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EXPERIMENTAL STUDY OF π^- DOUBLE CHARGE EXCHANGE WITH ^{7}Li

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Abstract: We have observed 150 double charge exchange events, $\pi^- + {}^7\text{Li} \rightarrow \pi^+ +$ anything, at an incident π^- lab kinetic energy of 102 MeV. The π^+ were recorded in an emulsion stack at 30° to the incident π^- beam. No significant peak due to the hypothetical reaction $\pi^- + {}^7\text{Li} \rightarrow \pi^+ + {}^7\text{H(g.s.)}$ was observed in the part of the π^+ energy spectrum corresponding to a ^{7}H binding energy between −5 MeV and +25 MeV. Our new upper limit for the corresponding differential cross section is 1.0×10^{-31} cm^2/sr (90% C.L.). The π^+ spectrum was recorded down to low energies (20 MeV < E_{π^+} < 100 MeV); its shape implies a strong final-state interaction among the π^+, the proton and the six neutrons. The differential double charge exchange cross section integrated over all π^+ energies was determined as $(\mathrm{d}\sigma/\mathrm{d}\Omega)_{\text{tot}} = (4.2 \pm 1.7) \times 10^{-30}$ cm^2/sr.

1. Introduction

The double charge exchange reaction of pions, i.e., $\pi^\pm + (Z, A) \rightarrow \pi^\mp + (Z \pm 2, A)$, is a good tool for studying nuclear states with proton or neutron excess. In particular, it may be helpful in searching for new nuclei. The feasibility of such experiments has been demonstrated by many groups (see, e.g., refs. [1-10]). As the cross sections for double charge exchange are small (typically 10^{-30} to 10^{-29} cm^2 for a given final nuclear state), experiments of this kind are of special interest if they are carried out at high-current accelerators ("meson factories").

We have performed a study of the reaction

$$\pi^- + {}^7\text{Li} \rightarrow \pi^+ + \text{anything}\,, \tag{1}$$

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in the high-intensity pion channel πE1 [ref. [11])] at SIN. We used stacks of nuclear emulsion plates to detect the π^+ and measure their energy. The preparation and scanning of the emulsion plates was done at the Laboratory of Nuclear Problems at JINR.

One purpose of our study was the search for the possible particle-stable nucleus ^{7}H, i.e. the search for the reaction

$$\pi^- + {}^7\mathrm{Li} \to \pi^+ + {}^7\mathrm{H(g.s.)}\,. \tag{2}$$

The question of the existence of a particle-stable heavy hydrogen isotope ^{7}H arose after the discovery of the isotope ^{8}He [refs. [12,13])] which has the same neutron number. As the π^- energy and the π^+ angle are fixed, reaction (2) would produce a peak in the π^+ energy spectrum, situated near the high-energy end of the continuous π^+ spectrum due to double charge exchange with prompt disintegration of the residual nucleus. This disintegration spectrum was recorded in our experiment down to low π^+ energies.

The stopped π^+ can be detected in the developed emulsion, among the many π^- tracks, because of their characteristic decay $\pi^+ \to \mu^+ + \nu_\mu$ (whereas the stopped π^- are captured in nuclei and produce stars). The energy of the π^+ and the π^- is determined by measuring their range in the emulsion. The nuclear emulsion technique is suitable for a first experiment because one can record the whole scattered π^- and π^+ energy spectrum simultaneously with a very simple experimental setup.

2. Description of the experiment

Our experimental arrangement is shown in fig. 1. Negative pions from the πE1 channel [11]) pass through a thin multiwire proportional chamber [14]) used to monitor the beam profile. The magnets and collimators of the πE1 channel were set for a central π^- momentum of 200 MeV/c and a momentum bite of 2% FWHM. The beam was focused upon a 0.8 g/cm^2 thick ^{7}Li target oriented as shown in fig. 1. This target was irradiated for three hours with a total of 5×10^{11} negative pions. A stack of 30 nuclear emulsion plates NIKPHI BR-2 (plate dimensions $110\times30\times0.6$ mm^3) was placed at 30° to the beam at a distance of 425 mm from the target center. The emulsion stack was shielded with lead bricks as indicated in fig. 1.

As mentioned in sect. 1, the emulsion plates were used to detect secondary pions of both signs. For test purposes we also irradiated further stacks of emulsion plates after replacing the ^{7}Li target by targets of beryllium and polyethylene.

3. Determination of the incident π^- energy

The π^- elastically scattered from the three targets mentioned above allowed an independent determination of the beam energy and energy spread. The observed π^- range distributions are shown in fig. 2 as solid lines. For all three targets the count of

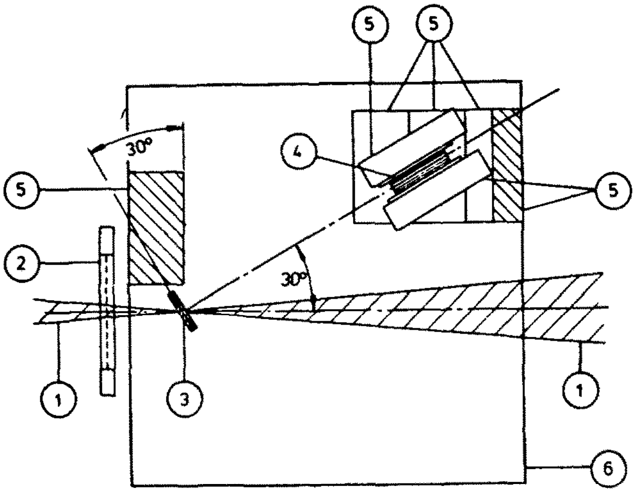

Fig. 1. Experimental arrangement: (1) Incident π^- beam envelope. (2) Multiwire proportional chamber used as beam profile monitor. (3) ^{7}Li target. (4) Stack of nuclear emulsion plates. (5) Lead bricks. (6) Supporting table.

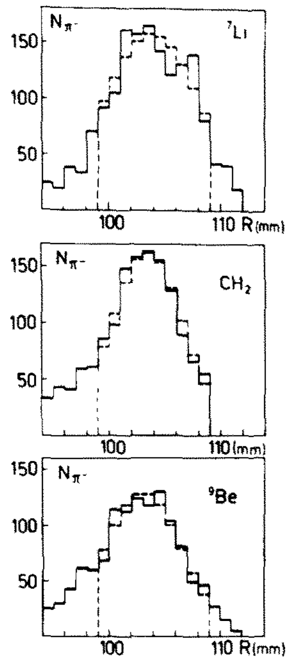

Fig. 2. Distribution of π^- ranges in the nuclear emulsion for the three scattering targets used, in the region of elastic π^- scattering. Solid lines: observed events. Dashed lines: gaussian fits; see text (sect. 3).

scattered π^- was concentrated in the domain of ranges expected for elastic scattering. The experimental π^- range distributions between 99 and 109 mm were approximated by gaussian distributions (dashed lines in fig. 2). In table 1 the mean projected range $\bar{R}$, the observed rms range spread ΔR, the corresponding mean incident π^- energy $\bar{E}_\pi$ and the incident pion rms energy spread ΔE_π are given. In the calculation of $\bar{E}_\pi$ a correction to the projected range and straggling [15]) were taken into account. In the case of ^{7}Li the fit is considerably worse than for the other targets (see table 1), possibly because of inelastic π^- scattering leading to the first excited state of ^{7}Li (excitation energy 0.48 MeV). In the case of polyethylene the contribution from elastic π^- scattering by hydrogen was neglected since the corresponding cross section ($\approx$13 mb) is much smaller than the cross section for elastic π^- scattering by carbon nuclei [16]) ($\approx$280 mb). The resulting incident pion energy, averaged over the three targets, is $\bar{E}_\pi = 99.6$ MeV. The experimental uncertainty of this $\bar{E}_\pi$ value is estimated to be about 2 MeV.

TABLE 1

Results on elastic π^- scattering

Target	$\bar{R}$ (mm)	ΔR (mm)	$\bar{E}_\pi$ (MeV)	ΔE_π (MeV)	χ^2
^{7}Li	103.8	4.4	100.0	2.3	19.7
CH_2	103.4	3.2	99.4	1.2	6.7
^{9}Be	103.0	3.5	99.3	1.5	8.8

The πE1 channel magnet and collimator settings mentioned in sect. 2 lead to a mean beam energy $\bar{E}_\pi = 104.3$ MeV and an rms energy spread $\Delta E_\pi = 1.4$ MeV. In this case, the estimated uncertainty of $\bar{E}_\pi$ is 1 MeV. The value $\Delta E_\pi = 1.4$ MeV agrees well with lines 2 and 3 of table 1; in the case of the first line (^{7}Li target) the emulsion value may be too large because of inelastic π^- scattering, as discussed above.

Our final estimates of the mean π^- energy and rms energy spread upstream of the ^{7}Li target are 102 ± 2 MeV and 1.4 ± 0.2 MeV, respectively.

4. Results for double charge exchange

In scanning the photoemulsion plates irradiated from the ^{7}Li target we found 257 π^+ mesons with ranges from 9 to 119 mm. The interval from 99 to 109 mm was not scanned for π^+ because of the presence of a large background due to stopping π^- mesons elastically scattered by lithium nuclei. In fig. 3 the double differential distribution $d^2N/(dE_\pi\, d\Omega)$ for the observed π^+ mesons is shown. Curve 1 in fig. 3 corresponds to the π^+ energy distribution expected for the reaction

$$\pi^- + {}^7\text{Li} \rightarrow \pi^+ + \text{p} + 6\text{n}\,, \qquad (3)$$

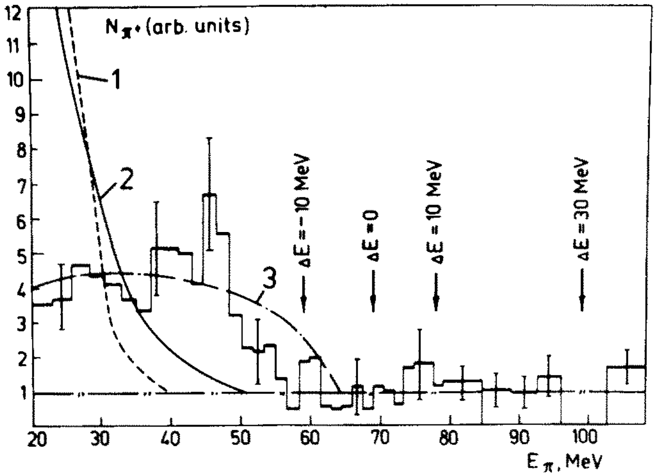

Fig. 3. Histogram with error bars: Distribution of π^+ kinetic energies derived from the observed distribution of π^+ ranges in the emulsion plates irradiated from the ^7Li target; the interval from 96 to 103 MeV was not scanned for π^+ because of a large π^- rate; see text. The horizontal line at an ordinate of 0.95 represents an estimate of the π^+ background not related to the ^7Li target. Vertical arrows indicate binding energies of the hypothetical ^7H ground state; cf. reaction (2). Curves 1, 2 and 3 are phase space predictions based on reactions (3), (4) and (5), respectively.

with all neutrons in the final state unbound. In the calculation a constant matrix element was assumed, i.e., the usual phase space distribution was calculated for a final state consisting of eight particles. Curve 2 in fig. 3 is the expected π^+ energy distribution for the reaction

$$\pi^- + {}^7\mathrm{Li} \rightarrow \pi^+ + {}^3\mathrm{H} + 4\mathrm{n}\,, \tag{4}$$

where the four final neutrons are, as before, assumed to be unbound (the final state consists of six particles). Curve 3 in fig. 3 is for the hypothetical reaction

$$\pi^- + {}^7\mathrm{Li} \rightarrow \pi^+ + {}^3\mathrm{H} + (4\mathrm{n})\,, \tag{5}$$

where now the four neutrons in the final state are assumed to be bound with zero binding energy. All curves in fig. 3 are normalized to the experimental spectrum in the energy interval from 20 to 65 MeV. This normalization was performed after subtraction of a flat (energy-independent) background from the experimental data. This flat background was determined from the events with $E_\pi > 65$ MeV; it is attributed to a π^+ background in the experimental area not related to the ^7Li target. The total background is estimated as 110 events, so we are left with about 150 double charge exchange events. Vertical arrows in fig. 3 correspond to the π^+ energies at which peaks would be expected in the spectrum if bound states of one proton and six neutrons with binding energy ΔE existed; negative values of ΔE correspond to the production of a "virtual" (particle-unstable) excited nuclear state. In the experimental spectrum of fig. 3 there are no significant peaks for $E_\pi > 65$ MeV. If a peak due to ^{7}H production is assumed to be of a gaussian shape with an rms width of 2 MeV (π^+ range straggling and the energy distribution of the incident π^- beam are taken into account), then it is possible to determine, from the data shown in fig. 3, the upper limit of the differential cross section ($d\sigma/d\Omega$) for the production of (p+6n) in bound states with binding energy from 0 to 25 MeV or in narrow excited states with negative "binding energy" from −5 to 0 MeV. Our result is

$$d\sigma/d\Omega < 1.0 \times 10^{-31}\ \mathrm{cm^2/sr}\ (90\%\ \mathrm{C.L.})\,. \tag{6}$$

This upper limit may be compared to the cross sections for other double charge exchange reactions leading to nuclear ground states, e.g.,

$$\pi^+ + {}^{18}\mathrm{O} \to \pi^- + {}^{18}\mathrm{Ne(g.s.)}\,, \tag{7}$$

which has been studied in refs. [7,8,10]. The authors [8]) find a cross section of $(3\pm1)\times 10^{-31}$ cm^2/sr at a π^+ energy of 148 MeV and $(2.1\pm0.8)\times10^{-31}$ cm^2/sr at 187 MeV; the scattering angle was 18° in both cases. At 0° the cross section is much larger [7]); in a recent more complete study of reaction (7) a diffraction minimum of the differential cross section has been observed [10]). It is not impossible that for our reaction (2) at $E_{\pi^-} = 102$ MeV there is a similar diffraction minimum near our angle of 30°. We therefore conclude from our data that the existence of a narrow ^{7}H state with a binding energy between −5 MeV and +25 MeV is rather unlikely but not safely excluded. Our upper limit [eq. (6)] is four times smaller than that of Gilly *et al.* [4]) for the same reaction (2), at 0°, obtained at a fixed secondary π^+ energy of 180 MeV and a variable incident π^- energy (180 MeV $\leq E_{\pi^-} \leq$ 260 MeV).

In the breakup region ($E_\pi < 65$ MeV) the experimental energy spectrum of fig. 3 cannot be explained on the basis of processes with six to eight known non-interacting particles in the final state (curves 1 and 2 in fig. 3). The hypothetical reaction (5), represented by curve 3, gives a fairly good fit to the data, and the same is true for reactions similar to (5) but with five or six neutrons, bound with zero binding energy, plus a deuteron or a proton, in the final state.

We could not determine the π^+ energy spectrum for $E_\pi < 20$ MeV, because the corresponding (upstream) part of the emulsion was too strongly blackened by heavy charged particles. Assuming that the π^+ spectrum in that region ($E_\pi < 20$ MeV) is described by the phase space curve for reaction (5) we obtain

$$(d\sigma/d\Omega)_{\mathrm{tot}} = (4.2\pm1.7)\times10^{-30}\ \mathrm{cm^2/sr} \tag{8}$$

for the differential cross section, integrated over π^+ energies, of reaction (1). The uncertainty of this result (one standard deviation) is mainly due to the estimated uncertainty of the extrapolation to $E_\pi = 0$ discussed above, to the uncertainty of the total number of incident π^- mesons and to the statistical error of the number of counted π^+ mesons.

5. Discussion and outlook

Our experimental data imply an important contribution from the interaction of several nucleons and possibly the π^+ in the final state of reaction (1). This conclusion is not altered by the considerations of ref. [17]) where it is suggested that double charge exchange is described by the diagram of fig. 4. Calculations that we have performed

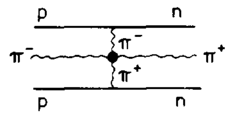

Fig. 4. Basic diagram for double charge exchange of pions discussed in ref. [17]) and used for fig. 5.

with this diagram for reactions (3), (4) and (5) have given π^+ spectra which practically coincide with those calculated over phase space. The results are shown in fig. 5; the curves are seen to be very similar to the results of the corresponding phase space calculations (fig. 3).

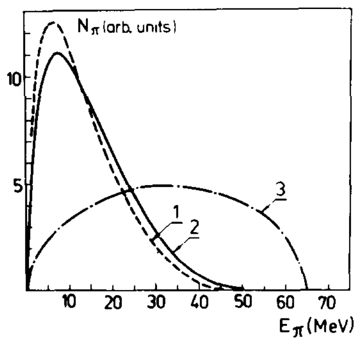

Fig. 5. Same as fig. 3; theoretical predictions based on ref. [17]). For curves 1, 2, 3; see caption to fig. 3.

Curve 3 of fig. 3 and fig. 5 corresponds to reaction (5). As mentioned in the previous section, other reactions give a similarly good fit, if there are three particles or resonances in the final state. The corresponding general diagram is shown in fig. 6.

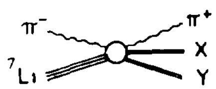

Fig. 6. Diagram for double charge exchange with two nucleon clusters X and Y.

Here X and Y are nucleon clusters. In order to test, e.g., reaction (5), an experiment in which coincidences of π^+ and ^{3}H are recorded, ought to be carried out. Besides, the systems $\pi^+ + \mathrm{p}$ or $\pi^+ + {}^3\mathrm{H}$ could be detected and used for missing mass spectra. The presence of lines in such spectra would indicate the existence of a group of correlated neutrons.

An alternative explanation of our experimental π^+ spectrum is based on the hypothesis that a three-particle resonance πNN with isospin component $T_Z = 0$ is formed with large probability in nuclei. Then the process occurs according to the diagram of fig. 7. During the lifetime of the resonance B the remaining nucleons scatter and the π^+ spectrum again corresponds to a three-particle final state (π^+nn).

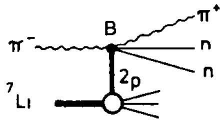

Fig. 7. Diagram with a resonance B of two nucleons and a pion.

Refs. [18,19]) contain indications of a strong attraction and even of a resonance arising in the system $N+\Delta_{33}$ in the state with $J^\pi = 2^+$ and $T = 2$. If this resonance contributes to the double charge exchange on ^{7}Li, then one may expect that the process on ^{6}Li will produce the same spectrum of π^+ mesons as on ^{7}Li. Also, this πNN resonance model can be tested by investigating the dependence of the π^+ spectrum on the incident π^- energy.

Finally it should be noted that our data (fig. 3) contain possible evidence for a broad excited state of ^{7}H at an excitation energy of about 25 MeV ($\Delta E = -25$ MeV). A further study of this energy region with improved statistics would help to clarify this.

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References

1) Yu.A. Batusov *et al.* JETP (Sov. Phys.) **46** (1964) 817
2) Yu.A. Batusov *et al.* JINR P1-3248, Dubna, 1967
3) J. Sperinde *et al.* Phys. Lett., **32B** (1970) 185
4) L. Gilly *et al.* Phys. Lett., **19** (1965) 335
5) P.E. Boynton *et al.* Phys. Rev. **174** (1968) 1083
6) D. Chultem *et al.* Nucl. Phys. **A316** (1979) 290
7) T. Marks *et al.* Phys. Rev. Lett., **38** (1977) 149
8) R. Corfu *et al.* Phys. Lett., **69B** (1977) 301
9) K.K. Seth *et al.* Phys. Rev. Lett., **41** (1978) 1589
10) K.K. Seth *et al.* Phys. Rev. Lett., **43** (1979) 1574
11) R. Frosch and P. Funk. SIN report TM-30-15 (1974)
12) Yu.A. Batusov *et al.* Phys. Lett. **22** (1966) 487
13) A.M. Poskanzer *et al.* Phys. Rev. Lett. **17** (1966) 1271
14) G.H. Eaton and F. Pozar. SIN report TM-33-02 (1975)

15) C.F. Powell, P.H. Fowler and D.H. Perkins, The study of elementary particles by the photographic method (Pergamon, London, 1959)
16) V.S. Barashenkov *et al.* JINR P2-4520, Dubna, 1969
17) J.F. Germond and C. Wilkin. Nuovo Cim. Lett. **13** (1975) 605
18) H. Arenhövel, Nucl. Phys. **A247** (1975) 475
19) V.B. Belyaev, K. Moller and Yu.A. Simonov. J. Phys. **G5** (1979) 1057