

## Two-Body Weak Decay Studies in an Ion Storage Ring

**Paul Kienle**

Excellence Cluster Universe Technische Universität München, D-85748  
Garching, Stefan Meyer Institut der ÖAW, A-1090 Wien

E-mail: Paul.Kienle@ph.tum.de

**Abstract.** We have studied in a heavy ion storage ring at GSI Darmstadt, Germany, the time dependence of the orbital electron capture decays of H-like  $^{140}\text{Pr}$ ,  $^{142}\text{Pm}$ , and  $^{122}\text{I}$  ions and found that the electron capture rate is not purely exponential but in addition time modulated with periods of  $T=7.06(8)$  s,  $7.10(22)$  s and  $6.11(3)$  s for  $^{140}\text{Pr}$ ,  $^{142}\text{Pm}$  and  $^{122}\text{I}$ , respectively, measured in the laboratory system of the ions moving with 71% of speed of light (Lorentz factor  $\gamma=1.43$ ). The modulation amplitude is  $a=0.20(3)$  in average for all three ions. Such modulation periods correspond to a small energy difference of  $8.6 \times 10^{-16}$  eV, and  $7.5 \times 10^{-16}$  eV, respectively, for a quantum beat type phenomenon. We attribute it to the mixing of massive electron neutrinos emitted in the decays with squared mass difference  $\Delta m^2 = 2.20(3) \times 10^{-4}$  eV<sup>2</sup>. It is about 2.9 times larger than latest value reported by the KamLAND antineutrino oscillation experiment.

### 1. Introductory remarks

We report on a program to investigate the illusive mass properties of neutrinos by studying the time evolution of quasi-free two-body weak decays with a quantum mechanically entangled pair of final states with mono-energetic neutrinos. Only the time of appearance of the entangled daughter ion is observed. It is in time, energy, momentum, and flavor entangled with the mixed massive electron neutrino emitted in such a process. Thus we can study very efficiently its properties without the ineffective direct neutrino detection.

The decay processes which we study is orbital electron capture of Hydrogen-like (H-like) ions with only one electron in the K-shell into a completely ionized daughter nucleus plus a quasi-mono-energetic electron neutrino, as two-body final state. Its time reversed process is  $\beta$ -decay of a completely ionized nucleus with the decay electron bound in the K-shell of an H-like daughter ion and a mono-energetic electron antineutrino. We can also study with our method bound  $\beta$  decay. In this report we focus on first experiments on orbital electron capture with H-like ions in the initial state and a completely ionized daughter ion and its entangled electron neutrino as final state. The point is that we study with a resolution of less than 1s the time evolution of the weak decay. This observation introduces an energy uncertainty in the measuring process of the daughter recoils of  $\delta E_d > 4 \times 10^{-15}$  eV. As the observed time modulation corresponds to an energy difference of the recoiling daughters of  $8.6 \times 10^{-16}$  eV and  $7.8 \times 10^{-16}$  eV, respectively, the interference condition, non-distinguishable decay channels for a quantum beat type of phenomenon, is fulfilled. Massive neutrinos transfer on the daughter ions different energies and momenta due to energy conservation in the decay process, which lead to the observed energy difference and thus quantum beats produced by massive neutrinos.

## 2. Experimental procedures

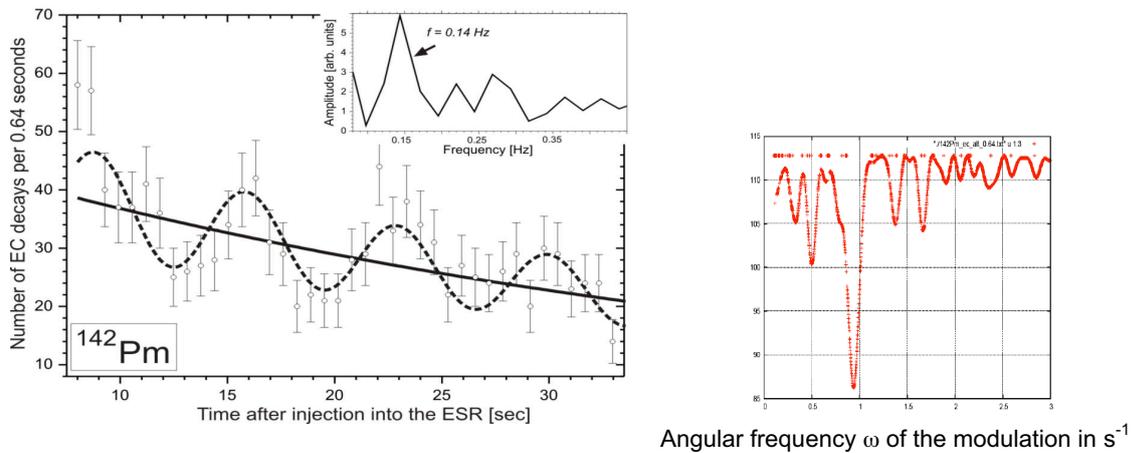
For the decay studies [1] we produced with a bunched heavy ion beam of less than 1 $\mu$ s duration and 500-600 MeV per nucleon energy on a 1-2g/cm<sup>2</sup> Be target projectile like fragments in high ionization states, with small momentum spread ( $\sim 1\%$ ), and focused in forward direction. With the 72 m long fragment separator FRS [2], we separate selected H-like EC decaying nuclei using the B $\rho$ - $\Delta E$ -B $\rho$  separation method [1,2], and kick their bunches into the ESR storage ring of the GSI Laboratory in Darmstadt/Germany at 400MeV per nucleon energy. The stored ions coast nearly loss free in the ESR in a vacuum of 10<sup>-11</sup> mbar, with a velocity of 71% of the speed of light ( $\gamma = 1.43$ ) and a revolution frequency of about 2MHz. Their original velocity spread of  $\sim 1\%$  is reduced by fast stochastic pre-cooling of a few fragments, followed by precision electron cooling within about 6-10 s to a velocity spread  $\Delta v/v \sim 5 \times 10^{-7}$ . Such a small velocity spread is required for precision Schottky Mass Spectroscopy (SMS) for detecting the mass decrease in the EC-decay of H-like ions. For cooled ions the change of the revolution frequency  $\Delta f/f$  is directly proportional to  $-\Delta M/q$  and as the charge  $q$  does not change in the EC decay it is proportional to  $-\Delta M$ , the mass decrease or the Q-value of the transition. The signal induced by the coasting ions in pickup plates is amplified and a Fourier Frequency Transform (FFT) spectrum is produced. The FFT signal is summed up for 64ms at the 30<sup>th</sup> harmonics of the revolution frequency. These FFT frames are digitized and stored in their time sequence. In such a FFT frame the signal to noise ratio was good enough for recognizing a single medium heavy ion. In the time resolved version of SMS a continuous time sequence of FFT frames was recorded from the time of injection of the ions in the ring ( $t = 0$ ) to the end of the observation period of about 60 s to 100 s. The time of decay is determined by the time  $t$  at which the correlated disappearance of the mother ion and the appearance of the daughter nucleus with a higher circulation frequency are observed in the time sequence of FFT frames. Note that the time of appearance of the daughter nucleus is somewhat delayed with a jitter in the delay due the anisotropic cooling force acting on the recoiling daughters. This affects only the accuracy of the determination of the phase angle of the modulation, but not the frequency.

Recently we reported [1] the experimental results of the (1<sup>+</sup>- 0<sup>+</sup>) GT orbital EC decays of H-like <sup>140</sup>Pr<sup>58+</sup> with a 99.4% branch to the ground state of stable <sup>140</sup>Ce<sup>58+</sup> ions with  $Q_{EC} = 3388\text{keV}$ ,  $T_{1/2} = 3.38$  m for neutral atoms. In order to test the  $Q_{EC}$  dependence of the modulation results, the (1<sup>+</sup>-0<sup>+</sup>) GT orbital EC decay of H-like <sup>142</sup>Pm<sup>60+</sup> with a 94.6 % branch to the stable <sup>142</sup>Nd<sup>60+</sup> ground state, with  $Q_{EC} = 4870$  keV and  $T_{1/2} = 40.5$  s was measured. In August 2008 we studied in addition the (1<sup>+</sup>-0<sup>+</sup>) GT orbital EC decay of H-like <sup>122</sup>I<sup>52+</sup> ions for investigating the mass ( $M$ ) and charge ( $Z$ ) dependence of the time modulation. Only results of a preliminary analysis are presented here [3]

## 3. Data analysis and results

The analysis of the time development of the FFT spectra of the published data [1] was carried out by at least two independent visual and one computer assisted analysis of each experimental run. In total about 6-7000 individual experiments for each decay were analysed. In the visual analysis each 64 ms long FFT frame or the average of two subsequent frames were recorded. For the computer assisted analysis 5 FFT frames had to be averaged to achieve an adequate signal to noise ratio [1].

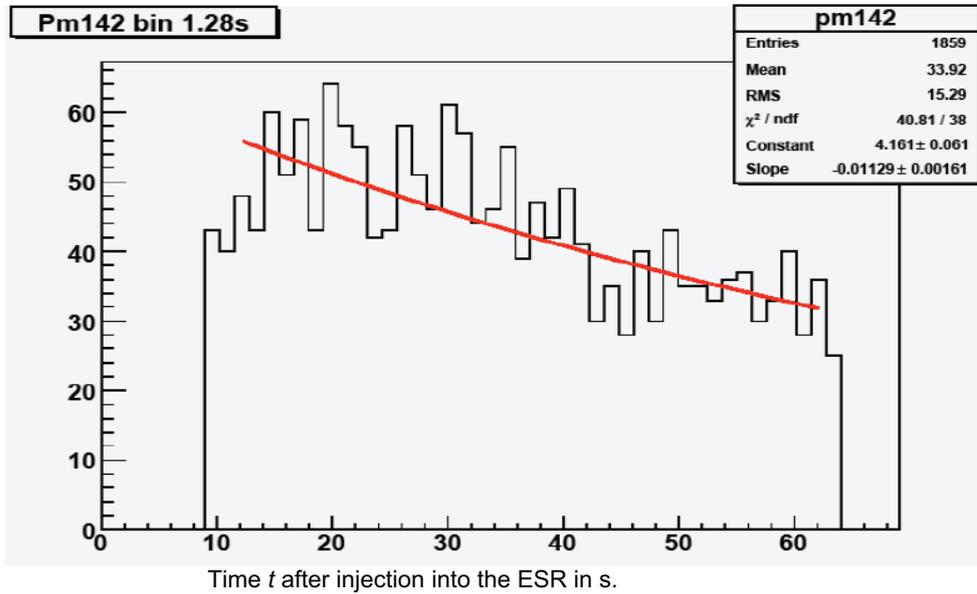
In Fig.1 we show as example the measured decay spectra for H-like <sup>142</sup>Pm ions. A fit with a pure exponential decay function,  $dN_{EC}(t)/dt = N(0) \cdot \lambda_{EC} \cdot e^{-\lambda t}$  (1) as indicated by the solid curve, failed to reproduce the data. It is evident that the expected exponential decay shows a superimposed periodic time modulation. To account for this modulation the data was fitted with the function  $dN_{EC}(t)/dt = N(0) \cdot \lambda_{EC}(t) \cdot e^{-\lambda t}$  (2) with a time dependent decay probability  $\lambda_{EC}(t) = \lambda_{EC} \cdot [1 + a \cos(\omega t + \Phi)]$  (3), representing a periodic modulation of a constant  $\lambda_{EC}$  with an amplitude  $a$ , an angular frequency  $\omega$ , and a phase  $\Phi$ . For the details of the result of all fit parameters of both experimental data sets see Table 2 of reference [1]



**Figure 1.** Decay rate of  $^{142}\text{Pm}$  (left panel) including a pure exponential fit (eq. (1) solid line) and a superimposed modulation (eq. (2) dashed curve). The inset is a FFT spectrum of the data. The right panel shows  $\chi^2(\omega)$  for the fit of eq. (2) to the data indicating quantitatively the statistical relevance of the solution with the minimum for  $\omega = 0.885(31) \text{ s}^{-1}$  [3].

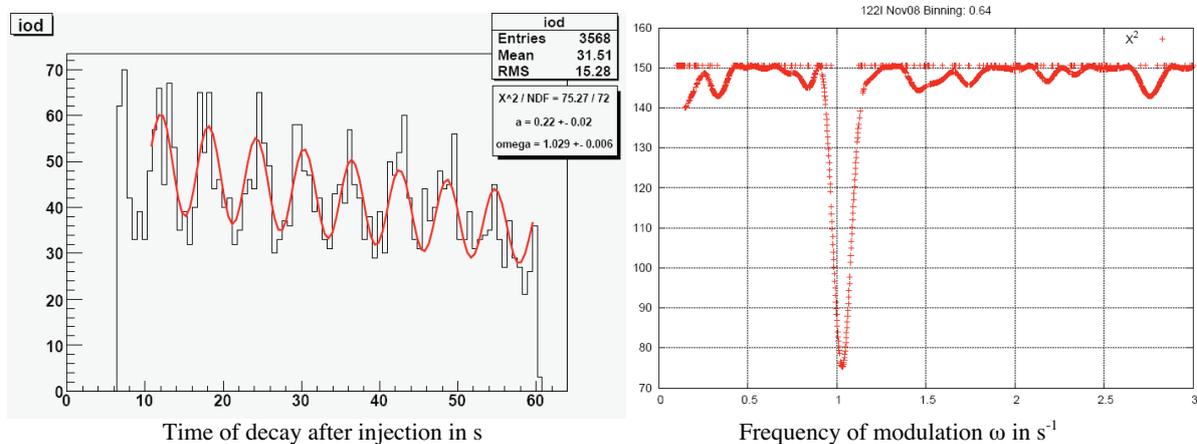
The total decay constants  $\lambda$  obtained from both fitting functions, eq. (1), and eq. (2) agree within their error margins for the  $^{140}\text{Pr}$  and for the  $^{142}\text{Pm}$  data. All thus deduced decay constants  $\lambda$  agree within two standard errors with the corresponding literature values for neutral atoms corrected for the missing electrons and taking into account the observed “enhancement” of the EC decay of H-like ions [4, 5]. From the angular frequencies  $\omega = 0.890(11) \text{ s}^{-1}$  and  $\omega = 0.885(31) \text{ s}^{-1}$  we extract the periods of modulation as  $T = 7.06(8) \text{ s}$  and  $T = 7.10(22) \text{ s}$  in the laboratory frame for the decays of  $^{140}\text{Pr}$  and  $^{142}\text{Pm}$ , respectively. Note that the modulation periods of both decays are within their errors the same and thus independent of the energies of the emitted neutrinos; in contrast they are compatible with scaling with the mass  $M$  of the ions. Also the amplitudes  $a = 0.18(3)$  and  $a = 0.23(4)$  for  $^{140}\text{Pr}$  and  $^{142}\text{Pm}$ , respectively agree within their error margins; the average amplitude of both systems is  $\langle a \rangle = 0.20(2)$ . The results for the phases of the modulation reflect the uncertainties introduced by the difference and the variation of the cooling times of the daughter ions as outlined before. It can be improved in the future, by taking the time of disappearance of the mother nucleus, as decay time  $t$ .

In the following we show some preliminary results gained with the goal to complement the observations so far reported in ref [1]. In order to test our measuring method and determine whether the observed modulation is a characteristic of the two body EC decay, the simultaneously observed decay spectra of the  $\beta^+$  decay of  $^{142}\text{Pm}$ , which is about three time stronger than the EC branch, was analysed [3]. In this case we could observe only the disappearance of the mother ion for the  $\beta^+$  decay whereas for the EC branch the mother–daughter correlation was used as previously [1]. Therefore the analysis is restricted presently on decays where we observed only one or two mothers in the ring. Fig.2 shows the preliminary time spectrum of the  $\beta^+$  branch of the  $^{142}\text{Pm}$  decay with 1858 entries including a fit with a pure exponential decay. A decay spectrum of the EC branch gained with the same data set and 736 entries showed the expected modulation with an angular frequency  $\omega = 0.90(2) \text{ s}^{-1}$  and an amplitude of  $a = 0.18(5)$ . At a modulation frequency of  $\omega = 0.90 \text{ s}^{-1}$  only a vanishing modulation amplitude of  $a = 0.03(3)$  is indicated for the  $\beta^+$  branch [3].



**Figure 2.** Preliminary decay rate of the  $\beta^+$  branch of the  $^{142}\text{Pm}$  decay as function of time  $t$  after injection into the ESR with an exponential fit of the data [3].

In August 2008 we performed an experiment [3] to study the decay spectrum of the EC decay branch of the  $(1^+ - 0^+)$  GT-transition of H-like  $^{122}\text{I}^{52+}$  to the ground state of stable  $^{122}\text{Te}^{52+}$ . Neutral  $^{122}\text{I}$  has a half-life of 3.63 m, a Q-value of 4.234(5) MeV, an EC branch of 15%, and a  $\beta^+$  branch of 67% to the ground state of  $^{122}\text{Te}$ . The main purpose of the experiment was to study the  $M$ - and  $Z$ -dependence of the observed modulation frequency. Fig. 3 shows an EC decay spectrum of H-like  $^{122}\text{I}^{52+}$  of a preliminary analysis of about 60% of the collected data with 3563 entries and a fit of a time modulated exponential decay to the data (left panel). It shows a modulation with an angular frequency  $\omega = 1.029(6) \text{ s}^{-1}$ , and an amplitude  $a = 0.22(2)$ . The right panel of Fig. 4 shows the mean square deviation,  $\chi^2(\omega)$  of the fit of the data to a modulated decay spectrum (eq. 2) as function of the angular frequency  $\omega$  with all other parameters free. A clear minimum of  $\chi^2(\omega)$  is seen at  $\omega = 1.029(6)$  with a statistical relevance of about  $15\sigma$ . So the reduced value of the observed modulation period of  $T = 6.11(3) \text{ s}$  for  $^{122}\text{I}$  compared with  $T = 7.06(8) \text{ s}$  for  $^{140}\text{Pr}$  indicates a scaling with the mass  $M$  of the decaying system.



**Figure 3.** Preliminary EC decay rate of  $^{122}\text{I}^{54+}$  (left).  $\chi^2(\omega)$  of the EC decay rate of  $^{122}\text{I}^{54+}$  from eq. 2 (right).

#### 4. Discussion of the results

The periodically modulated exponential EC decay has now been observed for three H-like systems  $^{140}\text{Pr}$ ,  $^{142}\text{Pr}$ , and  $^{122}\text{I}$  (preliminary). The amplitude of modulation is within their error margins the same in all three systems. Its periods  $T$  scale with the mass  $M$  of the systems and are independent of their  $Q_{\text{EC}}$ -values and half-lives. The three-body  $\beta^+$  decay of  $^{142}\text{Pm}$  is according to a preliminary analysis not modulated with a limit of its amplitude  $a = 0.03(3)$ , whereas its simultaneously measured two-body EC branch is found to be modulated with  $\omega = 0.90(2) \text{ s}^{-1}$  and an amplitude of  $a = 0.18(5)$  in agreement with the results reported in [1]. This result, though preliminary, is most important, because it indicates that the modulation is directly connected to the weak decay properties, as it is present for the two-body decay branch and not for the three body branch of the same decaying ion. Thus it excludes experimental effects and also nuclear properties of the initial state; it points to an effect of the time evolution to the quantum mechanically entangled pair with the daughter nucleus and its massive electron neutrino. A further important result is that the time averaged decay probability of the modulated decays is fully consistent with the decay constant of neutral atoms after proper correction. This excludes the influence of possible oscillatory transitions between the  $F=1/2$  hyperfine ground state of the H-like system and its  $F=3/2$  excited state which is inert against weak decays; if a component of it would be populated with a period of 7s (Pr and Pm) or 6 s (I) its time averaged decay probability would be strongly decreased, which is not the case.

So what is the origin of these so called “GSI Oscillations?” There are strongly controversial arguments put forward, one which connects the observations with mixed massive neutrinos and the other, which claims that the effect has nothing to do with neutrinos. We think the latter [6,7] does not respect the time differential observation of the evolution of the decay in our experiments but describes only the time integrated final state which indeed would show no modulation. There is in addition an experimental observation against the assertion of Giunti [6], and Kienert et al. [7] that the observed modulations are caused by quantum beats of mother states with tiny energy differences of unknown origin. In this case the positron branch should be also modulated, which is not the case and the systematic  $M$ -dependence of the modulation periods would be accidental. Finally there is the very recent proposal by Gal [8], that the modulation period should scale with the  $Q_{\text{EC}}$  value and thus the neutrino energy, which is experimentally not observed.

Let us turn now to the explanation of the observed modulation in terms of the mixing of massive neutrinos. Lipkin [9] has pointed out the essential features behind the observation of the time modulation of the EC decay as studied at GSI and has predicted the period of oscillation as  $T = 4\pi\gamma M/\Delta m^2$ , with  $M$  and  $\gamma$  denoting the mass and the Lorentz factor of the stored ion, respectively, and  $\Delta m^2 = m_2^2 - m_1^2$ , the squared mass difference of the mixed neutrinos with mass  $m_1$  and  $m_2$ . Ivanov, Reda, and Kienle [10] have developed a decay theory for the time resolved detection of the orbital EC decay products of H-like ions and found the decay probability being modulated with a period  $T = 4\pi\gamma M/\Delta m^2$  which scales with the mass  $M$  of the decaying system, and with  $T = 4\pi\gamma Q_{\text{EC}}/\Delta m^2$  which scales with  $Q_{\text{EC}}$ , not observed in the present experiment. Kleinert, and Kienle [11] developed a theory for “Neutrino Mass Differences from Interfering Recoils” based on a calculation of the time dependence of the interfering recoil wave functions initiated by the kick transferred by massive neutrinos with  $m_1$  and  $m_2$ : a modulation period of  $T = 4\pi\gamma M/\Delta m^2$  was again found as in [9, 10]. In summary all three approaches [9, 10, 11] predict time modulation of the decays with periods scaling with  $M$  as observed in the reported data for three systems. The modulation period  $T$  corresponds in a quantum beat like phenomenon to an energy difference  $\Delta E = E_2 - E_1 = \Delta m^2/2\gamma M$  (with  $\hbar/2\pi = c=1$ ), as pointed out already in [1]. It is equal to the energy difference of the two neutrino components transferred in the decay to the recoiling daughter nuclei and is derived by respecting the energy conservation in the decay [9, 10, 11].

We can determine  $\Delta m^2$  for the decay observed as  $\Delta m^2 = 2.20(3) \times 10^{-4} \text{ eV}^2$  which is about 2.9 times larger than the latest KamLAND- oscillation results [13]. A solution of this problem in terms of neutrino mass corrections, induced by the interaction of massive neutrinos with a strong Coulomb

field of the daughter ion through virtual  $lW^+$  pair creation is proposed by Ivanov et al [14]. In view of our present result that  $\Delta m^2$  from the  $^{140}\text{Pr}$  and  $^{122}\text{I}$  decay are within their errors the same, the explanation by Ivanov et al [14] of the difference of  $\Delta m^2$  with the KamLAND result [13] is not confirmed. Actually our technique allows studying the apparently small mass modifications by vacuum polarisation systematically using precise modulation period measurements of decays with different  $M$  and  $Z$ . If precise enough, it may even lead to a determination of neutrino masses. As antineutrinos from bound  $\beta$  decay experience opposite mass corrections as neutrinos, such a comparison may become a very interesting additional method for studying neutrino properties.

The modulation amplitudes are within their errors as expected about equal for all three transitions observed with an average of  $a = 0.20(2)$ . The amplitude contains information on the mixing angle of the neutrinos. Its small value in the present experiments points out sources of reduction, such as a contribution due to a higher modulation frequency  $\omega = \Delta m^2/2Q_{\text{EC}}$ , which can not be observed in the present experiment [10] and/or a reduction of the phase correlation due to the preceding photon transition from the  $F = 3/2$  excited hyperfine state with a life-time of about 10 ms and a population which is higher than the  $F = 1/2$  ground state. The possible effect of the hyperfine structure on the modulation phenomenon and amplitude in particular, can be experimentally studied by investigating the decays of He-like ions with no hyperfine structure.

Finally we like to point out that the decay theory of Ivanov et al. [12] applied to three-body weak decays predicts no modulation for the  $\beta^+$  branch, because it is averaged out by the broad neutrino spectrum as observed in our preliminary results [3].

## 5. Summary

We have developed a new method for studying neutrino properties by observing the time development of two body decays in a storage ring under quasi free conditions. The method makes use of lepton entanglement in a two body decay which ensures that the daughter ion contains all information on the properties of the entangled neutrino. In this way we avoid the inefficient direct detection of neutrinos. In addition we learn for the first time about the properties of the superimposed mass eigenstates of electron neutrinos by observing their time development from the creation of the decaying nucleus to its decay into a mass superimposed flavor eigenstate.

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