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ISOSPIN RESOLVED DOUBLE PION PRODUCTION AT CELSIUS *

M. Andersson[a], Chr. Bargholtz[a], E. Fumero[a], K. Fransson[a]
L. Holmberg[a], K. Lindh[a], L. Mårtensson[a], D. Protic[b]
I. Sitnikova[a], P.-E. Tegnér[a], P. Thörngren Engblom[a]
G. Weiss[a], K. Wilhelmsen Rolander[a],

Members of the WASA/PROMICE collaboration[c]

[a]Department of Physics, Stockholm University
Box 6730, S-113 85 Stockholm, Sweden
[b]Institut für Kernphysik, Forschungszentrum Jülich
Postfach 1913, D-52425 Jülich, Germany
[c]Department of Radiation Sciences, Uppsala University
Box 533, S-751 21 Uppsala, Sweden

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Two-pion production close to threshold has been measured in d+d and p+d reactions at CELSIUS. The results are compared to results at higher energies.

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1. Introduction

Single-pion production near threshold in light-ion reactions has been studied for a long time, and accompanying theoretical work has led to a good understanding of the underlying processes. This progress has not been paralleled for the case of double pion production, where data are scarce and some remarkable near-threshold phenomena are still lacking theoretical explanation. One such phenomenon is the ABC effect first observed in inclusive $\mathrm{p} + \mathrm{d} \to {}^3\mathrm{He} + X$ reactions for beam energies corresponding to energies in the centre of mass system (CM) greater than 125 MeV above the threshold for producing two neutral pions [1]. We have studied the reactions $\mathrm{d} + \mathrm{d} \to {}^4\mathrm{He} + X$, inclusively at E_d=569 MeV, and the exclusive reactions $\mathrm{p} + \mathrm{d} \to {}^3\mathrm{He} + 2\pi^0$ and $\mathrm{p} + \mathrm{d} \to {}^3\mathrm{He} + \pi^+ + \pi^-$ simultaneously at

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E_p=477 MeV at CELSIUS approximately 30 MeV above the $2\pi^0$ threshold in order to increase our understanding of the production of two pions in states of low relative momentum. In the first reaction the two pions are produced in a pure isospin $T = 0$ state while the $T = 0$ and $T = 1$ contribution to the third reaction can be deduced from the second (pure $T = 0$).

2. Experimental set up

The mesurements have been done using the CELSIUS accelerator [2] in Uppsala. CELSIUS is a synchrotron storage ring using the Gustaf Werner cyclotron as injector. Light-ion beams of *e.g.* protons, deuterons or alpha particles as well as heavier beams up to ^{40}Ar are available. The maximum energy of protons is 1.36 GeV. Beams with low momentum spread are obtained by electron cooling. Two stations for internal targets are avaible. At the cluster-jet target hydrogen, deuterium and several noble gases are available with densities up to approximately 10^{14} atoms per cm^{-2}. A pellet target produces pellets of frozen hydrogen with average densities of 10^{16} atoms per cm^{-2}.

In these experiments a deuterium cluster-jet target has been used. The He nuclei emitted in forward directions in the laboratory were detected in a zero-degree spectrometer [3], built in collaboration with the detector laboratory at Institut für Kernphysik in Jülich. The spectrometer uses the quadrupole and dipole magnets of the CELSIUS ring to focus the particles onto a charged particle telescope, made of solid state detectors (high-purity germanium and silicon), installed into the beam tube 6 m downstreams of the target. For these measurements three detectors were used in a $\Delta E - \Delta E - E$ configuration.

For the exclusive reactions the WASA/PROMICE detector set up [4] around the cluster-jet target was used in addition. Neutral pions were detected by their decay into photons in a central calorimeter consisting of two arrays of CsI scintillators with plastic scintillators in front to signal charged particles. Charged pions were detected in the central calorimeter and in the forward detector which comprises layers of plastic scintillators and straw chambers.

3. The ABC effect

The ABC effect was first observed in inclusive $\mathrm{p} + \mathrm{d} \rightarrow {}^3\mathrm{He} + X$ reactions for beam energies between 624 and 743 MeV [1]. These beam energies correspond to an energy, $Q = E_{\mathrm{CM}}^{\mathrm{tot}} - M_{\mathrm{He}}c^2$, available to the system X in the overall centre of mass system, in the range 395 to 464 MeV/c^2. The energy Q equals the maximum of the invariant mass, M_X, of the system

X. This reaction was systematically investigated by Banaigs *et al.* [5] at SATURNE by measuring the momentum spectrum of the ^{3}He particle at different emission angles for several deuteron beam energies corresponding to Q in the range 473 to 711 MeV. Beside a peak at a momentum corresponding to $M_X = 135$ MeV/c^2 for single π^0 production, there appears a rapid variation in the differential cross section giving a peaklike structure for M_X around 310 MeV/c^2 (the exact position varies between 297 and 365 MeV/c^2 depending on angle and beam energy). This, so called, ABC effect is seen mainly for ^{3}He emitted backwards in CM. Interpreting this effect in terms of the s-wave pion-pion interaction in the isospin zero channel, Abashian *et al.* [6] obtained a scattering length, $a^{T=0}_{L=0} = 2.5 m_\pi{}^{-1}$. Such an interpretation is ruled out by later measurements of the free pion-pion scattering length, *e.g.* in the K-meson decay, yielding a much weaker interaction with $a^0_0 = 0.26(5) m_\pi{}^{-1}$ [7]. In fact, in the momentum spectrum, the increase of the differential cross section in the ABC region as a function of increasing momentum (and increasing M_X) is more or less proportional to the increase of the three-body phase space, indicating a rather constant amplitude for two-pion production for M_X close to $2m_\pi$. Thus, the observed "peak" may be the result of the combination of an increasing phase space and a decreasing matrix element. Under isospin conservation $T = 0$ or $T = 1$ is possible for the system X. By measuring the corresponding reaction to the isobaric analogue nucleus ^{3}H, where X has pure $T = 1$, Banaigs *et al.* [5] concluded that the ABC effect appears only in the $T = 0$ channel.

4. The $\mathrm{d} + \mathrm{d} \to {}^4\mathrm{He} + X$ reaction

For the pure $T = 0$ reaction $\mathrm{d} + \mathrm{d} \to {}^4\mathrm{He} + X$, investigated at beam energies corresponding to Q in the range 399 to 892 MeV Banaigs *et al.* [7] showed that the spectrum is dominated by the ABC effect, but, again, the "peak" may be the result of a decreasing production matrix element weighted by the increasing phase space (as a function of increasing M_X). For pure T=0 the cross section in the laboratory can be written as

$$d\sigma = |M|^2 \frac{1}{32(2\pi)^4 m_2 p_1} \frac{p^2_{\mathrm{He}}}{E_{\mathrm{He}}} \left(\frac{1}{3}\sqrt{1 - \frac{4m^2_{\pi^0}}{M^2_X}} + \frac{2}{3}\sqrt{1 - \frac{4m^2_{\pi^\pm}}{M^2_X}} \right) dp_{\mathrm{He}} d\Omega_{\mathrm{He}} \,, \tag{1}$$

where m_2 is the mass of the target nucleus, p_1 the beam momentum and p_{He} and E_{He} the momentum and total energy of the detected He particle. $|M|^2$ is the square of the T=0 two-pion production matrix element averaged over the spins of the incoming particles and the direction of the pions in their CM. In figure 1 $|M|^2$ corresponding to the maximum of the ABC effect is shown

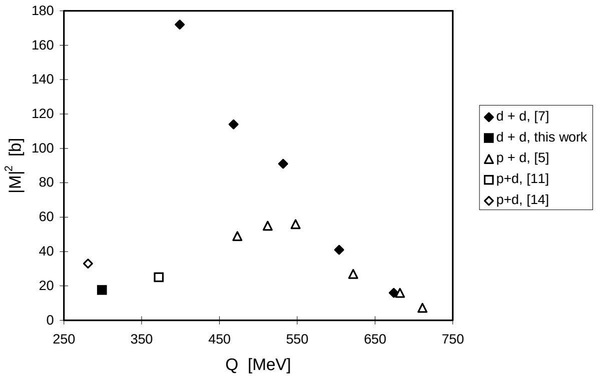

Fig. 1. The squared matrix element $|M|^2$ as a function of Q. For the Banaigs data ([5] and [7]) the value was determined at the maximum of the ABC peak from the spectra taken at $\theta_{\rm lab} = 0.3^0$ (assuming pure $T = 0$ in both reactions). The values from MOMO [11] and IUCF [14] are obtained using the charged pion part of Eq. (1) and their total charged pion cross section.

as a function of Q. The value of $|M|^2$ is seen to increase monotonically as Q decreases from 892 to 399 MeV.

We have studied the inclusive $\mathrm{d} + \mathrm{d} \to {}^4\mathrm{He} + X$ reaction at CELSIUS closer to threshold at a beam energy of 569 MeV, corresponding to Q=299 MeV [8]. For the detection of the He particles the zero-degree spectrometer was used. In the measured missing-mass spectrum, there is no evidence of a narrow enhancement at the lowest missing mass. Rather, a cross section proportional to the phase space (modified by the free pion-pion interaction) fits the spectrum very well. Thus, these results are consistent with the assumption that, at this energy, both pions are produced in s-wave in the CM. The extracted value of a constant $|M|^2$, 18 b, is an order of magnitude smaller than that deduced for the ABC enhancement for Q=399 MeV.

A model for two pion production in the $\mathrm{d} + \mathrm{d} \to {}^4\mathrm{He} + X$ reaction has been proposed by Gårdestig, Fäldt and Wilkin [9]. In this model the pions are produced in two independent nucleon-nucleon collisions, $N+N \to d+\pi$. Using measured NN amplitudes, the model seem to explain the experimental data of Banaigs *et al.* rather well at a beam energy of 1250 MeV ($Q = 604$ MeV). According to measured NN cross sections, p-wave pion production in the ${}^1D_2p$ channel dominates at this energy, and should be contributing significantly already a few MeV above threshold [10]. Thus, this model predicts ABC structures even at $Q = 299$ MeV in contradiction to our results.

5. The $p + d \rightarrow {}^3\mathrm{He} + 2\pi$ reaction

The MOMO collaboration has reported results of exclusive measurements of the reaction p + d $\rightarrow$ ^{3}He + π^+ + π^- for proton energies of 546 MeV and 477 MeV, corresponding to Q = 349 and 307 MeV [11]. They could not confirm any enhancement for pion pairs of low invariant mass, but rather reported a deficit compared to a pure phase-space dependence below 320 MeV/c^2. One possible explanation of these data is that the pions are produced predominantly in a relative p-wave [12]. Due to the symmetry of the pion-pion wavefunction only $T = 1$ is then possible.

In order to resolve the contribution from the two possible isospin channels, we have made exclusive measurements of the p + d $\rightarrow$ ^{3}He+2π reaction by detecting pions in coincidence with ^{3}He particles in CELSIUS at a beam energy of 477 MeV [13]. The He particles were detected in the zero-dergree spectrometer and the pions were detected in the WASA/PROMICE detector set-up around the cluster-jet target. In this reaction two neutral pions are produced only in $T = 0$ while the charged pion pair can have either $T = 0$ or 1. Using Eq. (1), assuming a constant matrix element, the ratio between the cross section for neutral and charged pion production is calculated to be 0.87 for pure $T = 0$. For pure $T = 1$ the ratio is zero. A preliminary result, based on part of the data, yields a ratio of the cross sections of 0.22(20) (assuming isotropic angular distributions in the CM). Our results, therefore, seem consistent with the assumption of dominance of relative p-wave in the pion-pion system at this energy. This reaction (inclusively and the exclusive charged pion channel) was studied very close to threshold ($Q = 2m_{\pi^+}c^2 + 0.6$ MeV) at IUCF [14]. From the data it seems clear that there is a contribution from neutral pion production.

6. Discussion

It seems evident that the mechanism for producing two pions changes when going from an energy regime where the available kinetic energy in the CM for the two pions exceeds 100 MeV to the low energy regime (20–30 MeV kinetic energy). In the pure $T = 0$ d+d reaction, p-wave production seems to dominate at higher energies (leaving the pions in a state of relative s-wave or d-wave), while closer to threshold s-wave production seem to dominate with a much smaller production matrix element. This is in contrast to the results of single pion production in nucleon-nucleon collisions where p-wave production dominates even rather close to the threshold. In the p+d reactions the $T = 0$ channel dominates the two-pion production at higher energies, whereas the $T = 1$ channel seem to dominate at lower energies, which excludes the possibility that both pions are produced in s-wave.

To further investigate this problem measurements in the energy region between our low-energy measurement and the lowest energy studied by Banaigs *et al.* are needed, as well as complete angular distributions to enable partial-wave analysis. The new CELSIUS/WASA detector that presently is installed around the pellet target at CELSIUS will be suitable for such studies. It consists of a central calorimeter which covers 96% of the solid angle and a forward detector for charged particles.

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REFERENCES

[1] A. Abashian, N.E. Booth' K.M. Crowe, *Phys. Rev. Lett.* **5**, 258 (1960).

[2] L.-O. Andersson *et al.*, in: A. Ingmarsson (Ed.), TSL Progress Report 1994-1995, The Svedberg Laboratory Uppsala Sweden, 1996, pp.8.

[3] Chr. Bargholtz *et al.*, *Nucl. Instrum. Methods* **A390**, 160 (1997).

[4] H. Calén *et al.*, *Nucl. Instrum. Methods* **A379**, 57 (1996).

[5] J. Banaigs *et al.*, *Nucl. Phys.* **B67**, 1 (1973).

[6] A. Abashian, N.E. Booth' K.M. Crowe, *Phys. Rev. Lett.* **7**, 35 (1961).

[7] J. Banaigs *et al.*, *Nucl. Phys.* **B105**, 52 (1976).

[8] Chr. Bargholtz *et al.*, *Phys. Lett.* **B398**, 264 (1997).

[9] A. Gårdestig, G. Fäldt' C. Wilkin, Report series ISSN 0284-2769, TSL/ISV-97-0185.

[10] S. Förtsch *et al.*, *Acta Phys. Pol.* **B27**, 2925 (1996).

[11] F. Bellemann *et al.*, *Acta Phys. Pol.* **B27**, 2945 (1996); A. Berg, Ph. D. Thesis, Bonn 1997.

[12] C. Wilkin, private communication.

[13] Details in the contribution to this conference: M. Andersson *et al.*, Study of the $\mathrm{p} + \mathrm{d} \rightarrow^{3} \mathrm{He} + 2\pi$ reaction at CELSIUS.

[14] A. C. Betker *et al.*, *Phys. Rev. Lett.* **77**, 3510 (1996).