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^{3}He PRODUCTION IN ^{4}He FRAGMENTATION ON PROTONS AT 6.85 GeV/c

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Abstract: The angular distribution of the inclusive reaction ^{4}He+p → ^{3}He+X was measured with 6.85 GeV/c incident alphas. At large angles, the observed kinematics corresponds to the elastic scattering on the target proton of an ^{3}He present in the incoming ^{4}He, the remaining neutron being a spectator. This shows the presence of an important component of ^{3}He in ^{4}He. The integrated cross section for ^{3}He production is $\sigma_{^3\text{He}} = 24.1 \pm 1.9$ mb.

1. Introduction

The measurement of ^{3}He production in the α-p interaction is of twofold interest:

(a) It allows the study of the fragmentation process in the simple case of a light nucleus. Furthermore, one hopes to gain access to the presence probability of ^{3}He (or ^{3}H) in ^{4}He (spectroscopic factor).

(b) The study of the ^{3}He inclusive production in the range of 1 GeV/nucleon, where the cosmic ray flux has its peak, is of considerable interest for astrophysics. In cosmic rays, the ^{3}He abundance is considerably higher (^{3}He/H ≈ 10^{-2}) than in ordinary galactic matter (^{3}He/H ≈ 2×10^{-5}). This overabundance is attributed to the break-up of ^{4}He by interstellar gas; hence, the knowledge of the cross section

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for this reaction will allow an evaluation of the amount of interstellar hydrogen typically traversed by the cosmic ray ^{4}He nuclei before escaping from the galaxy [1,2]).

Furthermore, it has recently been proposed that in the center of the galaxy, the whole of the deuterium and ^{3}He in the ordinary interstellar gas could result from spallation of interstellar ^{4}He by cosmic ray protons [3]).

However, this reaction has been little studied because in the p-^{4}He mode it requires the detection of very low energy nuclei that are unlikely to get out of the target. The ^{4}He-p mode is much more favorable, as the break-up products are emitted with large energies. But until recently, no intense ^{4}He beam of a few GeV/c was available.

2. Experimental set-up

The acceleration of alphas in the synchrotron Saturne made it possible for us to measure with precision the differential cross section for the inclusive reaction $\alpha + p \rightarrow {}^3He + X$. This was part of a systematic exploration of the α-p interaction [4-6]).

We have used an external beam of 2×10^{10} alphas per pulse (15 cycles/min) at 6.85 GeV/c. For comparison, this is equivalent to protons incident on a helium

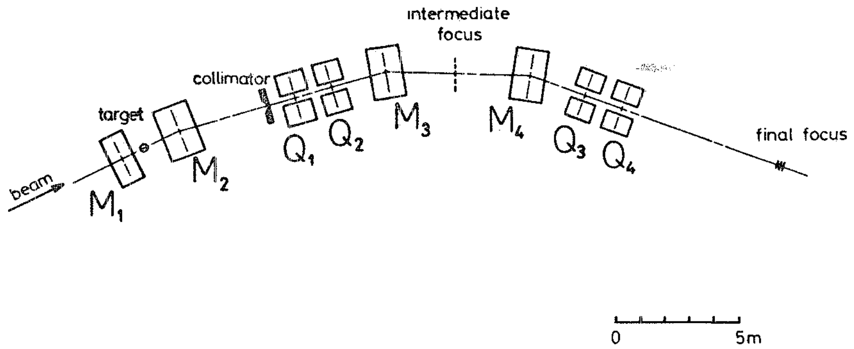

Fig. 1a. Schematic lay-out of the spectrometer in the 0° case. Lateral dimensions of the beam elements have been exaggerated for clarity.

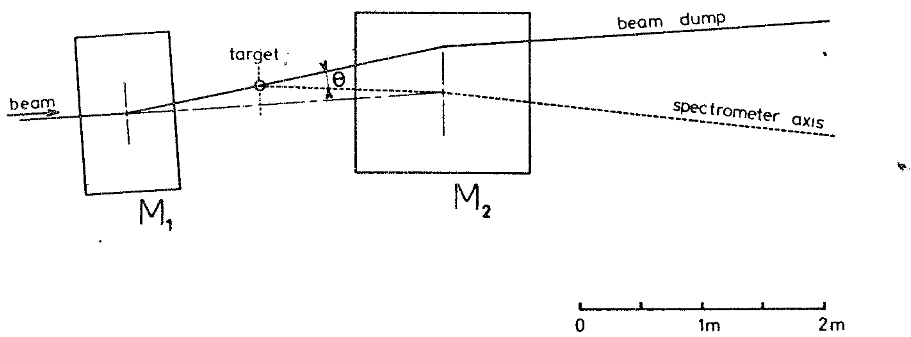

Fig. 1b. Details of the target area when a non-zero scattering angle θ is measured. Lateral dimensions of the beam elements have been exaggerated for clarity.

target with a momentum of 6.85/4 = 1.71 GeV/c (or a kinetic energy of 1.02 GeV).

The α-beam is focussed onto a 5.9 cm long liquid hydrogen target. The beam spot is approximately 2 cm wide by 1 cm high. The absolute intensity is obtained by measuring the production of ^{11}C in a graphite target by the known reaction ^{12}C(α, X)^{11}C [ref. [7]]. This method allows the measurement of incident α-fluxes with a precision of the order of 5 %.

The secondary particles produced in the hydrogen target are analysed by an achromatic double focussing spectrometer sketched in fig. 1a in its 0° configuration.

Under these conditions, bending magnet M_1 is not energized, and the beam goes straight through onto the target. The bending magnet M_2 separates the higher momentum incident beam from the secondary particles. It steers the latter into an 8 cm × 8 cm aperture defining collimator. The quadrupole pair Q_1-Q_2 serves to form an image of the target on a five counter hodoscope placed downstream of the analyzing magnet M_3.

Each element of the hodoscope is 1 cm wide. This provides an intrinsic resolution $\Delta p/p = 1\,\%$ FWHM, as measured in small angle α-p elastic scattering [5,6].

The secondary particles continue their path through the analyzing magnet M_4 and the quadrupole pair Q_3-Q_4 to be recombined into an achromatic focus 14 m downstream from the hodoscope. There, a set of three scintillation counters completes the detection and identification system. The velocity of the desired particles is ascertained by the 14 m time-of-flight base between the intermediate and final foci. Doubly charged particles are selected by amplitude discrimination in each of the four counters involved.

Along most of their path, the secondary particles travel in vacuum to reduce multiple scattering. A Monte Carlo calculation has shown that the efficiency of the system is flat for $p\beta/Z > 0.4$ GeV/c, where p is the momentum, Z the charge and β the velocity of the detected particle. The acceptance corresponding to the $\pm 0.44°$ angular bite covered by the collimator in front of Q_1 is $\Delta\Omega\Delta p/p = 2.38$ μsr. To insure reproducibility of the spectrometer momentum, the two analyzing magnets M_2 and M_3 are provided with nuclear magnetic resonance gauges.

Fig. 1b shows in detail how scattering at angles other than 0° can be obtained. The target is moved sideways in discrete positions corresponding to $\frac{1}{2}°$ steps in the scattering angle. Magnet M_1 is now energized and its current set to steer the beam onto the new position of the target; this operation is monitored by multiwire ionization chambers located upstream of M_1 and in front of the target housing. The currents in the spectrometer elements are set as in the 0° case, except for M_2, whose current is reduced by a percentage calculated so as to move the source position by an amount corresponding to the lateral displacement of the target. In fig. 1b, the path of particles scattered at an angle θ is indicated by a dashed line, while a solid line shows the fate of the less deflected main beam that gets lost in the beam dump area.

The calibration of the actual angles has been obtained from the positions of the α-p elastic peaks [5,6]) and other two-body reactions. At small angles, where the former method is inaccurate, two additional constraints were used: (a) Sending the main beam through M_2 and into the center of the collimator in front of Q_1. This sets the conditions corresponding to the true 0°. (b) Checking the consistency for cross sections measured at small negative angles as well as positive ones. This was done for the present reaction and for the triton charge exchange reaction $^3H+p \rightarrow {}^3He+n$ [ref. [8])].

Due to the fact that only the central hodoscope element is truly located at the focus, and because of other optical aberrations, efficiency corrections have to be made. The efficiency coefficients are determined by taking overlapping data on a smooth momentum spectrum.

3. Results

Momentum spectra of ^{3}He were measured in the angular interval from 0 to 11°. Their general shape looks like a wide peak centered at about three-quarters of the incident momentum (see figs. 2a to e) suggesting a quasi-two-body reaction broadened by the Fermi momentum of ^{3}He in ^{4}He. The positions of the maxima of the spectra change, however, with the angle of observation, as displayed in fig. 3. This behavior, where nuclear fragments have about the same momentum per nucleon as the projectile, has been observed earlier in similar reactions with heavy ions [9]).

Except in one instance, no attempt was made to detect the narrow peak expected at the upper end of the spectra from the reaction $\alpha+p \rightarrow {}^3He+d$. Our only measurement at this energy, at a lab angle of 6.02°, yields a cross section $d\sigma/d\Omega_{lab} = 7 \pm 1.4$ μb/sr. This is about two orders of magnitude below the levels obtained at 4.0 GeV/c, where a systematic survey has been made [10]). The contribution of this reaction to the inclusive production of ^{3}He is completely negligible.

When the momentum spectra are integrated over all momenta for a given angle, one obtains the angular distribution of the cross section represented in fig. 4 and listed in table 1. To perform the integration, continuity of the shape with angle was used to supplement missing information on the tails of some of the spectra. The errors quoted reflect the uncertainties introduced by this procedure.

By further integrating $d\sigma/d\Omega$, one obtains the cross section for ^{3}He production:

$$\sigma_{^3He} = 24.1 \pm 1.9 \text{ mb}.$$

The error quoted is the quadratic combination of three independent contributions: (a) integration of the momentum spectra, 0.7 mb; (b) ^{4}He beam calibration, 1.2 mb; and (c) uncertainty in the angles, 1.3 mb.

Several studies of p-α interactions at energies comparable to ours can be found in the literature. The experiments of Kozodaev *et al.* [11]) and of Riddiford and Williams [12]) at 630 and 970 MeV made use of a Wilson chamber. The ^{3}He production cross sections that have been deduced therefrom by Meyer [2]) are somewhat higher than ours: 39.9 ± 9 and 35^{+6}_{-10} mb respectively. But for reasons explained in the

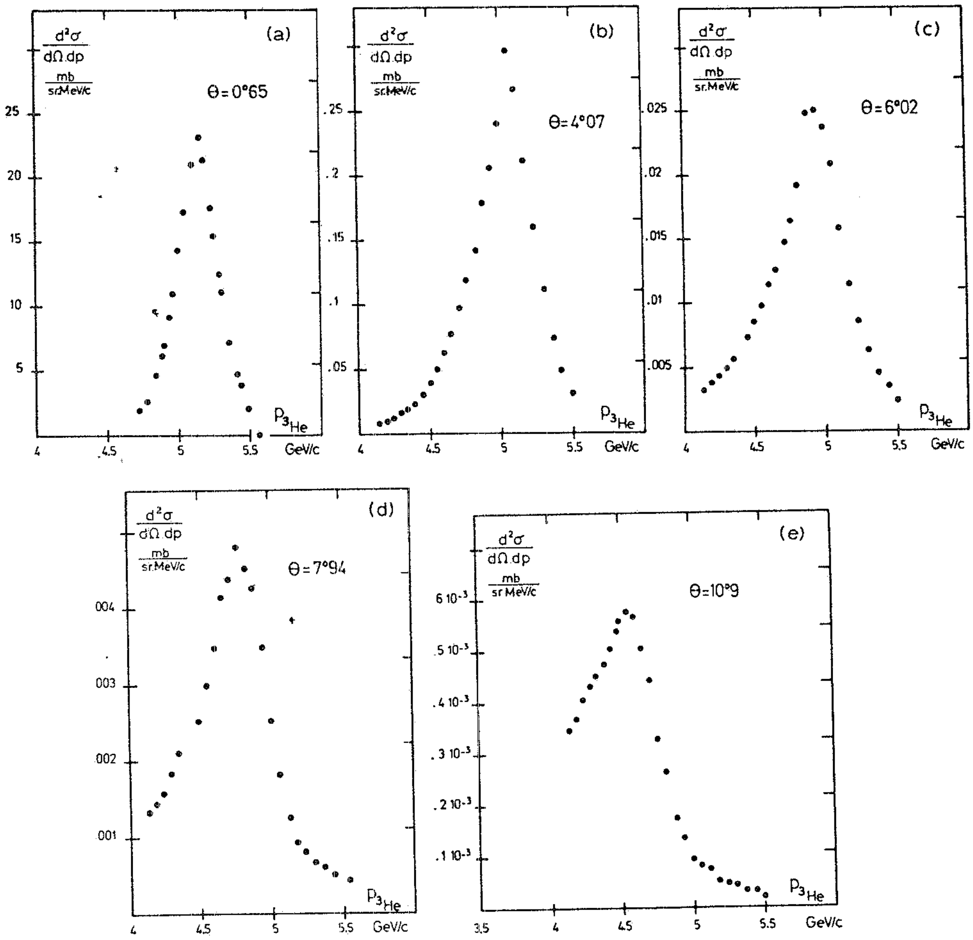

Fig. 2. Some ^{3}He momentum spectra for lab angles of (a) 0.65°, (b) 4.07°, (c) 6.02°, (d) 7.94° and (e) 10.90°. A target-empty effect representing about 10 % has been subtracted.

TABLE 1

Cross sections

θ_{lab} (deg)	$d\sigma/d\Omega$ (mb/sr)	θ_{lab} (deg)	$d\sigma/d\Omega$ (mb/sr)
0.24	$(1.24 \pm 0.08) \times 10^4$	4.07	151 ± 7
0.65	$(8.95 \pm 0.34) \times 10^3$	6.02	15.8 ± 0.3
1.19	$(4.20 \pm 0.29) \times 10^3$	7.94	3.33 ± 0.25
2.15	929 ± 60	10.90	0.62 ± 0.09
3.07	315 ± 39		

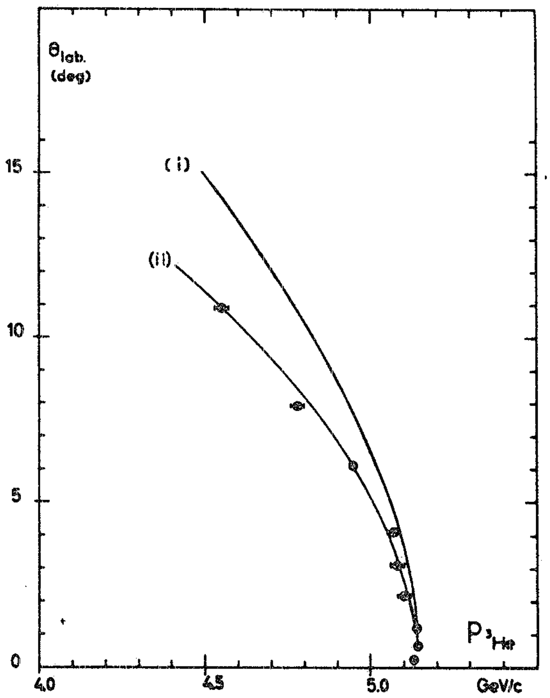

Fig. 3. Experimental ^{3}He peak position as a function of the lab angle, compared with the two hypotheses: (i) Knock-out of a neutron and (ii) elastic ^{3}He-p scattering.

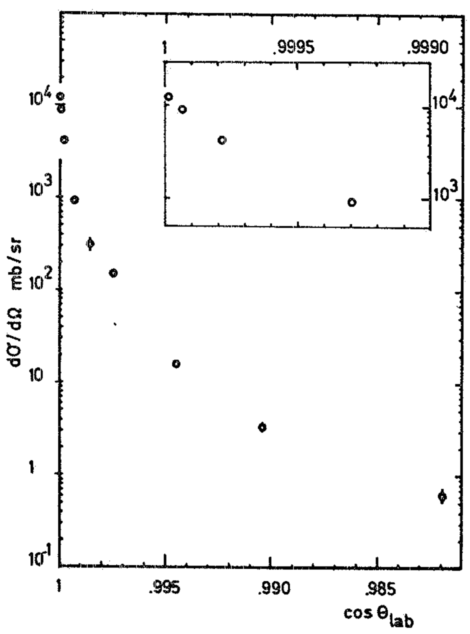

Fig. 4. Differential cross section as a function of the cosine of the lab angle.

introduction, the technique used as well as the poor statistics that ensue did not allow an accurate determination of the cross sections. In ref.[2]), an indirect estimate at higher energy of $\sigma_{^3\text{He}} = 29 \pm 3.6$ mb is deduced from the radio-chemical measurement by Lebowitz and Miller of tritium production by 2.2 GeV protons on ^{4}He.

Our measurement opens the way to a more accurate, and above all more reliable, study of the propagation of ^{4}He nuclei component of the cosmic ray radiation.

4. Discussion

The peak positions of the momentum spectra in fig. 3 can be compared with the following two hypotheses:

(i) Knock-out of a neutron from the incoming alpha by the target proton, the ^{3}He being a spectator. The following argument was used to predict the peak position as a function of angle: At a fixed angle, a given ^{3}He momentum is obtained by transforming some Fermi momentum vector from the c.m. system of the ^{4}He into the lab system. The ^{3}He spectrum in the lab will peak for a value of p_{lab} corresponding to the smallest possible Fermi momentum in the c.m., yielding the highest value for the wave function describing a ^{3}He in the ^{4}He.

(ii) Elastic scattering on the proton target of a ^{3}He with a momentum equal to $\frac{3}{4}$ of the incident one.

At large angles, the agreement of the experiment with the latter hypothesis is striking. Hence, we propose to explain the production mechanism of the reaction $\alpha + p \rightarrow {}^3\text{He} + X$ by the presence of an important component of ^{3}He in ^{4}He.

At small angles, no information can be gained from the positions of the peaks, since the two kinematics are indiscernable. At 0° in the lab, our data extrapolate to 16 b/sr; on the other hand, the p-^{3}He elastic cross sections measured at SPES I [ref. [14])] with 1.05 GeV protons (our data correspond to 1.02 GeV) extrapolate to 8 b/sr at 0°. This indicates that both processes (i) and (ii) contribute at small angles.

It is worth noting also that if we add our integrated cross section of 24.1 mb for the inclusive production of ^{3}He and an estimate for tritium production evaluated according to ref. [2]) as $\sigma_{^3\text{H}} = (\sigma_{pp}/\sigma_{pn})\sigma_{^3\text{He}} = 28.8$ mb, we reach 52.9 mb for these two related cross sections. This is a substantial fraction of the reaction cross section for p-^{4}He given by Igo *et al.* [15]) of $\sigma_R = 111 \pm 10$ mb.

Setting the spectroscopic factor equal to one, Bizard and Tekou [16]) have made a calculation based on Glauber multiple scattering theory, taking as elementary amplitudes the two aforesaid mechanisms. Their results are in qualitative agreement with the observed momentum distributions.

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