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ELEMENTARY PARTICLE APPROACH TO SOME NUCLEAR PION REACTIONS

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A B S T R A C T

An elementary particle approach is applied to the nuclear pionic pion capture and charge exchange pion-nucleus scattering under the soft pion hypothesis. A relation between the muon capture, radiative pion capture and pionic pion capture is discussed.

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1. -

The nuclear capture of the negative muon and pion from its lowest Bohr orbit, raising the nuclear state from the ground state of the parent nucleus to a definite bound (excited or ground) state of the daughter nucleus, goes mainly in three channels

The ratio of the cross-section of the processes (3) and (2), at threshold,

$$P = \frac{\sigma_a (\pi^- + N_1 \rightarrow N_2 + \pi^0)}{\sigma_a (\pi^- + N_1 \rightarrow N_2 + \gamma)} \quad (4)$$

is known as the Panofsky ratio.

As noticed by many authors ^{1),2)}, the process (1) is governed by the vector and axial vector form factors (i.e., their nuclear matrix elements) while process (2) proceeds only through axial form factors, in the soft pion limit. We point out here that under the soft pion hypothesis process (3) is governed by the vector form factors only and that a relevant relation exists between these three processes. Further, under the same hypothesis, we obtain the cross-section of the charge exchange scattering of negative pions. The purpose of this communication is to forward this idea using our elementary particle approach ^{3),4)}.

2. -

The muon capture rate of the process (1) is written in the form ³⁾

$$\Gamma(\mu^- \rightarrow \nu_\mu) = \frac{G^2}{2} \frac{1}{(2\pi)^2 16 (2J_1 + 1)} (Z_1 \alpha m'_\mu)^3 C_\mu \frac{1}{m_1 m_\mu} \frac{s - m_\pi^2}{s} \langle B_\pi \cdot L \rangle \quad (5)$$

where m_i , p_i and j_i are the mass, four-momentum and spin, respectively, of the nucleus N_i . The mass and reduced mass of the muon are denoted respectively by m_μ and m'_μ . s is the Mandelstam variable, but is equal to $(m_1 + m_\mu)^2$ in this process. C_μ is the effective charge correction to the muon orbital defined by $C_\mu = (Z_{1\text{eff.}}/Z_1)^4$. The quantity $\langle B_j \cdot L \rangle$ is given by the contraction of the nuclear and leptonic tensors :

$$\langle B_j \cdot L \rangle \equiv B_j^{\mu\nu} L_{\mu\nu}$$

$$B_j^{\mu\nu} \equiv (2\pi)^6 \sum_{\text{pol } N_1, N_2} \langle N_2 | J^\mu(0) | N_1 \rangle \langle N_1 | J^{\nu\dagger}(0) | N_2 \rangle \quad (6)$$

$$\begin{aligned} L_{\mu\nu} &\equiv (2\pi)^6 \sum_{\text{pol } \mu, \nu_\mu} \langle \nu_\mu | \ell_\mu^\dagger(0) | \mu \rangle \langle \mu | \ell_\nu(0) | \nu_\mu \rangle = \\ &= 8 [q_{1\mu} q_{2\nu} + q_{1\nu} q_{2\mu} - g_{\mu\nu} (q_1 \cdot q_2) + i \epsilon_{\mu\nu\lambda\tau} q_1^\lambda q_2^\tau] \end{aligned}$$

Here and in the next Sections q_1 and q_2 are the four-momentum of the incoming and outgoing light particles. $\ell^\mu(x)$ is the weak leptonic current and $J^\mu(x)$ stands for the hadronic weak current, which is a sum of a vector part, $V^\mu(x)$, and an axial vector one, $A^\mu(x)$.

3. -

Under the use of current algebra and in the soft pion limit the radiative pion capture rate from the $1s$ orbit [process (2)] can be written ³⁾ as

$$\Gamma(n \rightarrow \gamma) = \frac{e^2}{f_\pi^2 m_\pi^2} \frac{1}{(2\pi)^2 8(2j_i + 1)} (Z_1 \alpha m'_\pi)^3 C_n \frac{1}{m_i m_n} \frac{s - m_\pi^2}{s} \langle B_A \cdot E \rangle \quad (7)$$

where f_π is the conventional pion decay constant ($f^2 \simeq 0.90$), $e^2/4\pi = \alpha$, $s = (m_1 + m_n)^2$ in this process, C_n is the effective charge correction for the pion orbital. Notice that C_n has contributions both from electromagnetic and strong interactions, nevertheless for light nuclei we can expect that $C_n \simeq C_\mu$ ²⁾. We denote by m_n the mass of the $\pi^\pm$ and, if needed to be distinguished, we will use m_0 for the mass of the neutral pion. Again

$$\langle B_A \cdot E \rangle = B_A^{\mu\nu} E_{\mu\nu}$$

$$B_A^{\mu\nu} \equiv (2\pi)^6 \sum_{p \in N_1, N_2} \langle N_2 | A^\mu(0) | N_1 \rangle \langle N_1 | A^{\nu+}(0) | N_2 \rangle \quad (8)$$

$$E_{\mu\nu} \equiv (2\pi)^3 \sum_{p \in \gamma} \langle 0 | \mathcal{A}_\mu(0) | \gamma \rangle \langle \gamma | \mathcal{A}_\nu(0) | 0 \rangle = \sum_{p \in \gamma} \epsilon_\mu \epsilon_\nu$$

where $\mathcal{A}^\mu(x)$ is the electromagnetic field and ϵ^μ is the polarization four-vector for the photon.

4. -

Let us now turn to the process (3), considering it as a charge exchange pion scattering. Using P.C.A.C. and the Ward-Takahashi ⁵⁾ identity we obtain for the invariant T matrix element in the soft pion limit

$$T = - \frac{1}{\sqrt{2} f_\pi^2 m_\pi^2} (q_1 + q_2)_\mu (2\pi)^3 \langle N_2 | V^\mu(0) | N_1 \rangle \quad (9)$$

where the σ term does not contribute to the process here considered. Then the differential cross-section can be written as

$$\frac{d\sigma}{dt} = \frac{1}{f_\pi^4 m_\pi^4} \frac{1}{32\pi (2j_1+1)} \frac{1}{\lambda(s, m_1^2, m_\pi^2)} \langle B_V \cdot Q \rangle \quad (10)$$

where $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$ and

$$\langle B_V \cdot Q \rangle \equiv B_V^{\mu\nu} Q_{\mu\nu}$$

$$B_V^{\mu\nu} \equiv (2\pi)^6 \sum_{p \in N_1, N_2} \langle N_2 | V^\mu(0) | N_1 \rangle \langle N_1 | V^{\nu+}(0) | N_2 \rangle \quad (11)$$

$$Q_{\mu\nu} = (q_1 + q_2)_\mu (q_1 + q_2)_\nu$$

and variables s and t are defined as usual $s = (p_1 + q_1)^2$, $t = (p_2 - p_1)^2$.

Then the pionic capture rate from the 1s orbit [process (3)] can be written

$$\Gamma(n^- \rightarrow n^0) = \frac{1}{2 f_n^4 m_n^4} \frac{1}{(2n)^2 8 (2j_{i+1})} (Z, \alpha m_n')^3 C_n \frac{1}{m_1 m_n} \frac{s - m_2^2}{s} \langle B_V, Q \rangle \quad (12)$$

In this case $s = (m_1 + m_n)^2$. Taking into account the kinematical factor for the relation between cross-sections at threshold and capture rates, the Panofsky ratio turns out to be

$$P = \frac{1}{8 \pi \alpha f_n^2 m_n^2} \frac{\lambda^{1/2}(s, m_2^2, m_0^2)}{s - m_2^2} \frac{\langle B_V, Q \rangle}{\langle B_A, E \rangle} \quad (13)$$

5. -

In Ref. 3) we developed the way to represent the nuclear tensors $B^{\mu\nu}$ in terms of invariant form factors. As it was proved there it is particularly simple to work in the Breit reference system defined by

$$p_1 = (\sqrt{m_1^2 + x^2}, 0, 0, x) \quad p_2 = (\sqrt{m_2^2 + x^2}, 0, 0, -x) \quad (14)$$

$$x = \sqrt{\frac{\lambda(t, m_1^2, m_2^2)}{4(2m_1^2 + 2m_2^2 - t)}}$$

Then

$$B_J^{\mu\nu} = t^\mu t^\nu \sum_L [A^{(L)}(t)]^2 + (t^\mu m_{(0)}^\nu + t^\nu m_{(0)}^\mu) \sum_{LL'} \sqrt{2L+1} \begin{pmatrix} 0 & L' & 0 \\ L & 0 & L \end{pmatrix} \cdot \quad (15)$$

$$\cdot A^{(L)}(t) F^{(L, L')}(t) + \sum_{m=\pm 1, 0} m_{(m)}^\mu m_{(m)}^{\nu*} \sum_{L L'} \sqrt{(2L+1)(2L'+1)} \cdot$$

$$\cdot \begin{pmatrix} m & L & 0 \\ 1 & m & e \end{pmatrix} \begin{pmatrix} m & L & 0 \\ 1 & m & e' \end{pmatrix} F^{(e', L)}(t) F^{(e, L)}(t)$$

where t^μ , $n_{(m)}^\mu$ are the components of the following four-vectors

$$t^\mu \equiv (1, 0, 0, 0) \quad m_{(0)}^\mu \equiv (0, 0, 0, 1) \quad m_{(\pm 1)}^\mu \equiv (0, \mp \frac{1}{\sqrt{2}}, \mp \frac{i}{\sqrt{2}}, 0) \quad (16)$$

The summation is extended to $|j_1 - j_2| \leq L \leq j_1 + j_2$ and $\ell = |L-1|, L, L+1$. If the initial and final nuclear states have the same parity, then ³⁾ the vector form factors are $A^{(L)}(t)$ with L even and $F^{(\ell, L)}(t)$ with ℓ odd and L arbitrary and the axial ones are $A^{(L)}(t)$ with L odd and $F^{(\ell, L)}(t)$ with ℓ even and L arbitrary. If the initial and final nuclear states have opposite parities, the assignment of vector and axial vector form factor goes the other way around. The quantities $B_A^{\mu\nu}$ and $B_V^{\mu\nu}$ are obtained immediately from $B_J^{\mu\nu}$ substituting zero to all the form factors of the type not considered.

Notice that since $B^{\mu\nu}$ is computed in the Breit system, the quantities $L_{\mu\nu}$, $E_{\mu\nu}$, $Q_{\mu\nu}$ must be also written in this reference system. At threshold (applicable to capture process) we have

$$q_1 \equiv \left(\frac{\mu_1}{m_1} \sqrt{m_1^2 + x^2}, 0, 0, \frac{\mu_1}{m_1} x \right) \quad q_2 \equiv \left(\sqrt{\mu_2^2 + \left(2 + \frac{\mu_1}{m_1}\right)^2 x^2}, 0, 0, \left(2 + \frac{\mu_1}{m_1}\right) x \right) \quad (17)$$

where μ_1 (μ_2) is the mass of the incoming (outgoing) light particle. Far away from threshold, where the electromagnetic mass differences of the pions can be neglected and $m \equiv m_1 \simeq m_2$ is a good approximation, we have for the charge exchange scattering process (3) ($t = -4x^2$)

$$q_1 = (\sqrt{m_n^2 + b^2 + x^2}, 0, b, -x) \quad q_2 = (\sqrt{m_n^2 + b^2 + x^2}, 0, b, +x) \quad (18)$$

$$b^2 \equiv \frac{1}{4m^2 - t} [\lambda(s, m^2, m_n^2) + ts]$$

Working all these things together we obtain

$$\begin{aligned}
 \langle B_{T \cdot L} \rangle &= 8 \left\{ \alpha(t) \sum_L X_L^2(t) + \beta(t) \sum_L Y_L^2(t) \right\} \\
 \langle B_{A \cdot E} \rangle &= \sum_{e, L} [F^{(e, L)}(t)]^2 \\
 \langle B_{V \cdot Q} \rangle &= 4m_n^2 \sum_L [A^{(L)}(t)]^2 \quad (\text{at threshold}) \\
 \langle B_{V \cdot Q} \rangle &= 4(m_n^2 + x^2 + b^2) \sum_L [A^{(L)}(t)]^2 + 2b^2 \sum_{L, L'} \sqrt{(2L+1)(2L'+1)} \begin{pmatrix} 1 & L & 0 \\ 1 & 1 & 2 \end{pmatrix} \begin{pmatrix} 1 & L & 0 \\ 1 & 1 & 2 \end{pmatrix} F^{(e, L)}(t) F^{(e, L')}(t) \\
 &\quad (\text{far away from threshold})
 \end{aligned} \tag{19}$$

where $\alpha(t) = 2(q_1 \cdot t)(q_2 \cdot t) - (q_1 \cdot q_2)$ and $\beta(t) = (q_1 \cdot q_2)$ and

$$X_L(t) = A^{(L)}(t) - \sqrt{\frac{L}{2L+1}} F^{(L-1, L)}(t) + \sqrt{\frac{L}{2L+1}} F^{(L+1, L)}(t) \tag{20}$$

$$Y_L(t) = -\sqrt{\frac{L+1}{2L+1}} F^{(L-1, L)}(t) + F^{(L, L)}(t) - \sqrt{\frac{L}{2L+1}} F^{(L+1, L)}(t)$$

Notice that to obtain $\langle B_{A \cdot E} \rangle$ we have used the Coulomb gauge ³⁾. Furthermore the equation for $\langle B_{V \cdot Q} \rangle$ at threshold has been obtained assuming that $|t| \ll m_1^2$, which is always satisfied. We obtain immediately for the Panofsky ratio :

$$P = \frac{1}{2\pi\alpha f_n^2} \frac{\lambda^{1/2}(s, m_\pi^2, m_0^2)}{s - m_\pi^2} \frac{\sum_L [A^{(L)}(t=0)]^2}{\sum_{L, e} [F^{(e, L)}(t)]^2} \tag{21}$$

As stated before, in the numerator only vector type form factors appear and in the denominator axial ones.

6. -

Let us consider now the application to $N_1 \equiv {}^3\text{He}(\frac{1}{2}^+; \frac{1}{2})$ and $N_2 \equiv {}^3\text{H}(\frac{1}{2}^+; \frac{1}{2})$ (isodoublet). The conventional nuclear form factors between N_1 and N_2 are

$$(2n)^3 \langle N_2(p_2 \lambda_2) | V^\mu(0) | N_1(p_1 \lambda_1) \rangle = \bar{u}(p_2 \lambda_2) [g_V(q^2) \gamma^\mu + i \frac{g_M(q^2)}{2M} \sigma^{\mu\nu} q_\nu] u(p_1 \lambda_1) \quad (22)$$

$$(2n)^3 \langle N_2(p_2 \lambda_2) | A^\mu(0) | N_1(p_1 \lambda_1) \rangle = \bar{u}(p_2 \lambda_2) [-g_A(q^2) \gamma^\mu \gamma_5 - \frac{g_P(q^2)}{2M} q^\mu \gamma_5] u(p_1 \lambda_1)$$

where $q = p_2 - p_1$, $\sigma^{\mu\nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu]$ and M is the proton mass. Our invariant form factors read in terms of the conventional ones introduced above as

$$A^{(0)}(t) = -2\sqrt{2} m [g_V(t) + \frac{t}{2mM} g_M(t)] \quad F^{(11)}(t) = -2\sqrt{-t} [g_V(t) + \frac{m}{M} g_M(t)] \quad (23)$$

$$F^{(01)}(t) = -2\sqrt{\frac{2}{3}} [(2a+m) g_A(t) + \frac{t}{4M} g_P(t)] \quad F^{(21)}(t) = -\frac{2}{\sqrt{3}} [(2a-m) g_A(t) - \frac{t}{2M} g_P(t)]$$

where $a \equiv \sqrt{m^2 + x^2}$.

The values of $A^{(0)}(t)$ and $F^{(1,1)}(t)$ can be obtained from the electron scattering experimental data of Collard et al.⁶⁾ and can be parametrized with an accuracy of a few per cent up to $t \simeq 5 \text{ fm}^{-2}$ by the expression

$$A^{(0)}(t) = -0.7943 \cdot 10^{+4} \text{ MeV} e^{+(0.141 \cdot 10^{-4} \text{ MeV}^{-2}) t} \quad (24)$$

$$F^{(11)}(t) = -30.57 \sqrt{-t} e^{+(0.203 \cdot 10^{-4} \text{ MeV}^{-2}) t}$$

From β decay of ^3H we obtain $F^{(0,1)}(0) = -1.668 \cdot 10^{+4} \text{ MeV}$ and its variation versus t is given by $F^{(0,1)}(t)/F^{(0,1)}(0) = A^{(0)}(t)/A^{(0)}(0)$. The value of $F^{(2,1)}(t)$ is obtained from P.C.A.C.³⁾

$$F^{(2,1)}(t) = \frac{1}{\sqrt{2}} [F^{(0,1)}(t) - \frac{m_n^2}{m_n^2 - t} F^{(0,1)}(0)] \quad (25)$$

Using these form factors all processes (1), (2) and (3) (capture and scattering) can be calculated. For process (1) we obtain³⁾

$$\Gamma(\mu \rightarrow \nu_\mu) = (1645 \pm 75) \text{ sec}^{-1}. \text{ For the process (2), } t = -1.8419 \cdot 10^{+4} \text{ MeV}^2$$

and therefore $F^{(0,1)}(t) = -12.414 \cdot 10^{+3}$ MeV and $F^{(2,1)}(t) = -2.781 \cdot 10^{+3}$ MeV and the radiative capture rate turns out to be

$$\Gamma(n^- \rightarrow \gamma) = 3.37 \cdot 10^{+15} \text{ sec}^{-1} \quad (26)$$

in good agreement with previous calculations $\Gamma = 3.46 \cdot 10^{+15} \text{ sec}^{-1}$ ²⁾, $\Gamma = 4.43 \cdot 10^{+15} \text{ sec}^{-1}$ ⁷⁾ and in disagreement with another theoretical value of $\Gamma = 0.97 \cdot 10^{+15} \text{ sec}^{-1}$ ⁸⁾. The Panofsky ratio is immediately calculated with the result

$$P = 2.20 \quad (27)$$

to be compared with the experimental values of $P = 2.16 \pm 0.28$ ⁹⁾ and $P = 2.28 \pm 0.27$ ¹⁰⁾.

For the charge exchange differential cross-section we obtain, e.g.,

$$\begin{aligned} \frac{d\sigma}{dt}(n^- + {}^3\text{He} \rightarrow {}^3\text{H} + n^0) &= \frac{1}{64\pi} \frac{1}{f_n^4 m_n^4} \frac{1}{\lambda(s, m^2, m_n^2)} \cdot \\ &\cdot \left[\left\{ 4m_n^2 - t + \frac{4}{4m^2 - t} [\lambda(s, m^2, m_n^2) + st] \right\} [A^{(0)}(t)]^2 + \right. \\ &\left. + \frac{2}{4m^2 - t} [\lambda(s, m^2, m_n^2) + st] [F^{(4)}(t)]^2 \right] \end{aligned} \quad (28)$$

For kinetic energies, E , of the incoming pion in the laboratory system between 0 and 150 MeV, we have $|t| \ll 4m^2$ and the t dependence on the denominators can be neglected. [Notice $s = (m+m_n)^2 + 2mE$, $\lambda(s, m^2, m_n^2) = 4m^2 E(E+2m_n)$.] Using for the form factors the expressions given in Eq. (24) the total cross-section can be calculated analytically, noticing that the t integration runs from $t = -[4m^2 E(E+2m_n)] / [(m+m_n)^2 + 2mE]$ to $t = 0$. The results are given in the Table.

It is worth noticing that for the total cross-section for energies $E \lesssim 100$ MeV, the main contribution is coming from the term $\left[4m_n^2 + \frac{1}{m^2} \lambda(s, m^2, m_n^2) \right] \left[A^{(0)}(t)\right]^2$. To neglect all the other terms gives an error of less than 10% at $E = 100$ MeV and decreasing very fast at lower energies. It is interesting to notice that in the absence of σ terms we can easily obtain the relations

$$\begin{aligned} \sigma(n^- + {}^3\text{He} \rightarrow {}^3\text{H} + n^0) &= \sigma(n^+ + {}^3\text{H} \rightarrow {}^3\text{He} + n^0) = \\ &= 2\sigma(n^\pm + {}^3\text{He} \rightarrow {}^3\text{He} + n^\pm) = 2\sigma(n^\pm + {}^3\text{H} \rightarrow {}^3\text{H} + n^\pm) \end{aligned} \quad (29)$$

which can be used as a test of the importance of the σ terms.

7. -

Finally let us apply this formalism to $N_1 \equiv {}^6\text{Li}(1^+; 0)$ and $N_2 \equiv {}^6\text{He}(0^+; 1)$. In this case we have one vector form factor $F^{(1,1)}(t)$ and three axial vector form factors $A^{(1)}(t)$, $F^{(0,1)}(t)$, $F^{(2,1)}(t)$. The last one will be neglected ³⁾. As it is explained in Ref. ³⁾ the vector form factor at $t = 0$ can be obtained from the electromagnetic decay of the excited state of ${}^6\text{Li}$ at 3.56 MeV, which is in the same isomultiplet as ${}^6\text{He}$, to the ground state. The variation with t of this form factor can be obtained from the backward electron inelastic scattering data. The $F^{(0,1)}(0)$ is determined from β decay of ${}^6\text{He}$ and we fix its variation with t assuming that it is the same as the smooth form factor $G^{(1,1)}(t)$ associated with $F^{(1,1)}(t)$ ³⁾. Finally using P.C.A.C., $A^{(1)}(t)$ can be computed.

Using this form factor, the muon capture rate was computed in Ref. ³⁾ and good agreement with the experimental data was found. For the radiative pion capture we have $t = -1.7882 \cdot 10^{+4} \text{ MeV}^2$ and get

$$F^{(0,1)}(t) = 0.38 \cdot 10^{+4} \text{ MeV} \quad (30)$$

(With an error that can be around 10% due to the uncertainty of the backward electron scattering experiences.) Then we obtain

$$\Gamma(n^- \rightarrow \gamma) = 0.15 \cdot 10^{+15} \text{ sec}^{-1} \quad (31)$$

with an error that can amount to 20 or 30%. There is no direct measurement of this quantity. Nevertheless two important quantities have been measured : the pion disappearance width from the 1s orbit

$$\Gamma_{1s} = 0.15 \pm 0.05 \text{ kev} \quad 11) \quad (32)$$

$$\Gamma_{1s} = 0.39 \pm 0.36 \text{ kev} \quad 12)$$

and the branching ratio to the radiative pion capture channel ¹³⁾

$$R \equiv \frac{\Gamma[(n^- + {}^6\text{Li})_{1s,2s,2p,\dots} \rightarrow {}^6\text{He} + \gamma]}{\Gamma[(n^- + {}^6\text{Li})_{1s,2s,2p,\dots} \rightarrow \text{all}]} = 0.010 \pm 0.001 \quad (33)$$

If the pion capture rate takes place totally from the 1s orbit we obtain from (32) and (33) the values $\Gamma[(n^- + {}^6\text{Li})_{1s} \rightarrow {}^6\text{He} + \gamma] = (2.3 \pm 0.8)10^{+15} \text{ sec}^{-1} \quad 11)$ and $(5.9 \pm 5.5)10^{+15} \text{ sec}^{-1} \quad 12)$ which must be comparable with the value given in Eq. (31). However, these values are questionable, since there exists some experimental evidence that the capture from other than 1s state in ⁶Li amounts to $(68 \pm 5)\% \quad 13)$, and if some capture modes are enhanced in the capture from the higher orbits, the value of $\Gamma[(n^- + {}^6\text{Li})_6 \rightarrow {}^6\text{He} + \gamma]$ will go down.

Furthermore the estimate (31) differs from Ericson's quoted by Deutsch ¹⁴⁾

$$\Gamma(n^- \rightarrow \gamma) = (2.0 \pm 0.4 - 0.2) 10^{+15} \text{ sec}^{-1} \quad (34)$$

by an order of magnitude. She used the impulse approximation and the detailed balance from the (γ, n) process upon proton and we used the soft pion approach. The question remains open for both.

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E MeV	$\sigma(\pi^- + {}^3\text{He} \rightarrow {}^3\text{H} + \pi^0)$ mb
25	3.40
50	3.20
75	3.06
100	2.93
125	2.86
150	2.81

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