropriate approach, as discussed e.g. in \[4\].

4. Final State Interaction

Similarly to the initial state interaction we describe the final state meson nucleus interaction within a folding approach, leading to an expression similar to eq. 4. However, the leading order part which is linear in the density must be extended because meson interactions with correlated pairs of nucleons are known to be important. Hence, the pion-nucleus contains significant contributions being proportional to the square of the target density:

$$U(r) = 4\pi f_{\pi N} \rho(r) + \delta U(\rho^2)$$

where $\rho$ is the nuclear density and $f_{\pi N}$ the pion-nucleon scattering amplitude. The leading order term, however, is modified by genuine in-medium contributions, denoted by $\delta U$. Important effects are the two-nucleon absorption mechanism and $N^{-1}\Delta$ excitations off the medium, both leading to contributions of at least $\rho^2$, see e.g. \[8\]. There have been detailed discussions on a microscopic level of the density dependence of pion-nucleus potentials for the low energy $s$-wave case \[8\]. Reactions like two nucleon absorption have been studied \[9\] and are implemented in our work. Because the two produced pions are sharing the momentum of almost $2 M_N$ we developed a semi-phenomenological description by extending an existing approach of \[10\]. As a starting point a Kisslinger type potential is used:

$$U_{opt} = U_s + \nabla U_p \nabla.$$

The derivatives covering the $U_p$ already indicates, that the $p$-wave part mainly contributes at the nuclear surface. As discussed in \[11\] in order to extend and improve the energy dependence of the $s$-wave part $U_s$ by taking into account higher resonances. By using a Krell-Ericson transformation $\Phi = (1 - U_p)^{-1/2}$ one derives a local potential:

$$U_N(r) = \left(\frac{\hbar c}{2 \omega}\right)^2 \left\{ \frac{U_s}{1 - U_p} - \frac{k^2 U_p}{1 - U_p} - \frac{k^2 U_p}{1 - U_p} \left[ \frac{k^2 U_p}{1 - U_p} \right] \right\},$$

where $\omega$ is the energy and $k$ the momentum of the pion. A Schrödinger equation is solved in eikonal-approximation, leading to a good description of the data over the whole energy range as shown in figure 3 and figure 4.
5. Summary and Outlook
Meson production in coherent, peripheral $pA$ reactions has been investigated in a fully quantum mechanical approach. Initial and final state interactions were treated by using realistic nuclear structure input and elementary reaction amplitudes. The different scales defined by the soft-scale nuclear properties on the one hand and by the hard-scale production dynamics on the other hand allowed to use a separation ansatz. The reactions as such take place in the low density region of the nuclear surface. Hence, a $tp$ folding approach is an appropriate first approximation. Cross sections for the two types of reaction mechanisms were presented in Distorted Wave Eikonal Approximation (DWEA). The in-flight scenario could be of potential interest also for the search for $pp$ or $pn$ baryonium bound states which will produce a distinct component in the spectra of the outgoing particles. The in-situ scenario is ideal for searching Pontecorvo-type reactions [14] given by the re-absorption of most of the produced mesons on the target nucleons. The two-meson channels, although being only a minor part of the $pA$ total cross section are of particular interest because of their comparatively simple channel configuration and clean kinematics. Extensions to $KK$ production is feasible and, in fact, is a work in progress. At higher energies, also $BB$ baryon-antibaryon channels will open, e.g. $ΛΛ$ hyperon production. These reactions are in principle measurable at PANDA, thus opening a new research path.

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