D. Bollini, F. Fossati, A.M. Paolillo and S. Rovera: ENERGY SPECTRUM OF PROTONS FROM Cs AND I WITH 17.6 MeV INCIDENT $\gamma$-RAYS.
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**Abstract.**

Energy spectra of protons from the \(^{127}(\gamma, p)\)Te\(^{126}\) and \(^{133}(\gamma, p)\)Xe\(^{132}\) reactions were measured at 17.6 and 14.8 MeV \( \gamma \)-rays energy. Pulse-shape discrimination has been used. The cross-sections for these reactions were estimated to be \( 2.5 \pm 0.3 \) mbarn. The spectra are consistent with the statistical theory for \( E_p < 4.75 \) MeV and present in the high region, effects of direct interactions.

This paper presents experimental results on the energy spectrum of protons emitted by Cs\(^{133}\) and \(^{127}\) of a CsI(Tl)-crystal, irradiated with 17.6 and 14.8 MeV \( \gamma \)-rays. The \( \gamma \)-rays are produced in the \( \text{Li}^7(p, \gamma) \) reaction at the 440 KeV resonance.

The crystal acts both as target and as detector for \( p \) and \( e^- \) particles; moreover, exploiting the property of the crystal to present a fluorescence decay time which depends on the particular particle detected, it is possible to discriminate between \( p \), \( e^- \) and electrons produced by \( \gamma \)-rays.

The use of pulse shape analysis allows one to increase the \( \gamma \)-flux, to use relatively thick crystals, and therefore to reduce corrections not easy to estimate, for protons escaping from the crystal.

Although it is impossible to separate the Cs\(^{133}\) and \(^{127}\) contributions to the observed reaction, it is reasonable to assume that both elements will behave similarly. In fact, the two nuclides are close together in \( Z \) and \( A \) values (\(^{127}Z=53; \) Cs\(^{133}Z=55\)) and both contain an odd number of \( p \) and an even number of \( n \). The \( (\gamma, p) \) reaction \( Q \)-values are practically equal (-6.25 MeV and -6.37 MeV for \(^{127}\) and Cs\(^{133}\)). Besides, the \( 4\pi \)-geometry of the target detector system, does not allow angular distribution measurements.

The work was carried out with a 560 KeV Cockroft-Walton accelerator with the radio-frequency source in a fixed magnetic field. The \( \gamma \) activity was monitored continuously during the irradiation with a Geiger-Müller counter.

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(20th Century Electronics G. 5H) calibrated with the $\beta^+$ activity induced in a copper foil by the reaction Cu$^{63}(\gamma, n)$Cu$^{62}$. With an ion current of 70 $\mu$A the $\gamma$-rays intensity was $1.2 \times 10^6 \gamma x sec^{-1}$ over the whole solid angle.

The experimental arrangement is shown in fig. 1. The CsI(Tl) crystal (a) has a diameter of 40 mm and a thickness of 3 mm. It is mounted, with a 10 mm high perspex light pipe (b), on a Dumont 6292 photomultiplier (c). An aluminium sheet of 0.18 mgr/cm$^2$ (d) covers the crystal and the light-pipe.

To avoid the counting of protons from $(\gamma, p)$ reactions in the surrounding metallic structures, a foil of polythene (e) of 2 mm thickness is placed over the crystal and absorbs protons with an energy up to 15 MeV.

The detector is screened by a 80 mm thick cylinder of Pb (f) with a 20 mm collimation hole (g) coaxial with the crystal (a).

The signals from the photomultiplier were sent to a discriminator circuit and analysed by a 100 channel pulse height analyser. The block diagram of the electronic apparatus is outlined in fig. 2; it is similar to that used by Marczan and al. (1).

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**Fig. 1**

**Fig. 2 - Pulse shape discriminator circuit.**
The calibration of the proton energy scale was made with 3.9 and 8.77 MeV $\alpha$-particles from a natural Th source. The energy calibration curves given by Dixon\(^{(2)}\) for $\alpha$ and p in a CsI crystal were used.

Experimental results and discussion.

The experimental spectrum of protons, representing a total of 22700 counts, is shown in fig. 3. This spectrum was obtained in a series of successive runs for a total irradiation time of 260 hours.

Fig. 3 - Experimental spectrum of protons.
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The following corrections were applied to the spectrum:

a) correction for protons escaping from the crystal, due to its particular geometry;

b) correction for the protons due to \((n,p)\) reactions in Cs and I and the recoil protons in polythene. Neutrons are produced by a \(\text{Li}^7(d,n)\) reaction, with deuterons from our unanalysed proton beam.

The correction (a) was calculated assuming an isotropic angular distribution of protons; and was found to change from 5\% for 6 MeV protons to 10\% for 10 MeV protons.

For correction (b), the number of protons due to neutrons from \(\text{Li}^7(d,n)\) was determined from the yield of the reaction and the \((n,p)\) cross-section in CsI. They do not alter substantially the spectrum shape.

The corrected spectrum seems to be in agreement with that of Sébaoun\(^{(3)}\) and Bormann-Neuert\(^{(4)}\).

Fig. 4 shows an analysis of the spectrum made according to the statistical theory. We plotted \(N(\varepsilon)/\varepsilon \times \sigma_c(\varepsilon)\) versus \(\varepsilon\), where \(N(\varepsilon)\) is the number of protons of energy \(\varepsilon\), and \(\sigma_c(\varepsilon)\) is the cross-section for the reverse process. Values of \(\sigma_c(\varepsilon)\) were taken from Shapiro\(^{(5)}\)'s work, assuming \(r_0 = 1.5 \times 10^{-13} \text{ cm}\). The plot shows that the spectrum in the lower energy region corresponds to a nuclear evaporation process of the form:

\[N_p(\varepsilon) = \text{cost} \cdot \sigma_c(\varepsilon) e^{-\varepsilon/\varepsilon_0}\]

with a nuclear temperature \(\varepsilon_0 = 0.23 \text{ MeV}\).

The high energy part of the spectrum, can be attributed to direct interactions, possibly two peaks are separable, one at 7 MeV and one at 9 MeV, in spite of the poor resolving power of the apparatus.

The analysis of the experimental spectrum shows that the protons emitted from the statistical process are about 21\% of those produced by the resonance direct mechanism.

According to Wilkinson\(^{(6)}\)'s theory for elements with \(Z=53-55\), the ratio of proton emission to total absorption is 0.85\% in the case of a bremsstrahlung beam with 23 MeV maximum energy. The same ratio, calculated by Weinstock\(^{(7)}\) with the statistical theory for bremsstrahlung of 22 MeV maximum energy is 0.2\%. Therefore the ratio between the evaporative process and the Wilkinson theory should be about 23\%. This value is in good agreement with our experimental value of 21\%.

To calculate the \(\sigma(\gamma,p)\), it was assumed that Cs\(^{133}\) and I\(^{127}\) were identical in behaviour, and that the cross-sections with 14.8 MeV incident \(\gamma\)-rays was equal to that with 17.6 MeV \(\gamma\)-ray. The last assumption is reasonable because the maximum of the giant resonance is at 15.2 MeV for Iodine and at 16.0 MeV for Cesium.

We estimated that the cross-sections for Cs\(^{133}(\gamma,p)\) and I\(^{127}(\gamma,p)\) reactions were: 2.5 ± 0.8 mbarn.

This value is to be compared with 1.5 mbarn obtained by Sébaoun\(^{(3)}\) and Kestelyi-Ero\(^{(8)}\) for the same reactions.
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