Medium modifications of the pion-pion interaction: A search for double pionic fusion in $^{14}N+d \rightarrow {}^{16}O+2\pi$ reactions

M. Andersson, Chr. Bargholtz, J. Blomquist, K. Fransson, E. Fumero, L. Holmberg, K. Lindh, L. Mårtensson, P.-E. Tegnér, and K. Wilhelmsen Rolander

Department of Physics, Stockholm University, Box 6730, SE-113 85 Stockholm, Sweden

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Double pion production in the reaction $^{14}N+d \rightarrow {}^{16}O^{*}+2\pi$ has been investigated 99 MeV above the $2\pi^0$ threshold in the center-of-mass frame by recoil detection. Upper limits (2 standard deviations) to the differential cross sections for producing ^{16}O in a particle-stable state and pion pairs in the invariant mass range of 270 to 310 MeV/c^2, $d\sigma/d\Omega(0°)_{c.m.}<1.7$ nb/sr and $d\sigma/d\Omega(180°)_{c.m.}<1.3$ nb/sr, were obtained. For invariant masses above 310 MeV/c^2 an upper limit to the cross section of 7 nb was obtained, assuming a constant production matrix element.

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The study of extended, strongly interacting matter is one of the central themes of nuclear physics. Under well-controlled conditions such matter is available to us in the laboratory only in the form of ordinary nuclei covering a very limited region of densities, neutron to proton ratios, and low temperatures. Predictions of the properties of strongly interacting matter under the conditions prevailing in the very early universe or in the centers of neutron stars so far rely on theoretical model calculations that still need to be tested against the results of experiments. In relativistic heavy ion collisions the phase transition from hadronic matter to the deconfined quark gluon plasma is sought for. This transition has been predicted to occur at a temperature between $kT=150$ and 200 MeV at very low baryon density or alternatively at low temperature at a baryon density 3–4 times that of ordinary nuclei. Chiral symmetry, which is spontaneously broken in the vacuum at low temperature, is restored in the deconfined phase. Recent calculations show that precursor effects of chiral symmetry restoration may be reflected in a modification of the pion-pion interaction already at moderate baryon density. In particular, it has been argued, a partial restoration of chiral symmetry may lead to a significant lowering of the σ-meson mass inside nuclei and, as a consequence, to an increased 2π strength just above threshold in the $J=T=0$, so called, σ channel in photonucleus or $(\pi,2\pi)$ reactions [1,2]. Such an accumulation of 2π strength in the vicinity of the threshold in $(\pi,2\pi)$ reactions on intermediate and heavy nuclei has indeed been reported by the CHAOS [3,4] and the Crystal Ball [5,6] collaborations. Already for ^{12}C targets a significant shift towards the threshold is observed in the invariant mass distribution of the pion pair as compared to targets of hydrogen and deuterium. However, the increased 2π strength by itself is no proof of chiral symmetry restoration. A modification of effective pion properties inside nuclear matter follows from the strong p-wave coupling of pions and nucleons resulting in a softening of the in-medium pion dispersion relation due to mixing with Δ-hole states with the quantum numbers of the pion. It has been shown that these effects produce an accumulation of 2π strength near threshold [7–9], which may by itself explain the observed effects [10,11]. In order to separate, in an unambiguous way, the effects of pionic collective modes from modifications on a more fundamental level comparisons of the results of detailed calculations and exclusive experiments are required. In the $(\pi,2\pi)$ experiments reported by the CHAOS and Crystal Ball Collaborations the final nuclear state is not well determined. Ideally the final nucleus (and any emitted nucleons) should be detected in the experiment along with at least one of the pions. Alternatively a reaction should be selected in which the identification of the nuclear state defines the state of the undetected pions. Double pionic fusion, i.e., a complete fusion reaction in which a pair of pions is emitted, leads to the simplest possible final state.

We have investigated the production of pairs of pions in the nuclear fusion reaction

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\begin{array}{c} ^{14}N+d \rightarrow {}^{16}O^{*}+2\pi \\ \downarrow \\ ^{16}O_{g.s.}+\gamma \end{array} \tag{1}
$$

by detecting recoiling ^{16}O nuclei. The measurement was done at the accelerator and storage ring CELSIUS [12]. A beam of $^{14}N^{7+}$ ions interacted in the internal deuterium cluster-jet target. The energy of the electron-cooled beam was 2800 MeV, corresponding to 99 MeV above the production threshold for producing two neutral pions in the center-of-mass frame (c.m.) for reactions populating the ground state. At this energy several excited states of isospin $T=0$, 1 or 2 in ^{16}O may be populated, but only particle-stable states are selected since the recoiling ^{16}O nuclei are detected. Thus, excitation of states above 9 MeV is heavily suppressed in our data since those states decay predominantly by particle emission (branching ratios for electromagnetic decays are of the order of 10^{-2} or much less). Especially, all isospin $T=1$ states around an excitation energy of 13 MeV have branching ratios less than 2×10^{-3} for electromagnetic decay. Thus, in reaction (1) two pions are created in an almost pure isospin $T=0$ state, leaving the oxygen nucleus excited by 0–8.9 MeV. The probability for creating charged pions is a factor of 1.7 larger than that for producing neutral pions, assuming isospin conservation and a constant production matrix element. The deviation from a factor of two is due to the dif-

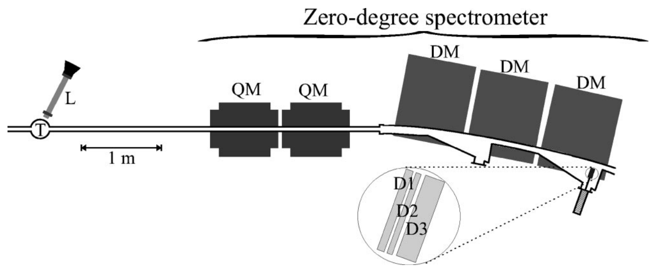

FIG. 1. Part of the fourth quadrant of CELSIUS and the 0° spectrometer, comprising target (T), quadrupole magnets (QM), dipole magnets (DM), and solid-state detectors (D). At the target there is a luminosity monitor (L), which consists of two thin plastic scintillators and a thick bismuth germanate (BGO) scintillator.

ferent energies available above threshold, 99 and 90 MeV for neutral and charged pions, respectively. The detection of the corresponding single-pion production reaction, $^{14}\mathrm{N}+d \rightarrow {}^{16}\mathrm{O}^{*}+\pi^{0}$, is strongly suppressed since it leaves the oxygen nucleus in an isospin $T=1$ state.

The uncertainty in the absolute value of the beam energy was 3 MeV and the energy spread was less than 0.3 MeV. The average beam current was 4.7 mA. The thickness of the windowless target was approximately 5.0×10^{13} atoms/cm^2. The accelerator was operated in cycles of 900 s, defined by injection of ions, acceleration, cooling, data taking during 780 s, and finally dumping of the beam. The luminosity during data taking was approximately $L=1.9\times10^{29}$ cm^{-2} s^{-1}. Variations in the luminosity, due to, e.g., incomplete overlap of beam and target or variations in the gas flow of the target, were continuously monitored by a scintillator telescope, aimed at the target, and were found to be small (less than 10% between 1-h data sets during a one-week run).

Recoiling nuclei were detected in the 0° spectrometer [13], which accepts particles emitted within approximately 0.5° of the circulating beam; cf. Fig. 1. In the present experiment the spectrometer was operated with a stack of solid-state detectors, cooled to liquid nitrogen temperature, 7 m downstream of the target. With three detectors of thicknesses 1.7 mm (denoted D_1 in the following), 1 mm (D_2), and 14.5 mm (D_3), ^{16}O recoils from reaction (1) could be completely stopped, and a good isotope identification was obtained. Detectors D_1 and D_3 were made of high-purity germanium and manufactured at the detector laboratory in Jülich, while D_2 was a silicon detector. The magnetic elements of the spectrometer (the quadrupole and dipole magnets of the CELSIUS ring itself) permit selection of magnetic rigidities and emission angles at the target. By positioning the stack of detectors with its center 88 mm (120 mm) from the circulating beam detection of forward (backward) emission in the c.m. was optimized with an acceptance of 8.9% (9.5%) of phase space. The integrated luminosity for the measurements at these positions were 2.7×10^{34} cm^{-2} and 2.4×10^{34} cm^{-2}, respectively. By using three detectors (as compared to two) the contribution from nuclear reactions in the detector stack can be reduced in the final data. Detector D_1 is position sensitive with its front divided into 66 vertical strips, each strip 1 mm wide. The rear side is divided into 18 horizontal strips, each 2 mm wide. All strips were read out individually. The signals from the vertical strips were fed, via constant-fraction discriminators, to coincidence registers, whereas the pulse heights of the signals from the horizontal strips were individually analyzed and stored. By using this information, the path of the detected ions can be traced and the multiplicity in D_1 can be measured. This helps to reduce the contribution from particles not emanating from reactions in the target and the contribution from double hits, leading to pulse pile-up in detectors D_2 and D_3. For the energy calibration of the detector stack a combination of data taken with radioactive sources and with beam were used. Especially, ^{15}O ions from quasifree single pion production, $^{14}\mathrm{N}+p/n \rightarrow {}^{15}\mathrm{O}+\pi^{0}/\pi^{+}$, were used, not only for energy calibration, but also for quantitative estimations of the influence of different gate conditions on the data.

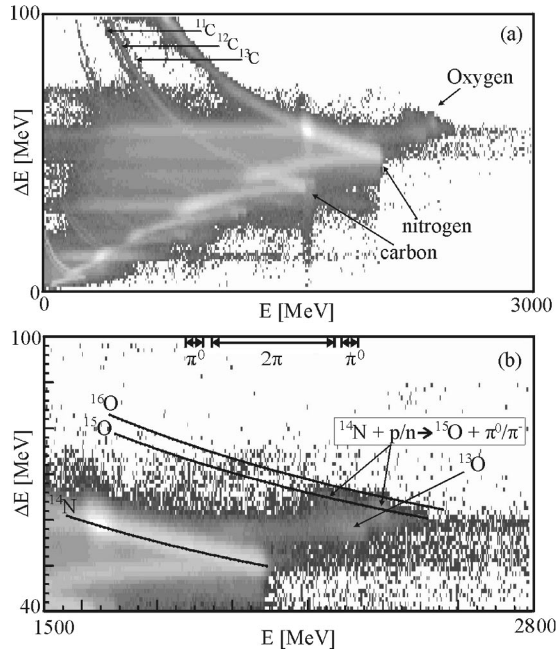

FIG. 2. Spectra (ΔE-E) from the detectors D_2 and D_3 showing part of the data collected with the center of the detector positioned 120 mm from the beam. The data are selected with the following conditions: The pulse-height of the signal from detector D_1 is required to be proportional to the pulse-height from D_2 and the multiplicity in D_1 is one. In part (a) structures corresponding to carbon, nitrogen, and oxygen ions are indicated and a clear separation of the different carbon isotopes can be seen. Bins with a content larger than 1 are displayed. Part (b) shows a closeup of the region of interest. Along the upper rim the energy intervals in detector D_3 are indicated with arrows where ^{16}O ions from the double-pion reaction (1) and from the corresponding single-pion reaction at 180° and 0° are expected. Contributions from ^{15}O and ^{13}O are also indicated. Solid lines correspond to the expected energy deposition of ^{16}O, ^{15}O, and of ^{14}N ions.

In Fig. 2 part of the raw data from the 0° spectrometer is shown in a ΔE-E representation for the pulse heights of detectors D_2 and D_3. Here the condition is that there is a signal in all three detectors, that the pulse heights from D_1 and D_2 are proportional (which excludes some background contributions), and that the multiplicity in detector D_1 is one.

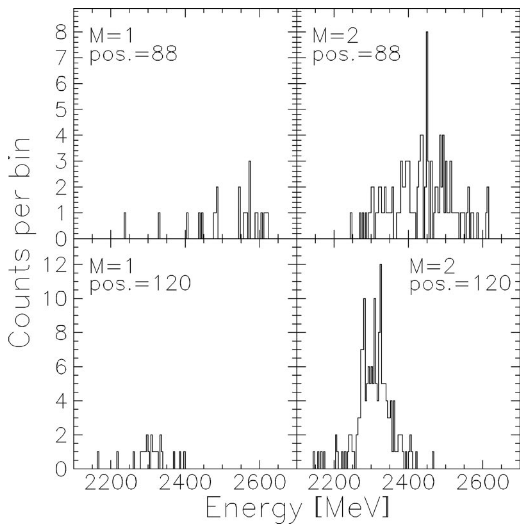

FIG. 3. Experimental kinetic energy spectra of selected events corresponding to multiplicity one ($M=1$) for the detector positioned with its center 88 and 120 mm from the beam, respectively, and the corresponding spectra for multiplicity two ($M=2$).

The regions are indicated where ^{16}O ions are expected from the reaction sought for (as well as from the corresponding single-pion reaction). It is clear that the contribution from ^{16}O is very small. Thus, the background must be efficiently handled. Contamination from ions other than ^{16}O, especially ^{15}O, was minimized by optimizing the pulse-height gates in the D_1-D_2-D_3 pulse-height space and by stringent gates in position. The energy deposition of ^{16}O and ^{15}O ions differs by approximately 8 MeV (3 MeV) in detector D_1 (D_2). The gate in D_1 (D_2) was chosen to ± 4 MeV (± 2 MeV) around the calculated energy-loss curve (cf. Fig. 2), which should be compared to a theoretically estimated energy straggling of 2.2 (1.2) MeV. Regarding the position information each detected ion was required to fulfill the conditions, obtained by ray-trace calculations, for an ^{16}O ion emanating from the target but not for an ^{15}O ion. In the data selected this way there may still be contributions from pile-up, i.e., two or more particles hitting the detector stack within some microseconds (amplifier time constant). Requiring that only one strip of D_1 is triggered (multiplicity one), this contribution was significantly reduced. In Fig. 3 kinetic energy spectra obtained with this condition are shown. From the number of detected double hits (multiplicity two), cf. Fig. 3, the contribution of double hits in a single strip has been calculated and subsequently applied as a correction. The applied cuts in the data led to a detection efficiency of approximately 20%.

Using multiplicity-one data corrected for pile-up, the net number of events of ^{16}O ions in the energy range corresponding to double pion production is -1 ± 3 and 6 ± 6 for the two detector positions, respectively. Thus we conclude that there is no significant contribution in the data from double pion production leading to ^{16}O. For invariant masses, $M_{\pi\pi}<310$ MeV/c^2, the acceptance is strongly peaked for ^{16}O ions emitted at 0° and 180° in the c.m. Differential cross sections of $d\sigma/d\Omega(0°)_{\text{c.m.}}=-0.9\pm 1.3$ nb/sr and $d\sigma/d\Omega(180°)_{\text{c.m.}}=-0.5\pm 0.9$ nb/sr were determined. Assuming a constant production matrix element a cross section for invariant masses larger than 310 MeV/c^2 was determined to 0.5 ± 3.3 nb. Under the same assumptions a total cross section of -0.6 ± 4.5 nb was obtained.

Analyzing the contribution from single-pion production in a similar manner we obtain likewise a differential cross section compatible with zero, $d\sigma/d\Omega(0°)_{\text{c.m.}}=-0.3\pm 1.4$ nb/sr and $d\sigma/d\Omega(180°)_{\text{c.m.}}=0.8\pm 1.4$ nb/sr. These small values are, however, not unexpected, in light of the small branching ratios for the decay of the isospin $T=1$ states to the ground state. Differential cross sections for single-pion production in proton-nucleus reactions in a comparative mass and energy range are of the order of a few hundred nanobarn per steradian at 0° [14].

In this experiment we have searched for double-pion production in ^{14}N$+d$ fusion reactions by recoil detection, 99 MeV above the production threshold for neutral pions. Double-pionic fusion to lighter nuclear systems, close to threshold, has been studied by recoil detection in several measurements at CELSIUS. In the pure isospin $T=0$ reaction $d+d\rightarrow {}^4\text{He}+2\pi$ at 570 MeV (29 MeV above the $2\pi^0$ threshold in the c.m.) no deviations from pure phase space were observed in the invariant mass spectrum of the two pions [15]. The total cross section was determined to 43 ± 5 nb. A model calculation for this reaction by Gårdestig *et al.* [16], which agrees well with experimental data at higher energies, underestimates the measured cross section at 570 MeV by a factor of 20. In the $p+d\rightarrow {}^3\text{He}+2\pi$ reaction, 37 MeV above the $2\pi^0$ threshold in the c.m., neutral and charged pions were detected in coincidence with the recoiling helium ions in order to determine the relative contribution of isospin $T=0$ and $T=1$ to the cross section [17]. The total charged and neutral pion cross section was determined to 160 ± 20 nb and 60 ± 10 nb, respectively. In the present study of double pionic fusion only upper limits to the cross section for producing ^{16}O in a particle-stable state could be established. For invariant masses of the two pions below 310 MeV/c^2 the upper limits (two standard deviations) to the differential cross section at 0° and 180° in the c.m. are 1.7 nb/sr and 1.3 nb/sr, respectively, and for invariant masses above 310 MeV/c^2 the limit to the cross section is 7 nb, assuming isotropic production. With the same assumptions an upper limit to the total cross section of 9 nb is obtained. We conclude that the experimental conditions for double pion production in nuclear fusion reactions to heavier nuclei have to be optimized. Larger acceptance can be achieved with more forward-peaked kinematics, e.g., by using a proton target, and by making the study closer to the kinematical threshold. This will probably also yield larger cross sections in light of the smaller momentum transfer needed to reach the same energy above threshold. At IUCF double pion production has been studied 29 MeV above the kinematical threshold in ^{12}C$+p$ fusion reactions leading to $^{13}\text{C}_{\text{g.s.}}$ [18], resulting in an upper limit to the cross section similar to ours. In this case, however, the isospin of the $\pi^+\pi^0$ pairs is $T=1$ and in the $(\pi,2\pi)$ studies at TRIUMF the contribution from $T=1$ production was negligible compared to $T=0$. For detailed studies a larger luminosity is required. At CELSIUS we have the possibility to raise the luminosity by an order of magnitude or more by using the pellet target. By including the WASA detector [19] the emitted pions can be detected for the purpose of isospin selection.

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