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Coincidences between neutrons and γ rays emitted by pions stopped in ^{28}Si

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Neutrons from the interaction of π^- at rest in ^{28}Si were measured in coincidence with γ rays which provided the identification of the resulting nuclei. Neutron energy spectra and neutron multiplicities were derived in discrete channels. A comparison is made with the interaction of 70 MeV π^+ with the same target investigated by proton-gamma coincidences. Despite their low detection efficiency, neutrons give information as valuable as protons and are an even better tool in the low-energy region under the experimental conditions. They give access to the study of all the secondary processes of the pion absorption.

[NUCLEAR REACTIONS ^{28}Si(π^-,n_γ), $E_{\pi^-}=0$; ^{28}Si(π^+,p_γ), $E_{\pi^+}=70$ MeV; neutron gamma and proton-gamma coincidences. Neutron and proton energy spectra, neutron and proton multiplicities for residual nuclei. Quasideuteron pion absorption model.]

I. INTRODUCTION

The exact nature of the primary interaction between pions and nuclei is still a matter of controversy. In the case of low energy pions, the absorption on a proton-neutron pair appears to be the dominant process. In the "quasideuteron" model,[1] with or without the formation of a Δ isobar, the total energy of the pion is transferred to the absorbing pair.

There are, however, experimental results in which a primary interaction seems to take place on more than two nucleons, typically on an α cluster.[2] As an example, processes such as $\pi^- + \alpha \to p + 3n$, $d+2n$, and $t+n$ have been given probabilities as large as 40% in the capture of π^- at rest in ^{12}C by means of the detection of 180°-correlated neutrons with deuterons or tritons, and from measurements with emulsions.[3]

In all experiments up to now, it has been difficult to get a clear-cut answer to the question of the possible absorption of pions on more than two nucleons. Instead, the nucleons or target fragments detected from the first step of the interaction are mixed up with those from the subsequent stages of the evolution toward stability of the highly excited nucleus so obtained. More specifically, the direct primary nucleons coming from the absorption of the pion undergo residual interactions, so that additional fast nucleons and light fragments are emitted before an equilibrium is reached. In the last stage, the classical evaporation of low energy particles from the equilibrated residues proceeds.

Experimental observations have dealt either with energy spectra of the emitted nucleons and light fragments, or with mass and charge distributions of the residual nuclei. Up to now, these two kinds of information were investigated separately. The yields of residual nuclei appear to be mostly dominated by the evaporation process and could not bring very reliable information about the primary interaction.[4] Several models of pion absorption were able to explain the overall behavior of mass and charge distributions with nearly equal success and difficulty.[5]

On the other hand, as already mentioned, inclusive energy spectra of nucleons contain yields from the various steps of the interaction: primary, preequilibriun, and evaporation. In the experiments, the most energetic nucleons were assumed to have been emitted in the primary step without any residual interaction. The number of these nucleons per pion interaction (multiplicity) has received much attention.[6] It was hoped that this multiplicity would be greater in the absorption of pions by alpha clusters than in the absorption by nucleon pairs.

Unfortunately, final state interaction induces a distortion of the energy spectra and an increase of the multiplicity since less energetic nucleons are created in the preequilibrium phase. This makes it impossible to separate out the nucleons of the initial absorption.

In order to get more detailed information, it seems necessary to perform more exclusive experiments involving the primary interaction and the subsequent deexcitation process with the intent of distinguishing between the two processes. One step in this direction is the measurement of the emitted protons and neutrons in coincidence with γ rays, allowing the identification of the final nuclides by their characteristic γ-decay lines. In such a semiexclusive experiment, one can expect nucleon energy spectra to be better understood if one knows the end product of the deexcitation chain. Of course, all ambiguities in channel paths are not removed by the mere identification of residual nuclei. However, one can hope to understand, from the differences between the energy spectra of various residues, the different steps of the deexcitation process and thus the primary interaction. For example, as more nucleons are removed from the target nucleus, one can expect the primary stage of the interaction to be washed out by secondary effects during the deexcitation process. On the contrary, neutron spectra in coincidence with A-2 or A-4 residues should give direct access to the mechanism of the π absorption on nucleon pairs or α clusters.

The first results of such a semiexclusive experiment were obtained recently with 70 MeV positive pions, when coincidences were measured between γ rays and fast protons and pions.[7,8] We report here the first data on coincidences between neutrons and γ rays obtained in the interaction of stopped π^- with ^{28}Si. In addition, we make a comparison with proton-gamma coincidences from the interaction of 70 MeV π^+ on the same target taken in an experiment similar to that of Ref. 7. In both measurements, proton and neutron multiplicities are derived for each residual nucleus. As the dominant process for low energy pions is absorption,[4] the proton multiplicities from the π^+ experiment and the neutron multiplicities from the π^- experiment on the same target should give the same information within the limits of the experimental accuracy.

In this respect, it should be noted that the spectra of the less energetic protons measured in the π^+ experiment must be corrected to take into account the energy loss in the thick target, and thus most of the data, given with good confidence, rely on protons of energy higher than 40–50 MeV.

The results reported in this work show that neutrons are as good a tool as protons and suggest they may be even better at low energies under our experimental conditions, i.e., low pion fluxes and thick targets, since no correction due to the target thickness is needed for neutrons.

II. EXPERIMENTAL METHOD

The experiment was performed on the low energy pion channel (PM2) of the 600 MeV Saclay ALS linear accelerator. Neutrons were measured in coincidence with γ rays from the capture of π^- stopped in ^{28}Si. The neutron detector consisted of two sets of four large liquid scintillator counters ($40\times20\times20$ cm) placed at a distance of 1.5 m on both sides of the target. Plastic scintillators were put in front of the liquid scintillators to veto charged particles. Gamma rays were detected with a resolution of 3 keV at 1 MeV in an 80 cm^3 Ge(Li) detector set underneath the target. The latter was a sample of natural Si, 2.5 g/cm^2 thick.

A good event required a triple coincidence between an incident pion (detected in an upstream scintillator counter), the Ge(Li) detector, and one of the eight neutron counters in a 150 ns time range. The neutron energy was measured by the time of flight method, the upstream scintillator triggering the zero time. Because of the low duty cycle of the accelerator (2%), the pion flux was limited to 6000 π^-/s in order to prevent incorrect neutron energy measurements from two close start signals.

Before the storage of a good event, it was also checked that no particle had triggered the upstream counter within a time range of ±150 ns around the triple coincidence. The discrimination between gamma rays and neutrons provided by the shape of the counter pulses was only fair as a result of the large size of the counters. The amplitude of the pulses was encoded to allow, in the data reduction process, a better discrimination between γ rays and fast neutrons by setting thresholds on the amplitude. For every stored event, the amplitude spectrum due to incident particles in the upstream counter was also encoded to suppress an electron contamination of about 20%. The efficiency of the neutron counters was calculated by a Monte Carlo program[9] for various thresholds on the amplitude of the pulses.

The confidence level in such a calculation was checked, in the energy range of interest, by the following three complementary experiments.

(i) In the 2–8 MeV range, a calibrated ^{252}Cf source was used. Neutron energies were measured by time of flight, the fission fragments being detected in coincidence.

(ii) In the 15–50 MeV range, the reaction $\gamma+p\to\pi^++n$ was used with a monochromatic photon beam in the energy range 270–380 MeV.[10] The pions were detected in the focal plane of a magnet; the efficiency of the neutron counter placed at the right angle is obtained from the π^+ flux, the reaction kinematics being entirely defined.

(iii) At 60 MeV, the efficiency was deduced by measuring coincidences between the two neutrons emitted when π^- were stopped in a deuterium target.

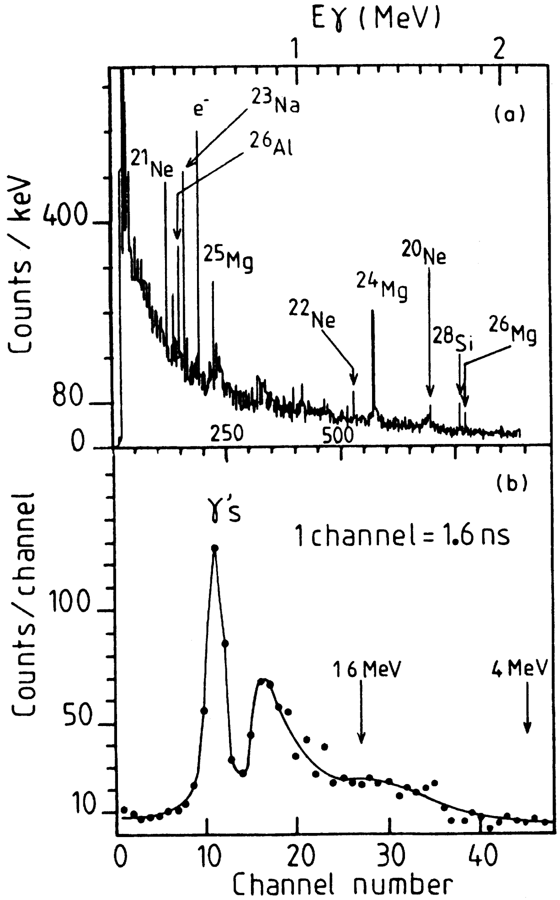

FIG. 1. (a) γ-ray spectrum from the capture of π^- stopped in ^{28}Si taken in coincidence with all the neutrons. (b) Neutron time of flight spectrum taken in coincidence with the 1369-keV γ-ray line in ^{24}Mg which can be seen on the previous spectrum. In the low energy region (see limits), this spectrum is not entirely reliable due to a background contribution from high energy neutrons interacting with the floor and the walls in the experimental area.

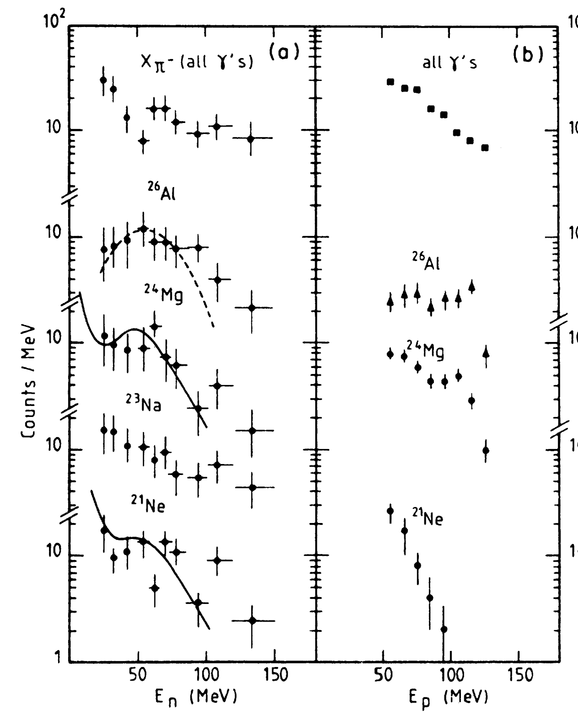

FIG. 2. (a) Neutron energy spectra taken in coincidence with pionic x rays and with ^{26}Al, ^{24}Mg, ^{23}Na, and ^{21}Ne γ rays following the absorption of stopped π^- in ^{28}Si. Only statistical errors are indicated. The dashed curve in the case of ^{26}Al is a Gaussian distribution peaked at 55 MeV, i.e., half the total available energy (pion mass minus the proton and neutron binding energies in ^{28}Si). Full curves for ^{24}Mg and ^{21}Ne are from a preliminary calculation including preequilibrium and evaporation and starting from the above ^{26}Al dashed distribution to describe the first interaction of the π^- with a nucleon pair (Ref. 11). (b) Proton energy spectra following the absorption of 70 MeV π^+ by ^{28}Si for ^{26}Al, ^{24}Mg, and ^{21}Ne channels and for all channels.

The absolute values of the multiplicities are only certain to ≈30% due to all the inaccuracies, including those in the total neutron efficiency (10%) and those from poor statistics and background subtraction (25%).

III. RESULTS

Figure 1 shows the γ-ray spectrum from the capture of π^- in ^{28}Si when all recorded coincidences are summed up. As expected, no line indicates masses greater than 26 except the 1.78 MeV of ^{28}Si due to secondary particles (mainly low energy nucleons) scattered by the target. The weak intensity of this line allowed us to estimate that the distortion of the neutron spectra due to secondary interactions in the thick target was negligible. All other identified nuclei were known from previous inclusive experiments.

Figure 1 also presents, as an example of the coincidence data, the time of flight spectrum of the neutrons in coincidence with the 417 keV line of ^{26}Al. By taking into account the variation of the detector efficiency with neutron energy, this spectrum is transformed into the energy spectrum displayed in Fig. 2(a) along with those from ^{24}Mg, ^{23}Na, and ^{21}Ne (see in column 3 of Table I the γ rays of each residual nucleus measured in coincidence with the neutrons). The neutron spectrum in coincidence with the pionic x ray of 151 keV represents some kind of average over the neutron spectra for all outgoing channels. One can notice in Fig. 2(a) that the shape of the curve for ^{26}Al is in fair agreement with the Gaussian distribution predicted, in the quasideuteron model, by a purely

TABLE I. Neutron multiplicities from π^- stopped in ^{28}Si compared with proton multiplicities from 70-MeV π^+ absorbed by ^{28}Si and with calculated neutron multiplicities (Ref. 11).

Residual nucleus	Removed charge and mass ΔZ ΔN	E_γ(MeV)	transition	Yield (%) in π^- capture by ^{28}Si[a] this expt	Yield (%) calc	Neutron multiplicity for $E_n \geq 20$ MeV[b] (this expt)	Proton multiplicity $E_p \geq 50$ MeV[c] (Ref. 8)	Neutron[d] multiplicity for $E_n \geq 50$ MeV[c] (this expt)	Neutron multiplicity $E_n \geq 40$ MeV (calc Ref. 11)
^{26}Al	$-1p$ $-1n$	0.417	2nd exc. st. → g.s.	4.6	4	2	1.93	1.47	1.4
^{26}Mg	$-2p$	1.808	1st exc. st. → g.s.	4.9	4.2			0.8	0.68
^{25}Al	$-1p$ $-2n$	0.450	1st exc. st. → g.s.	1.2	0.2		0.76		
^{25}Mg	$-2p$ $-1n$	0.585	1st exc. st. → g.s.	6	19.3		1.19	1	1.15
^{24}Mg	$-2p$ $-2n$	1.368	1st exc. st. → g.s.	10.9	13.8	2.02	1.84	1.38	0.92
^{23}Na	$-3p$ $-2n$	0.440	1st exc. st. → g.s.	9.4	8.2	1.18	0.80	0.78	0.63
^{22}Ne	$-4p$ $-2n$	1.274	1st exc. st. → g.s.	3.9	3.8		0.71	1.04	0.46
^{21}Ne	$-4p$ $-3n$	0.350	1st exc. st. → g.s.	7.4	6.7	1.37	0.88	0.90	0.63
^{20}Ne	$-4p$ $-4n$	1.632	1st exc. st. → g.s.	2.9	3.8		1.74	0.86	0.6

[a] From the single γ spectrum.

[b] Normalized by taking for $E_n \geq 20$ MeV a neutron multiplicity of 2 for ^{26}Al. Accuracy in these relative values is ≈ 20%.

[c] The proton multiplicities are only available for $E_p > 50$ MeV due to the absorption of the less energetic protons by the target. The total energy available in the π^+ experiment (210 MeV) being higher than in the π^- experiment (140 MeV), the proton multiplicities should be compared to neutron multiplicities with a lower threshold.

[d] Same normalization as in (b). ^{25}Mg multiplicity can be too low because of missing decay lines (see the calculated yield).

geometrical description of the π-nucleus interaction. The neutron spectrum of ^{26}Al should indeed be quite representative of the direct capture of a π^- on a p-n pair.

In Fig. 2(a), the neutrons associated with ^{24}Mg seem to belong to two groups: one at high energy similar to the ^{26}Al distribution, which thus could represent the component from the initial stage of the interaction; the other group at low energy would result, rather, from final state interactions. In the case of ^{23}Na and ^{21}Ne, where more nucleons have been removed from the target, more rescattering effects should take place and we observe a reduction of the high energy component and an enhancement of the low energy part.

For comparison, Fig. 2(b) shows the proton spectra which were measured for ^{26}Al, ^{24}Mg, and ^{21}Ne, following the absorption of 70 MeV π^+ by ^{28}Si.[9] There is a great similarity between these neutron and proton spectra. The agreement becomes quite good between the two experiments if one shifts the maximum of the ^{26}Al distribution and all the neutron spectra by ≈35 MeV to take into account the total available energy, which is larger in the in-flight π^+ experiment (210 MeV) than in the present one (140 MeV).

Both proton and neutron coincidence spectra of Fig. 2 show clearly that the monotonic exponential decreases, with increasing nucleon energies observed in the previous inclusive experiments and reproduced by the average spectra at the top of Fig. 2, were due to a compensation for very important differences between the separated spectra in coincidence with each final nucleus. For nuclei close to the target, such as ^{26}Al and ^{24}Mg, proton spectra show a high energy component in analogy to neutron spectra. In both neutron and proton cases, this component is decreasing with increasing number of emitted nucleons and disappears for nuclei far from the target (^{21}Ne). Thus, one can attribute this high energy part to the direct process, more or less distorted by final state interactions, and the low energy part of the spectrum to the preequilibrium process with an increasing slope as more nucleons are emitted.

Another piece of information on the primary interaction can be obtained through the neutron multiplicities associated with each final nucleus. From the total number of neutrons in each spectrum, divided by the neutron detector solid angle, and using the intensities of the associated lines in the single γ spectrun, one can infer the neutron multiplicity for each residual nucleus. These multiplicities are reported in Table I (column 6). They are given for neutrons of energy ⩾ 20 MeV because in the lower energy region (i.e., the evaporation region mainly), a possible contribution from the background given by fast neutrons interacting with the surrounding of the counters leads us to consider the spectrum unreliable. They are to be compared with the proton multiplicities measured in the interaction of 70 MeV π^+ with Si (column 7). They are also given for a higher threshold ($\geq$40 MeV) in column 8. The overall errors in these figures are ±20%. In principle, proton and neutron multiplicities should be comparable within these experimental uncertainties and this appears to be the case.

IV. DISCUSSION

In the quasideuteron model, the nucleon multiplicity should be 2 for ^{26}Al and more or less close to unity for the other nuclei since the second neutron or proton undergoes residual interactions before escaping. In agreement with the data (columns 6 and 7), a lower multiplicity is expected when many nucleons with low energies have been emitted as a result of these interactions, i.e., for nuclei far removed from the target. In addition, the contribution of the absorption on a *p-p* (or *n-n*) pair yielding only one neutron (proton) instead of two also leads to a decreasing multiplicity with an increasing number of emitted nucleons. In that respect, the neutron multiplicity of ^{26}Mg compared to ^{26}Al is a good example of the absorption on *p-p* pairs, which is only expected in that case.

For ^{26}Al, it can be seen from Fig. 2(a) that the low energy part of the Gaussian distribution is not entirely included in the multiplicity of neutrons with energies $\geq$40 MeV. It explains why the neutron value in column 8 is lower than the one for protons in column 7. On the contrary, with a threshold of 20 MeV, too many low energy neutrons from final state interactions are included for ^{23}Na and ^{20}Ne in comparison with protons of $E_p \geq 50$ MeV.

The nucleon multiplicities are close to 1 in accordance with the model. One exception is the multiplicity for ^{24}Mg, which is higher and close to that of ^{26}Al for both protons and neutrons. This can be taken as an indication of some direct formation of ^{24}Mg by a primary interaction of the pion with an α cluster. There is also some evidence for this effect in ^{20}Ne in the case of protons.

Calculations in the framework of the quasideuteron model should lead to a detailed comparison with the multiplicities of 20–100 MeV neutrons derived in this experiment for discrete channels. Such calculations have to include the intranuclear interactions and rearrangement processes which take place after the initial absorption of the pion. The special case of the removal of one alpha particle should be given much attention since the detection of both protons and neutrons seems to show an enhanced multiplicity.

Calculations of this kind are in progress and will be published in full detail later. They use a quasideuteron approach for the primary interaction and an exciton model for the preequilibrium stage. Preliminary figures for multiplicities of neutrons above 40 MeV are given in Table I (column 9). There is an overall agreement with the data of column 8 except for ^{24}Mg. It then seems necessary to include an interaction of the pion with an α cluster in the calculation.

In summary, by performing coincidences between protons or neutrons and residual nuclei in the interaction of pions with nuclei, it has been possible to get a more detailed approach of the different steps of the interaction and of the subsequent deexcitation process. The knowledge of both proton and neutron multiplicities associated with each residual nucleus shows real progress in the understanding of the interaction of pions with nuclei.

This experiment also shows that the neutron method was powerful enough, despite its lower efficiency, to compare the most interesting features of the capture of π^- by ^{28}Si with the interaction of in-flight π^+ on the same target. Moreover, it does not seem very difficult to lower the threshold for neutron detection under the 20 MeV limit of the present experiment and consequently to have a knowledge of the full spectrum, including the evaporation stage. Under our experimental conditions, the stage is inaccessible for the detection of protons even if the Coulomb barrier reduces its contribution in the very low energies. In addition, as the neutron spectrum is not distorted by the target, the Monte Carlo corrections applied to proton spectra for energies lower than 50 MeV are avoided. For these reasons, the detection of neutrons seems a good experimental approach at low energies. This experiment thus points out the capability of neutrons as a powerful tool for understanding the interaction of pions with nuclei through all its successive steps, from direct interaction to preequilibrium and to evaporation.

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