Nuclear Reactions Induced by Stopped Negative Pions in $^{133}$Cs, $^{93}$Nb and $^{45}$Sc

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The absorption of stopped negative pions in $^{133}$Cs, $^{93}$Nb and $^{45}$Sc has been investigated by means of activation technique. The gamma ray spectra of the obtained activities have been measured with a Ge(Li)-spectrometer. The yields of residual radioactive isotopes have been determined. In addition, the yield of the reaction $^{133}$Cs($\pi^-$, p)$^{132}$I has been determined to be $(2.0\pm0.8)\times10^{-5}$ per stopped pion. Isomeric yield ratios have been deduced for the isomeric pairs $^{86\text{m}}\text{Y}$ and $^{87\text{m}}\text{Y}$. On the basis of the obtained results absorption mechanisms are discussed.

1. Introduction

The main interest in the reactions induced by stopped negative pions arises from the fact that the nucleus receives an energy equivalent to the pion mass (140 MeV) without momentum transfer. Due to the momentum and energy conservation a $\pi^-$ at rest is absorbed by a quasideuteron [1] or by an alphaparticle [2]. Single nucleon absorption involves the nucleon momentum of 500 MeV/c which exceeds significantly the momentum cut-off inside the nucleus and hence it is strongly suppressed [3,4].

The absorption of negative pions has been studied in the past by emulsion, neutron dosimetry and activation technique reviewed for instance by Koltun [5] and by HÜfner [3]. In the last years using more precise experimental technique the formation and the de-excitation of the residual nuclei [6-14], neutron and charged particle spectra [16,17] were observed.

However, there is insufficient systematic information about neutron multiplicity, charged particle emission and angular momentum transfer.

The aim of this work was to investigate the absorption of $\pi^-$ at rest by means of activation technique in natural monoisotopic targets of $^{133}$Cs, $^{93}$Nb and $^{45}$Sc extending the experimental data over the intermediate mass region. $^{133}$Cs and $^{45}$Sc are still not investigated. In $^{93}$Nb gamma rays following the $\pi^-$-capture at rest were measured by Engelhardt et al. [6].

The emission probability of a single proton should be very small with respect to the well established reaction mechanism [3]. Up to now the yield of the ($\pi^-$, p) reaction on $^{12}$C ($4.5\times10^{-4}$ per stopped pion) was obtained by Coupat et al. [18].

The sensitivity of the activation method allows the observation of low yield reactions. For this purpose the targets mentioned above were chosen, which should make it possible to observe the products of the ($\pi^-$, p)-reactions.

2. Experimental Method

The investigations were performed with negative pions with an energy of 30 MeV of the bio-medical beam of the Dubna Synchrocyclotron. A plastic degrader was used. The density of stopped negative
pions was $10^2 \text{g}^{-1}\cdot\text{s}^{-1}$. Targets about 1.2 ± 2.0 g/cm$^2$ were irradiated for 1 to 3 h. The external thermal neutron background was suppressed by covering the targets with 1 mm thick cadmium foil. Additional experiments were performed using a thicker degrader to estimate the contributions of the reactions induced by background high energy neutrons and gamma rays. In the case of $^{133}\text{Cs}$ from some of the irradiated targets iodine activities were chemically separated. The obtained activities were measured with a Ge(Li)-detector (30 cc) having a resolution of 2.0 keV for the 1,332.5 keV $\gamma$-line of $^{60}\text{Co}$. The gamma-spectra were analyzed with a small computer "Minsk 2". The monitoring of the stopped pions was not possible directly. It could be estimated by dosis measurements.

The applied experimental technique permitted to observe activities with half-life between 20 min and 100 d. The independent yields of the identified radioactive isotopes were determined using the abundance of well established gamma lines given in the tables [19, 20] or in some cases deduced from recent papers. The given errors are derived only from standard deviations and detector efficiency and do not include the systematic errors from beam monitoring and decay schemes.

3. Experimental Results
3.1. $^{133}\text{Cs} + \pi^-$

Three types of experiments were carried out:

a) CsCl targets about 1.2 g/cm$^2$ was irradiated for 1 h. Yields of Xe and I isotopes were deduced.

b) CsCl (1.2 g/cm$^2$) dissolved in water was irradiated for 3 h and during the irradiation Xe was blown away by a He stream. A thicker degrader was used. Yields of I isotopes and yields of background reactions were determined.

c) CsNO$_3$ (1.5 g/cm$^2$) was irradiated for 3 h. From the irradiated targets I isotopes are chemically separated. The obtained $\gamma$-ray spectrum of the I isotopes is shown in Fig. 1. The results on the basis of the three experiments are listed in Tables 1 and 2.

In these measurements special attention was paid to the observation of the $(\pi^-, p)$-reaction. We checked carefully the distribution of the weak 772.7 keV $\gamma$-line, which was attributed, with an energy accuracy of 0.1 keV to the decay of $^{132}\text{I}$. This $\gamma$-line was observed only in the experiment (c) where the Compton background was essentially lower. It should be noticed, that no $\gamma$-lines close to 772.7 keV are known in I isotopes which could overlap it. It should be added, that the isomeric state $^{132m}\text{I}$ (83 min) was not ob-

Fig. 1. $\gamma$-ray spectrum from I separated from irradiated Cs target, cooling time 40 min, measuring time 3 h