SINGLE-NEUTRON EMISSION INDUCED BY STOPPED π^- IN 1p-SHELL NUCLEI^{*})

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ABSTRACT

A search for the (π^- ,n) reaction on ^6Li , ^7Li , ^9Be , ^{10}B , ^{12}C , and ^{14}N has been made via a careful investigation of the high-energy part of the π^- -induced neutron spectra. In the case of ^6Li , ^7Li , and ^{12}C , distinct peaks could be observed, corresponding to a single neutron emission rate of 2×10^{-3} per stopped pion. The observed rate is compared with other pion-induced single-nucleon reactions and their inverses.

Nuclear reactions (π^- ,n) on ^6Li , ^7Li , ^9Be , ^{10}B , ^{12}C ,
and ^{14}N ; $E = 0$; measured rate E_n .

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1. INTRODUCTION

The process of non-radiative single-neutron emission following the absorption of stopped negative pions in complex nuclei has been the focus of strong interest during the last two decades. Assuming a single-nucleon mechanism without distortion effects, this reaction was expected to probe the high-momentum components of the nuclear wave function and to give access to one-hole states in the residual nucleus as well. In this picture the reaction should be strongly suppressed. LeTourneux¹⁾ reported a fraction of 10^{-4} to 10^{-3} of the total rate for 2P absorption in ^{16}O , according to his calculation. However, also the enhancement of the rates caused by distorted wave effects of the emitted nucleon²⁾ as well as the mechanism of absorption by a correlated pair, where one nucleon is "trapped" by the nucleus³⁾, was already considered a long time ago.

Despite this early interest, the (π^-, n) process has not been confirmed experimentally for nuclei heavier than helium^{4, 5)}. Only the (π^+, p) reaction, which offers better experimental conditions, has been observed in several studies⁶⁻⁹⁾. Owing to charge symmetry, the latter type of reaction should have strong similarities. The same is also true for the inverse reaction (p, π^+) , which has been extensively studied experimentally as well as theoretically in the last few years. Both these reactions showed cross-sections which are too big to be explained with a single-nucleon mechanism and plane-wave description of the pion and the proton¹⁰⁾. Distorted waves or a two-nucleon mechanism have to be considered in order to find a satisfactory description¹¹⁾.

One difference between the reactions involving π^+ and π^- should be kept in mind. The π^+ reactions cannot be performed with zero pion momentum as in the case of stopped π^- . As a consequence, the energy momentum mismatch, one of the most important features of (π, N) reactions and their inverse, is less pronounced in experiments involving positive pions.

Very recently the (π^-, n) reaction has been discussed as an indicator for a possible pion condensate in nuclei¹²⁾. In these considerations the pions from the condensate contribute to the momentum balance of the absorption process and

allow pion absorption on a single nucleon^{13,14)}. With this idea in mind, experimental research, which was made with an activation measurement on an ¹⁸¹Ta target, showed no positive evidence and gave an upper limit of 10^{-5} for the corresponding (π^- ,n) reaction¹⁵⁾. In the present paper an experimental study of this reaction on six nuclei of the 1p-shell is reported.

2. EXPERIMENT

We have investigated the energy spectra of fast neutrons emitted after the absorption of stopped π^- mesons, thus measuring the inclusive reaction ${}^Z_A(\pi^-, n){}^{Z-1}_{N-1}B + \text{anything}$. The measurements were performed at the CERN Synchrocyclotron (SC) in parallel with an experiment which investigated the reaction ${}^Z_A(\pi^-, 2n){}^{Z-1}_{N-2}B$. The details of the apparatus and the latter experiment are described elsewhere¹⁶⁾.

Thick targets of 3-5 g/cm² of ⁶Li, ⁷Li, ⁹Be, ¹⁰B, ¹²C, and ¹⁴N have been used. The outgoing neutrons were detected with a large-area, position-sensitive, time-of-flight counter placed 5.8 m from the target. The sensitive volume of the neutron counter was 2 m wide $\times$ 48 cm high $\times$ 9 cm thick, thus covering a solid angle of ~ 25 msr. In order to determine the exact length of the neutron time-of-flight path, the counter was subdivided into eight layers of scintillators in height and six layers of scintillators in depth. In total, it consisted of 48 rods (6 cm height $\times$ 1.5 cm depth $\times$ 2 m length) made of NE 110 plastic scintillator. A total of 30 small phototubes (Philips 1110) showed the pattern of the rods that have given a signal for each event. The rods were assembled into eight bundles. Each bundle was viewed by two 56 DVP photomultipliers, one at each end. The position information along the counter was taken from the time difference between these two photomultiplier signals. This time difference, the time-of-flight information taken between one side of the counter and the pion stop-signal, the pattern information from the small tubes, as well as the pulse heights on both sides, were written on tape event by event.

The pion stop-trigger was obtained from a telescope with standard (1, 2, 3, $\bar{4}$) logic. Counter 2 was used as the start counter for the time of flight. The time resolution of this counter was 300 psec for 2 MeV pulses. The degrader was placed between counters 2 and 3 and the target between counters 3 and 4. The pulse height of counter 3 was used to determine the pion range in the target along the beam direction. A hodoscope with four fingers of 2 cm width each, was placed in front of the target to determine the stopping point in the target in the horizontal direction. An additional thin counter (0.5 mm thickness) between the hodoscope and the target enabled us to reject those pions which stopped in the hodoscope. The stopping-point information was used together with the position information from the neutron counter to determine the path length of the neutron within ± 1.5 cm.

During the measurements reported here, restrictions in time of flight and in pulse height have been made. Only events with a time of flight below 53 ns have been registered, corresponding to a kinetic energy of about 70 MeV. The pulse height was required to be above a threshold of 25 to 35 MeV electron equivalent, depending on the target. The restriction in pulse height was made to improve the time resolution. In the off-line analysis a still higher threshold was applied, as will be described later.

Discrimination against charged particles could be achieved in the off-line analysis by rejecting events which

- a) triggered the first layers of the counters, and
- b) in addition showed a linear relation between pulse height and kinetic energy.

Gammas could be easily identified by their fixed time of flight of 19.3 ns for 5.8 m distance. They were used as calibration for the time-of-flight zero. In addition, monoenergetic neutrons of 68.0 MeV from the $\pi^- + d \rightarrow 2n$ reaction in a D_2O target could be used for energy calibration. Consistency checks of our calibration have also been made using well-identified peaks in the missing-mass spectrum observed in the $(\pi^-, 2n)$ reaction which has been measured in parallel. The energy resolution was about 4 MeV in the range of 90-120 MeV neutron energy.

The neutron detection efficiency has been calculated according to Kurz¹⁷⁾. In Fig. 1, calculated¹⁸⁾ efficiency curves are shown for different thresholds. During the off-line analysis these thresholds have been applied to the geometrical mean between the pulse heights on both sides of the counter. This threshold has always been chosen to be higher than the effective hardware threshold given by the electronics.

Owing to light attenuation in the scintillator rods, the effective hardware threshold is dependent upon the position of the interaction vertex in the counter. In order to be sure that during the off-line analysis the software threshold was set high enough, the uniformity of the position-distribution along the counter has been checked. A uniform position-distribution proved at the same time the non-existence of any anisotropic background. Since the hardware threshold has been changed for different targets, the height of the software threshold varied between 30 and 40 MeV electron equivalent. A further increase of the software threshold by 10 MeV did not noticeably change the corrected spectra or the absolute rates.

Figure 2 shows part of a typical time-of-flight spectrum obtained with a ${}^6\text{Li}$ target. The prompt peak at the left and the sudden rise of the neutron spectrum at the right are clearly visible. The region in between shows a fairly constant rate, which can be attributed to accidental coincidences between the stop-signal and the neutron counter. The number of these accidental counts is, however, relatively small. This can be seen better in the corresponding energy spectrum in Fig. 3. As the ratio dt/dE as well as the efficiency changes only slowly (dt/dE decreases by 2.6% between 100 MeV and 120 MeV), the chance coincidences remain almost on a straight line with a very small negative declination as a function of energy.

Another source of background is the neutrons from the $(\pi^-, 2n)$ reaction. The shape of the corresponding energy spectrum leading to a definite state in the residual nucleus ($A - 2$) should correspond to the three-body phase-space density, provided the transition matrix element does not change strongly in this limited energy range. In Fig. 3 such phase-space density distributions¹⁹⁾ are shown as

examples. The experimental resolution has been folded in. Only the heights of the curves have been arbitrarily adjusted in order to give optimal fits to the experimental curves. It is important to notice that according to these curves, background from $(\pi^-, 2n)$ reactions cannot produce peaks in the spectrum. Similar considerations hold for neutrons from (π^-, np) reactions, which however are known to occur with rates of about a factor of 3 to 10 smaller. Also, reactions with more than two emitted nucleons, which might become important at lower neutron energies, produce a continuous background in the neutron spectra. This situation is similar for all targets.

In principle there is also a neutron background from ^{12}C which is produced by pions which have been absorbed in the scintillator material of the telescope, especially of counter 4. The number of these pions should, however, be below 5% compared with the number of stops in the target. Assuming comparable yields of the (π, n) reaction from the target nuclei and ^{12}C , the corresponding background should also be in the percent region. Moreover, the neutrons from the $(\pi^-, 2n)$ reaction in ^{12}C are below 100 MeV and thus below the observed structures discussed here.

3. RESULTS

In Figs. 3-8 neutron spectra obtained by stopped negative pions on various lp-shell nuclei are shown. Absolute rates per MeV and stopped pion are given. Only statistical errors are indicated.

^6Li spectrum (Fig. 3)

A broad peak at 110 MeV is visible, which can be attributed to transitions to the ground state of ^5He . Since the $(\pi^-, 2n)$ channel opens at about the same energy, a continuous contribution from this reaction type can occur in the energy range of the peak. The expected shape of the contribution corresponding to transitions to the ground state of ^4He calculated with the three-body phase-space density, as well as the contributions leading to an excited state in ^4He around 20 MeV, are also shown. The population of both these states have been observed in our $(\pi^-, 2n)$ measurement. The transitions to the excited states show a broader recoil momentum

distribution, which should be less restrictive for extreme unequal energy-sharing between the two neutrons. The calculated distributions together with the background from chance coincidences (which is also shown) explain the measured spectrum, at least qualitatively. A small population of the very broad state in ${}^5\text{He}$ at 4 MeV can, however, not be excluded.

A comparison with data from $(p,2p) {}^{20-22)}$ and high-energy $(\gamma,p) {}^{23)}$ measurements shows that apart from excitations at 16-20 MeV, only the ground state of ${}^5\text{He}$ is strongly populated in these reactions.

${}^7\text{Li}$ spectrum (Fig. 4)

The spectrum is similar to that of ${}^6\text{Li}$ and shows a peak at 109 MeV which corresponds to the population of the ground state and 1.8 MeV first excited state in ${}^6\text{He}$. The $(\pi^-,2n)$ threshold is only 1.6 MeV higher and corresponds to 107.4 MeV neutron energy. Also in $(p,2p) {}^{20,21)}$ and $(\gamma,p) {}^{23)}$ reactions a peak at lower excitation energies has been observed, which has been attributed to the ground state and the 1.8 MeV state in ${}^6\text{He}$.

${}^9\text{Be}$ spectrum (Fig. 5)

A shoulder has been observed which seems to have a contribution from the ground state of ${}^8\text{Li}$. The $(\pi^-,2n)$ threshold corresponds to a neutron energy, which is too low to explain the observed shoulder alone. Contributions from the 0.9 MeV and 2.2 MeV states in ${}^8\text{Li}$ can of course not be excluded. It is interesting to notice that the $(p,2p) {}^{20,21)}$ reaction, and also the $(\gamma,p) {}^{23)}$ reaction populate a low-lying state, very likely the ground state.

${}^{10}\text{B}$ spectrum (Fig. 6)

The spectrum extends to relatively high energies. In fact the (π^-,n) as well as the $(\pi^-,2n)$ reaction can produce rather high neutron energies up to 117.7 MeV and 116.2 MeV, respectively. Owing to the exceptionally small separation energy of the lowest bound neutron in ${}^9\text{Be}$ these two energies are, however, very close and do not allow an identification of the (π^-,n) process on the basis of the neutron energy only. On the other hand, indications of peaks at 108 MeV and 113 MeV could correspond to transitions to excitation energies in ${}^9\text{Be}$ at 4.7 MeV and 7.9 MeV.

Because of the high level density of the ^9Be nucleus, these attributions are however uncertain. The $(p,2p)$ reaction²¹⁾ on this target nucleus shows three peaks corresponding to 0 MeV, 5.3 MeV, and 10.5 MeV excitation energy in ^9Be .

^{12}C spectrum (Fig. 7)

This nucleus is a good candidate for studying the single nucleon emission, in the sense that the (π^-,n) threshold is 11.4 MeV above the $(\pi^-,2n)$ threshold. In fact the spectrum shows a distinct peak at 111 MeV, which corresponds to the ground state in ^{11}B .

Very likely there are more states in ^{11}B above 4 MeV excitation energy that are populated, but which cannot be attributed owing to the high level density in that range.

In $(p,2p)$ ²²⁾ measurements, mainly transitions to the ground state of ^{11}B have been observed in the region of low excitation energies. Also in the (γ,p) ²³⁾ and $(e,e'p)$ ²⁴⁾ reaction a strong peak, which corresponds to the ground-state transition, dominates the excitation spectrum.

^{14}N spectrum (Fig. 8)

This spectrum shows very little structure. An indication of a shoulder at 114 MeV could correspond to the $(\pi^-,2n)$ threshold at 116 MeV neutron energy. Neutrons above this energy can come from the (π^-,n) reaction leading to the ground state of ^{13}C . There is, however, very weak evidence for this transition. From $(p,2p)$ measurements the population of states with 0 MeV, 7.8 MeV, and 12.3 MeV excitation energy in ^{13}C have been reported²⁰⁾.

4. DISCUSSION

Evidence of single-neutron emission has been searched for in the structures at the high-energy tail of the neutron spectra of Figs. 3 to 8. In the case of ^6Li , ^7Li , and ^{12}C a clear peak has been observed. A shoulder is visible in the ^{10}B spectrum, and -- less pronounced -- one in the ^9Be spectrum. Apart from the difference in the Q-values between the respective (π^-,n) and $(\pi^-,2N)$ reactions, the sensitivity of our method is expected to depend also on the spread of the populated levels in the residual nuclei. It should be mentioned in this context, that also

the (p,2p) reaction, for instance, exhibits a simple excitation spectrum with one pronounced peak in the case of ${}^6\text{Li}$, ${}^7\text{Li}$, and ${}^{12}\text{C}$, whereas the spectra from ${}^9\text{Be}$ and ${}^{10}\text{B}$, and even more pronounced from ${}^{14}\text{N}$, reveal increasing complexity²²⁾. The fact that more evidence for single-neutron emission is found in three nuclei could therefore be just a consequence of the nuclear structure and does not exclude the existence of an effect of similar size for the other nuclei studied.

The integrated peak areas in the neutron spectra from the lithium isotopes and from ${}^{12}\text{C}$ all have a similar size of 2×10^{-3} per stopped pion. Also the structures in the spectra of ${}^{10}\text{B}$ and ${}^9\text{Be}$ are compatible with this rate. As our observation does not include transitions into higher excited states, this number has to be considered as lower limit, in principle.

The charge symmetric reaction (π^+ ,p) has been observed for the first time by Witten et al.⁶⁾ in ${}^{12}\text{C}$ with 70 MeV pions. Also Amato et al.⁷⁾ searched for this reaction in ${}^6\text{Li}$, ${}^9\text{Be}$, ${}^{12}\text{C}$, and ${}^{16}\text{O}$ with pions of the same energy. Positive evidence, however, was only found for ${}^6\text{Li}$ and ${}^{12}\text{C}$. Recently, more detailed studies have been made on the reactions ${}^{16}\text{O}(\pi^+,p){}^{15}\text{O}$ ¹⁸⁾ and ${}^{12}\text{C}(\pi^+,p){}^{11}\text{C}$ ⁹⁾ with pions of 60 MeV and 50 MeV, respectively. In the case of ${}^{16}\text{O}$, final states with large one-hole strength have been observed, whereas in the case of ${}^{12}\text{C}$ the strongest transitions lead to states with more complicated configurations. The reported differential cross-sections vary strongly with the lab. angle. No integrated cross-sections have been given.

For ${}^{12}\text{C}$ the integrated cross-section for $0 \leq E_\gamma < \sim 10$ MeV can, however, be estimated from the published data^{6,7,9,25)} to (0.5-1) mb in the range of (50-60) MeV pion energy. No total absorption cross-section is known for this pion energy. At 130 MeV, Belotti et al.²⁶⁾ measured 190 mb for the total absorption in ${}^{12}\text{C}$. Assuming $\sigma_{\text{tot}}(50 \text{ MeV})/\sigma_{\text{tot}}(130 \text{ MeV}) = \sim 1/2$, the single-nucleon emission for 50 MeV π^+ would be $(5-10) \times 10^{-3}$ of the total absorption. This number seems to be somewhat larger than our respective number of 2×10^{-3} for π^- at rest.

It seems also interesting to compare our results with the reaction (π^-,p), which is definitively forbidden in the one-nucleon picture and should therefore show smaller rates. For the reaction ${}^{12}\text{C}(\pi^-,p){}^{11}\text{Be}$, Coupât et al.²⁷⁾ observed a probability of $(4.5 \pm 0.8) \times 10^{-4}$ per stopped pion, which is in fact an order of

magnitude below our (π^-, n) rate. Also the differential cross-sections for (π^-, p) and (π^+, p) on ^{16}O at 45° measured by Bachelier et al.⁸⁾ with π^+ and π^- of 66 MeV differ by an order of magnitude. Finally, it should be mentioned that the ratio of the cross-sections for (p, π^-) and (p, π^+) reactions are also between $1/10$ and $1/20$ ¹¹⁾.

An attempt has been made to attribute the observed structures in our neutron spectra to known levels of the residual nuclei. Although an identification in the strict sense was not possible in general within the present resolution, the observed similarity with $(p, 2p)$ and related reactions suggests to some extent that states with predominant one-hole configuration are populated. Such a result would fit in a naive way with the picture of a single-nucleon mechanism. However, also a degenerated two-nucleon mechanism, where the "trapped" nucleon remains at its old position, must be considered. In fact Schneider²⁸⁾ has found that according to his calculation it is more probable that the stuck nucleon stays below the Fermi level than that it reaches a free position above this level.

Very recently the single-nucleon emission following the absorption of stopped pions has been brought into connection with a possible pion condensate in nuclei. According to Troitskii et al.¹³⁾ such a condensate would increase the probability for single-nucleon emission by a factor 10^2 - 10^3 . Also Pirner¹⁴⁾ found a relation between the amplitude of such a condensate and the single-nucleon emission rate. Assuming the latter to be $(3-6) \times 10^{-3}$ for ^{12}C , he found a pion density due to this condensate of less than $1/500$ of the nuclear density. As the experimental value for the single rate has now turned out to be rather smaller, the corresponding pion density would be further reduced. On such a level the influence from a possible condensate seems to be much smaller than the influence of other mechanisms in pion absorption. One would also expect that effects caused by a pion condensate should increase with A , which seems not to be the case for single-nucleon emission in the range of nuclei studied here.

In conclusion we summarize that we accumulated inclusive (π^- ,n) spectra from six lp-shell nuclei, and that strong evidence for the single-neutron emission is obtained in the cases of ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{10}\text{B}$, and ${}^{12}\text{C}$; the spectrum from ${}^9\text{Be}$ is also consistent with this reaction. A lower limit of 2×10^{-3} /stopped pions is established for the effect on the Li isotopes and ${}^{12}\text{C}$.

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Figure captions

- Fig. 1 : Neutron counter efficiencies for high thresholds T , calculated according to Ref. 3. The resolution ΔT at threshold T , which also enters into the calculation, has been taken as $\Delta T = \frac{1}{2}(T)^{1/2}$. The thresholds are $T = 20, 25, 30, 40$, and 45 MeV for curves A, B, C, D, E, and F, respectively.
- Fig. 2 : Typical TOF spectrum for a ${}^6\text{Li}$ target. It shows the part between the prompt peak and the onset of the neutron spectrum (bin width = 376 ps).
- Fig. 3 : Neutron energy spectrum for a ${}^6\text{Li}$ -target. Background from chance coincidences (dashed-dotted line) and from the $(\pi^-, 2n)$ reaction leading to the ground state and an excited state in ${}^4\text{He}$ around 20 MeV are indicated (dashed and dotted lines). The transition to the ground state of ${}^5\text{He}$ will produce a peak of approximately Gaussian shape (full line).
- Fig. 4 : Neutron energy spectrum from ${}^7\text{Li}$. Threshold 40 MeV.
- Fig. 5 : Neutron energy spectrum from ${}^9\text{Be}$. Threshold 35 MeV.
- Fig. 6 : Neutron energy spectrum from ${}^{10}\text{B}$. Threshold 35 MeV.
- Fig. 7 : Neutron energy spectrum from ${}^{12}\text{C}$. Threshold 35 MeV.
- Fig. 8 : Neutron energy spectrum from ${}^{14}\text{N}$. Threshold 35 MeV.

Fig. 1

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