rapidly for larger baryon densities.[1,8] These conclusions remove a long-standing uncertainty in big-bang nucleosynthesis and are consistent with the view that essentially all ^{6}Li is produced in the galactic cosmic rays.

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Coherent Pion Production near Threshold with a ^{3}He Projectile

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Pion production in ^{3}He-^{3}He collisions has been measured at energies below the threshold for production in free ^{3}He-nucleon reactions, with use of the ^{3}He beam from the Orsay synchrocyclotron. Discrete states of the recoil nucleus, corresponding to the coherent process ^{3}He(^{3}He, π^+) ^{6}Li, have been observed with sizable cross sections at 268.5- and 282-MeV kinetic energy. The ground-state data are consistent with pionic atom information.

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High-momentum-transfer processes such as coherent (p, π) (Ref. 1) or (p, d) (Ref. 2) reactions have been investigated intensively in medium-energy nuclear physics over the past decade, but there is still much controversy surrounding the basic reaction mechanisms.[3] It could be that further valuable clues will be provided by reactions which involve the transfer of two or more nucleons and in this hope we have started a program to study coherent pion production with a low-energy ^{3}He beam.

There have, as yet, been very few attempts at measuring exclusive pion production with anything more complex than a proton. Data exist on the coherent (π^+, d) reaction[4] and the inverse (d, π^-) process.[5] On the other hand, discrete final nuclear states were not observed in previous pion production experiments with ^{3}He projectiles.[6,7] In this Letter we report the first results on the coherent reaction $^3\mathrm{He} + {}^3\mathrm{He} \rightarrow \pi^+ + {}^6\mathrm{Li}$ leading to the ground and first excited states of ^{6}Li.

The Orsay synchrocyclotron can furnish ^{3}He beams of several hundred nanoamperes intensity with an energy continuously variable between 235 and 283 MeV. With use of the same experimental setup as described before,[8] a ^{3}He target[9] of 57-mg/cm^2 thickness was employed. After being focused by a quadrupole doublet, pions were detected with a spectrometer, which gave a momentum acceptance of $\Delta p/p = \pm 2.5\%$ and a solid angle $\Delta\Omega = 6.2 \pm 0.3$ msr. Particle trajectories were determined with two multiwire chambers triggered by a 1-mm-thick scintillator (A) placed in front of the spectrometer and three more 3-mm-thick scintillators (B, C, and D) placed behind the chambers. Two times of flight were measured to be used for background rejection and these, together with chamber information, were digitized and fed into an on-line computer. The efficiency of the system for detecting and measuring pions was very good for pion kinetic energies of above about 18 MeV (overall efficiency 88%). Using this energy as a lower cutoff provides an upper limit upon the laboratory production angle which we could study. Thus, at 282 MeV, the cross section for the production of the ^{6}Li ground state could be examined out to a center-of-mass angle $\theta_{\mathrm{c.m.}} = 90°$, whereas for the first excited state we were confined to $\theta_{\mathrm{c.m.}} < 60°$. The situation is much worse at 268.5 MeV, where only the ground state could be reliably determined and that at one rather small angle.

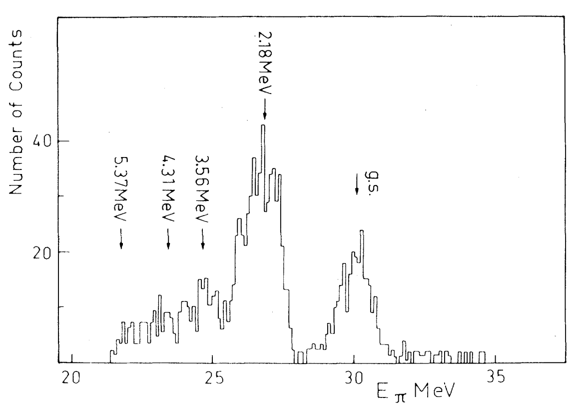

FIG. 1. Spectrum of pions produced at 20° by the reaction ^{3}He(^{3}He,π^+)^{6}Li with 282-MeV ^{3}He ions. The positions of the lowest energy levels of ^{6}Li are marked.

In Fig. 1 we show the spectrum obtained in the focal plane of pions produced at a laboratory angle of 20° by ^{3}He ions of 282-MeV energy. This is the value at the middle of the target but the different energy loss of the ^{3}He and pion through the target was the main contribution to our experimental peak widths of 1.5 MeV full width at half maximum (FWHM). However, because of the kinematics, this corresponds to an energy resolution in the final ^{6}Li nucleus of 1 MeV (FWHM). This value is obtained after a scaling of the spectra, computed from the pion kinetic energy and including the recoil effect. Several measurements were performed with the magnets tuned to different central pion momenta, but with overlapping bins, to provide a reliable determination of the spectrum. In addition, one was made for pions beyond the kinematic limit and, as can be seen from Fig. 1, the signal/background ratio is quite good. The two peaks, corresponding to the production of the ground state (1^+) and the 2.18-MeV (3^+) level in ^{6}Li, are clearly resolved. Higher levels are not seen distinctly but there is good evidence for the excitation of the 3.56-MeV (0^+) state. Studies with an empty target indicated that the background due to the walls, which were very thin (12.7 μm) steel, was negligible.

In Table I we present the differential cross sections for the three states at 282 MeV as well as the ground-state point at 268.5 MeV. Though we have not measured a well-isolated peak corresponding to the 3.56-MeV level, we have been able to extract a value for a cross section at 282 MeV and this point is also presented in Table I.

TABLE I. Center-of-mass differential cross section for the production of pions by the reaction ^{3}He(^{3}He, π^+)^{6}Li leading to the three levels 1^+(0, 0 MeV), 3^+(2.18 MeV), and 0^+(3.56 MeV).

T (^{3}He) (MeV)	Level	$\theta_{\mathrm{lab.}}$ (degrees)	$\theta_{\mathrm{c.m.}}$ (degrees)	$d\sigma/d\Omega_{\mathrm{c.m.}}$ (nb/sr)
282	1^+	20	30.8	24.0 ± 1.7
282	1^+	40	60.3	18.3 ± 2.2
282	1^+	60	87.3	9.4 ± 2.9
268.5	1^+	20	33.6	16.0 ± 1.6
282	3^+	20	31.6	42.9 ± 4.3
282	3^+	40	61.8	26.3 ± 3.2
282	0^+	20	32.2	9.2 ± 2.7

The error bars include only the statistical and background uncertainties, but, in addition, we have systematic errors of ±20% due to beam calibration, target thickness, solid angle, and efficiency. Corrections were applied for in-flight decay of the pions, absorption of the pions in the different counters (~1.5%), and muon contamination (1–2%). This last value is estimated from the decay of π after the second wire chamber, other muons being rejected either by the magnetic elements or by the trajectory reconstruction system.

Because the two ^{3}He particles in the initial state are identical, the cross sections are only functions of $\cos^2\theta_{\mathrm{c.m.}}$, and in Fig. 2 the 282-MeV data are plotted against this variable. If we assume a linear dependence, the cross section for the production of the ground state integrated over 4π sr solid angle is

$$\sigma = 111 \pm 11 \text{ nb}. \tag{1}$$

The ratio R of the cross sections yielding the 2.18-MeV and ground states of ^{6}Li at the same laboratory angle is about 1.7. In low-energy transfer reactions, where the driving mechanism could be completely different, values for R of this order of magnitude are generally found. For example, the reaction $^3\mathrm{He}(^4\mathrm{He},p)^6\mathrm{Li}$ at 42 MeV (Ref. 10) gives $R \sim 2.2$ in the three-nucleon-transfer domain. In such a case, the momentum transfer between the ^{3}He and ^{6}Li, in the rest frame of the latter, is only $\Delta p = 0.8\ \mathrm{fm}^{-1}$, whereas for our

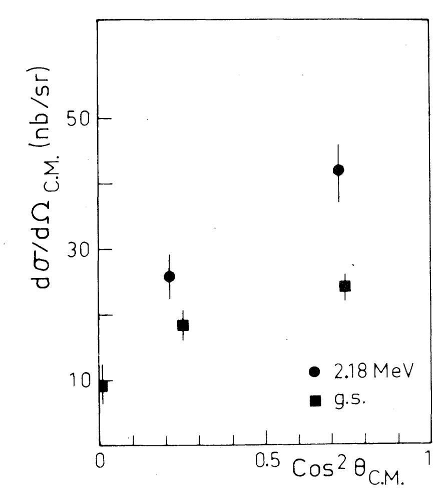

FIG. 2. Center-of-mass differential cross section for $^3\mathrm{He}(^3\mathrm{He},\pi^+)\,^6\mathrm{Li}$ yielding the first two levels in ^{6}Li induced by 282-MeV ^{3}He ions. The cross section is only a function of $\cos^2\theta_{\mathrm{c.m.}}$

pion production it is of the order of $3\ \mathrm{fm}^{-1}$. In an extremely naive model, where the ^{6}Li is assumed to consist of a ^{3}He-^{3}H pair and the pion is emitted by a single ^{3}He in plane-wave approximation, the matrix element (before antisymmetrization) is proportional to the $^6\mathrm{Li} - {}^3\mathrm{He}\ {}^3\mathrm{H}$ wave function evaluated at the rather large momentum Δp. Simple estimates for the cross-section ratios can then be obtained if the 3^+ state is assumed to be a $1d$ relative wave function coupled to spin 1, and the 1^+ and 0^+ a similar $2s$ function coupled to spins 1 and 0, respectively. The deviations of the predicted values ($1^+ : 3^+ : 0^+ \approx 1 : \frac{4}{5} : \frac{1}{2}$) from the data shown in Table I ($\approx 1 : 1.7 : 0.4$) may reflect either more complicated nuclear structure or reaction mechanism.

The low pion energy of this experiment allows us to make a meaningful comparison with the results obtained from pionic atoms for the ^{6}Li ground state as we did earlier with the reaction $^3\mathrm{He}(p,\pi^+)^4\mathrm{He}$.[8] In terms of a center-of-mass amplitude f and momentum k the unpolarized pion production cross section is

$$d\sigma(^3\mathrm{He} + {}^3\mathrm{He} \to \pi^+ + {}^6\mathrm{Li})/d\Omega = 3(k_\pi/k_{^3\mathrm{He}})\langle |f^2| \rangle, \tag{2}$$

where the angular brackets denote averaging over the ^{3}He and ^{6}Li spins. At threshold, where $l_\pi = 0$, only one of the four spin-dependent elastic π-^{6}Li scattering amplitudes survives, and the imaginary part of that is given completely by the optical theorem in terms of the ^{6}Li total absorption cross section:

$$k_\pi \sigma(\pi + {}^6\mathrm{Li} \to \text{absorption}) \xrightarrow[k_\pi \to 0]{} 4\pi \,\mathrm{Im}(f_{\pi\mathrm{Li}\to\pi\mathrm{Li}}). \tag{3}$$

The left-hand side remains finite in this limit since the absorption cross section diverges like $1/k_\pi$. The right-hand side may be estimated from pionic atom shifts and widths,[11]

$$\mathrm{Im}(f_{\pi\mathrm{Li}\to\pi\mathrm{Li}}) = 0.055 \pm 0.003 \text{ fm}. \tag{4}$$

The branching ratio of the decay of the pionic atom into the tt channel[12] is $(3.4 \pm 0.5) \times 10^{-4}$. However, though the tt configuration originates essentially only from an s-wave pionic atom,[13] the s state represents only 0.4 ± 0.09 of the total decay rate into all channels.[14] Hence the branching ratio for the s-state decay into two tritons compared to all s-state decays is

$$B = (8.5 \pm 2.3) \times 10^{-4}. \tag{5}$$

As a consequence the tt production rate is

$$k_\pi \sigma(\pi + {}^6\mathrm{Li} \to t + t) = 4\pi B \,\mathrm{Im}(f_{\pi\,\mathrm{Li}\to\pi\,\mathrm{Li}}). \tag{6}$$

At threshold there is no angular dependence of the differential cross section so that it is easy to deduce from this relation the $tt \to {}^6\mathrm{Li}$ average amplitude as defined by Eq. (2). Using detailed balance and noting the identical nature of the ^{3}He particles we obtain

$$\langle |f^2| \rangle_{k_\pi = 0} = (B/2k_t)\,\mathrm{Im}(f_{\pi\,\mathrm{Li}\to\pi\,\mathrm{Li}}), \tag{7a}$$

$$= (7.8 \pm 2.2) \times 10^{-6}\ \mathrm{fm}^2, \tag{7b}$$

where k_t is the triton momentum.

Our data at a laboratory angle of 20° yield

$$\langle |f^2| \rangle = \begin{cases} (6.8 \pm 0.6) \times 10^{-6}\ \mathrm{fm}^2 \ \text{ at } 268.5\ \mathrm{MeV}, & \text{(8a)} \\ (7.7 \pm 0.5) \times 10^{-6}\ \mathrm{fm}^2 \ \text{ at } 282\ \mathrm{MeV}. & \text{(8b)} \end{cases}$$

Corrections for the Coulomb damping of the pion flux at the edge of the nucleus[15] should increase (8a) by about 12% and (8b) by 8%. These Coulomb-corrected results are impressively close to the threshold value of Eq. (7b), which corresponds to a ^{3}He kinetic energy of 251 MeV.

Previous experiments with ^{3}He beams were not able to resolve discrete peaks of the final nuclear states. This is not surprising in the case of Wall, Craig, and Enrow[7] who detected two photons from the reaction $^{12}\mathrm{C}(^3\mathrm{He},\pi^0)$. The energies of the produced pions were similar to the ones reported here, but their inclusive cross section $d^2\sigma/d\Omega\, dE_\pi$, of a few picobarns per steradian per megaelectronvolt, is about three orders of magnitude smaller than ours. This must reflect the increased target complexity. The CERN experiment[6] on $^6\mathrm{Li}(^3\mathrm{He},\pi^-)$ was carried out at a much higher energy (900 MeV) and, though they found events in the region of the discrete states of ^{9}C, the inclusive cross section there was in the similar picobarn level. The reduction compared to our results could be ascribed to the heavier target and the higher pion energy, and hence larger momentum transfer.

There is evidence for a decline of the two-nucleon transfer pion production cross section with energy from (d,π) reactions. The Saturne measurements[5] of $^6\mathrm{Li}(d,\pi^-)^8\mathrm{B}$ indicate a cross section for the production of the ground state of about 500 pb/sr for 300-MeV deuterons, but almost an order of magnitude less for 600 MeV. Similar reactions have been measured at Los Alamos[4] with pion beams. Thus, $^{12}\mathrm{C}(\pi^+,d)^{10}\mathrm{C}^*(2^+)$ at 50 MeV yields a cross section equivalent to 1 nb/sr for the inverse (d,π^+) reaction at $T_d \sim 200$ MeV.

Large-angle pion production by $^3\mathrm{He}(p,\pi^+)^4\mathrm{He}$ also shows a steady falloff with energy in what is essentially the three-nucleon transfer region.[8-16] At threshold, the average squared matrix element is two orders of magnitude greater than that determined for the ^{3}He-induced production described in this Letter. This seems to be understandable in terms of a theoretical model[17] where a pion is absorbed on an α particle inside ^{6}Li yielding one ^{3}He, a second one being formed in a final-state interaction.

In summary, the measurements of $^3\mathrm{He}(^3\mathrm{He},\pi^+)^6\mathrm{Li}$ have given surprisingly high cross-section values in the near-threshold region. From the comparison with the scarce existing results and first theoretical approaches,[17,18] it seems likely that coherent pion production by composite particles is maximal somewhere in the near-threshold region. To progress we plan to extend the present experiments to higher energies and heavier targets and also to exploit the ^{4}He beams which are available at Orsay.

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Influence of Shell Structure on Neutron and Proton Exchange in the Reactions of ^{144}Sm on ^{144}Sm and ^{154}Sm on ^{154}Sm

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The reactions of ^{144}Sm on ^{144}Sm and ^{154}Sm on ^{154}Sm have been studied at energies 30% in excess of the barrier. Whereas the number of exchanges nucleons is similar in both reactions, the number of exchanged protons is considerably larger at small energy losses in the ^{144}Sm system. On the basis of the shell-corrected liquid-drop potential energy surface these observations are attributed to the closed $N = 82$ neutron shell which, for ^{144}Sm, hinders the neutron exchange and leads to a preferential transfer of protons.

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Among the different reactions between complex nuclei the completely damped or deep-inelastic collisions have been studied most intensively. A problem of special interest is the microscopic mechanism responsible for the energy dissipation and for mass and charge transport between the colliding ions, respectively. In this context, systematic studies analyzing the increase of the variance σ_Z^2 of the element distributions as a function of the loss of total kinetic energy (TKEL) have been shown to be particularly instructive. In the earlier data reviewed by Schröder and Huizenga[1] σ_Z^2 appeared to be rather similar for different systems at not too large TKEL. Later results for the U+U system,[2,3] however, showed a much larger variance at given energy loss indicating a smaller average energy loss per exchanged proton. In contrast, in the Pb-Pb system[4] comparatively small σ_Z^2 values are observed. It has been suggested[3,4] that these differences might be due to the shell structure of target and projectile; the different TKEL versus σ_Z^2 curves, in fact, have been explained by means of a structure term which is connected with an average binding energy of the valence nucleons.[5] The general influence of the shell structure on the energy-loss mechanism has been worked out recently by Dakowski, Gobbi, and Nörenberg.[6]

The data mentioned so far do not contain any information on the mass variances σ_A^2. However, in order to prove a possibly existing influence of structure effects on the diffusion process it seems necessary to measure also the nuclear-mass distribution. The independent study of the transfer of neutrons and protons and their correlation then might shed some light onto the origin of such a correlation. At present a few data for simultaneously determined σ_Z^2 and σ_A^2 values[7-10] are available, which allow one to deduce a correlation coefficient.

In this Letter we present results of a study of the ^{144}Sm + ^{144}Sm and ^{154}Sm + ^{154}Sm systems at energies 30% in excess of the barrier (beam energies of 1000 and 970 MeV, respectively). The choice of identical reaction partners precludes any drift. The two systems with the same atomic

