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COHERENT PION PRODUCTION IN NUCLEUS-NUCLEUS REACTIONS

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1 INTRODUCTION

The coherent pion production process can be considered as the creation of virtual pions followed by their elastic scattering with the nucleus which is left in its ground state. The energy transferred during the collision is converted into one degree of freedom : the real pion.

Virtual pions are created through collective spin-isospin excitations in the projectile and target nuclei. The resonance in the pion-nucleon system is the Δ -isobar. The study of the Δ -isobar in the nucleus is closely related to the behavior of the pion in the nuclear medium. The interaction governing this type of excitations is an important component of the nucleon-nucleon force.

Even if the predicted signatures of the coherent process are very clear, its experimental identification is not easy, namely because of the very small cross section.

The search for coherent pion production in nucleus-nucleus col-

lisions has been made in two energy domains : far below threshold at GANIL, in $^{12}\text{C} (^{12}\text{C}, ^{12}\text{C})$ reaction at 95 MeV/nucleon and above threshold in $^{12}\text{C} (^3\text{He}, t)$ reaction at 2 GeV bombarding energy at SATURNE.

2 COHERENT SUBTHRESHOLD PION PRODUCTION

Subthreshold pion production in heavy-ion collisions requires a large overlap of the projectile and target density distributions¹⁻³, pions are therefore created preferably in central collisions. However, to research coherent phenomena, peripheral collisions are certainly more appropriate since the main features of coherent effects are characteristic of forward direction and they rapidly disappear with increasing transverse momentum transfer.

Brown and Deutchman⁴ suggested that pion production in peripheral heavy-ion collisions can occur because of a coherent spin-isospin excitation through the Δ -hole channel in either projectile or target.

As an example, let us consider the reaction :

$$^{12}\text{C} + ^{12}\text{C} \rightarrow ^{12}\text{C}(1^+, T=1; E^* = 15.1\text{MeV}) + \pi^0 + X. \quad (1)$$

The projectile (target) is excited to the $1^+T=1$ state through a Gamow-Teller transition ($\Delta S = \Delta T = 1$) decaying dominantly by the emission of a M1 photon of 15.1 MeV. Thus, the projectile (target) acts as a source of virtual pions scattering elastically on the target (projectile) nucleus and exciting a Δ -hole state which decays by emitting a pion.⁵

The full identification of the process can be done by a coincidence measurement of the ejectile (^{12}C), the 15.1-MeV photon and the two photons from the π^0 decay.

An experiment to study this process has been performed at GANIL at 95 MeV/nucleon⁶. The ejectile has been analysed by the SPEG spectrometer which allows the full identification of charge, mass and energy. A set of 30 BaF₂ detectors was used for simultaneous measurement of the 15.1-MeV photon and of the photons from the π^0 decay.

By way of preliminary, only one high-energy gamma, assumed to originate from the π^0 decay, has been measured giving an upper limit of the process under investigation.

Fig. 1 : Energy spectrum of photons detected in coincidence with ^{12}C ejectile.

The energy spectrum of photons, triggered by the kinematical conditions imposed to the ^{12}C ejectile, clearly shows a peak around 15.1 MeV and corresponding to the M1 transition in ^{12}C (Fig.1). The estimated upper limit for the cross section for coherent π^0 production in the $^{12}\text{C}[^{12}\text{C}, ^{12}\text{C}(1^+, T=1; E^*=15.1\text{MeV})]$ reaction at 95 MeV/nucleon is 60 nb. This result is consistent with theoretical predictions ⁷ giving a range of values from 60 to 110 nb depending on the choice of the NN- $N\Delta$ interaction.

However, it should be emphasized that at subthreshold energy, where the transferred momenta are as large as $2\text{-}4\text{ fm}^{-1}$, the theoretical predictions may contain large uncertainties. The incident projectile wave function is distorted and attenuated in the nuclear medium apart from the pionic interactions. Since the projectile acts as a source of the virtual pion beam this latter is also attenuated. These distortion effects are difficult to calculate at high momentum where nuclear wave functions are not well known.

3 COHERENT PIONS IN CHARGE-EXCHANGE REACTIONS ABOVE THRESHOLD

At higher energies, far above threshold, theoretical calculations are more accurate and coherent pion production might be easier to observe. Interesting data come from recent experiments performed at SATURNE using a $^{12}\text{C}(^3\text{He}, t \pi^+)$ reaction at 2 GeV ⁸.

Fig. 2 : The spin-longitudinal (solid) and spin-transverse (dashed) form factors squared (FF^2) for several projectile-ejectile systems ⁹.

This reaction is an especially interesting probe since the $(^3\text{He}, t)$ form factor enhances very much the spin-longitudinal excitations, the pion-like modes ⁹ (Fig.2). By the way, as we can see in Fig.2, this kind of enhancement is also expected for $(^{12}\text{C}, ^{12}\text{N})$ (or $(^{12}\text{C}, ^{12}\text{C})$) system as far as large momenta are concerned. Thus, one of the two responses, spin-longitudinal or spin-transverse, can be emphasized by proper choice of projectile-ejectile systems.

The charge-exchange transition of the projectile is a source of virtual pions transferred to the target. The virtual pions propagate through the nucleus exciting Δ -hole states which decay by emitting a real pion.

In the SATURNE experiment the tritons were analysed with a dipole magnet and two sets of drift chambers. The Diogene detector allowed the identification of charged pions and the measurement of their vector momenta.

For events corresponding to the transferred energy $w \sim 250$ MeV, the angular correlation between the transferred momentum $\vec{q}$ and the momentum $\vec{p}_\pi$ of the pion has been examined. In the reaction probing the spin-longitudinal pionic modes with a $\vec{S} \cdot \vec{q}$ spin structure, the angular correlation is, in principle, characterized by a $(\vec{S}^+ \cdot \vec{p}_\pi)(\vec{S} \cdot \vec{q})$, i.e. a $(\vec{p}_\pi \cdot \vec{q})$ dependence on the momentum vectors.

Fig. 3 : The angular correlation between the transferred momentum $\vec{q}$ and the momentum of pions for different gates in the missing mass spectrum indicated in the insert. The gate around the ground state includes events in which missing mass is less than 11.2 GeV.⁸

In fact, a strong angular correlation has been observed for events in which the ^{12}C target is left in its ground state or low-lying states (Fig.3). It seems that the pion is emitted in the direction of the transferred quantum. Moreover, the virtual pion is not much off-shell and the target recoil energy is of the order of 1 MeV.

Fig. 4 : Energy transfer spectra for different channels ⁸.

The energy-transfer spectra show that, for the events with the target left in its ground state, the Δ -peak is shifted ($w \sim 235$ MeV) in comparison with inclusive data (Fig.4). In general, the downward shift of the Δ -peak for nuclear target is attributed to Δ -hole correlations in the spin-longitudinal channel ⁹ reflecting the Δ -hole interaction in the medium.

The cross section for coherent pion production has been estimated to be about 7% of the inclusive $^{12}\text{C}(\text{He}, t)$ cross section. The width of the peak in the energy-transfer spectra for the coherent pions as well as the observed shift are reasonably well reproduced by theoretical calculations ¹⁰. However, the predicted cross section are 2 to 3 times larger than those estimated from the experimental data.

It should be emphasized that the finite resolution in the missing mass (FWHM ~ 25 MeV) does not allow the clear selection of the ground state of the target. Furthermore, due to the DIOGENE acceptance, a significant part of the pion events in which the target is left in a bound state is lost.

Therefore, the pion angular correlation cannot be determined for small triton angles ($\theta_t < 2.5^\circ$) and a precise estimation of the coherent pion production cross section cannot yet be done.

4 COHERENT PIONS PRODUCED NEAR THRESHOLD

Existing data come from two experiments performed far below and above pion production threshold. There is however an interesting intermediate region near threshold where the interpretation of data is easier than at 100 MeV/nucleon and where some of the interesting effects, observed at higher energy, might be enhanced. In fact, Deutchman¹¹ has recently demonstrated that a coherent addition of Δ -hole states increases the magnitude of the form factor, i.e. of the cross section, particularly at large momentum transfer values (Fig.5). Furthermore, the shift of the Δ -peak down in energy is expected to increase with momentum transfer⁹.

Fig. 5 : Magnitudes of the coherent form factor as various Δ -hole states in ^{12}C are induced.¹¹ A corresponds to the $(1p_{\Delta}) (1p)^{-1}$ state only. B corresponds to the to A plus the $(1s_{\Delta}) (1s)^{-1}$ state. C corresponds to B plus the $(2p_{\Delta}) (1p)^{-1}$ and $(2s_{\Delta}) (1s)^{-1}$ states. D corresponds to C plus the $(3p_{\Delta}) (1p)^{-1}$ and $(3s_{\Delta}) (1s)^{-1}$

However, one should be aware of distortion effects which could complicate the analysis. For this reason a new measurement has to be as complete as possible. This implies low thresholds, good

accuracy and large solid angles for the detection of the reaction products.

Fig. 6 : Scheme of the experimental arrangement

As far as the $^{12}\text{C}[^{12}\text{C}, ^{12}\text{C}(1^+, T=1; E^* = 15.1 \text{ MeV}), \pi^0]$ reaction is concerned, it can be studied at SIS at 200-400 MeV/nucleon. TAPS, a large-solid-angle detector of photons is particularly well suited for the registration of the π^0 and of the 15.1-MeV photon. In order to be complete, the measurement should include the identification of the projectile and of the target (Fig.6). The study of the coherence in both nuclei is possible using the additional information given by the Doppler shift of the 15.1-MeV photon.

5 CONCLUSIONS

Coherent pions are produced through collective spin-isospin excitations in projectile and target nuclei. The energy transferred during the collision is almost totally converted into one degree of freedom, the pion.

Results from two experiments searching for coherent pions are available. The $^{12}\text{C}(^{12}\text{C}, ^{12}\text{C})$ reaction has been studied at GANIL at 95 MeV/nucleon giving an upper limit for the cross section $\sigma_{\pi^0}^{\text{coh}} \leq 60 \text{ nb}$.

The recent measurement performed at SATURNE using the $^{12}\text{C}(^3\text{He}, t)$ reaction at 2 GeV clearly shows a strong indication for coherent pion production and a large shift of the Δ -peak observed

in the coherent channel. Both reactions probe the spin-longitudinal response of nuclei.

In the intermediate region, near pion production threshold, the distortion effects are less important than at low energy and moreover, the coherence effects might be enhanced.

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