A proton recoil telescope for neutron spectroscopy

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A new proton recoil telescope (PRT) detector is presented: it is composed by an active multilayer of segmented plastic scintillators as neutron to proton converter, by two silicon strip detectors and by a final thick CsI(Tl) scintillator. The PRT can be used to measure neutron spectra in the range 2–160 MeV. The detector characteristics have been studied in detail with the help of Monte Carlo simulations. The overall energy resolution of the system ranges from about 20% at the lowest neutron energy to about 2% at 160 MeV. The global efficiency is about $3 \times 10^{-5}$. Experimental tests have been performed by using the reaction $^{13}$C(d,n) at 40 MeV deuteron energy.

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1. Introduction

Future nuclear energy production will rely on new concepts for waste disposal and for the solution to the inherent safety problem of critical reactor design. New ideas have been proposed to solve these problems, such as accelerator driven sub-critical fission reactors or transmutation of radioactive waste [1,2]. These concepts require new neutron interaction data in the range between 20 MeV and several hundreds MeV. In addition, cancer therapy with proton and ion beams, the so-called hadron therapy, will require the knowledge of the secondary neutron flux produced by nuclear reactions along the penetration path in tissue. The fast neutrons produced in this way (with energies up to hundreds MeV) contribute to the dose in patient treatment irradiations, but experimental data are rather scarce [3,4].

In all the above mentioned cases, the use of neutron beams with energies between few and several hundred MeV requires the knowledge of parameters as their total fluence, the energy spectrum and the angular distribution. The development of ad-hoc neutron detectors is thus mandatory. Liquid scintillators are commonly used for neutron measurements. They are widely employed thanks to their ability to discriminate neutrons from gamma-rays by pulse-shape discrimination (PSD), the neutron energy being determined by time-of-flight (TOF) measurement. The energy accuracy scales with the inverse of the distance of the detector from the target point, thereby reducing the global efficiency due to the solid angle coverage. Activation methods can be also used [5].

An alternative type of detector for neutron spectrum measurement is the proton recoil telescope (PRT) [6–14]. The PRT is based on the detection of the recoil proton elastically scattered by a neutron in a thin hydrogenated target. The energy of the recoil proton $E_p$ is related to the incident neutron energy $E_n$ by the relationship

$$E_n = \frac{E_p}{\cos^2(\theta)}$$

where $\theta$ is the angle between the incident neutron and the recoil proton directions. In such systems, a well defined point-like neutron source is needed to define the direction of the neutron. Consequently, the simultaneous measurement of proton energy and recoil angle allows the initial neutron energy to be determined.

A variety of PRT have been designed for different purposes such as the diagnostic of hot plasma sources [6,7] or fluence measurements of high energy [8,9] or low energy [10] neutrons. In such systems, neutron converters and proton tracking depends on the particular application. Generally, the efficiency of PRT detectors is intrinsically limited by the $(n,p)$ conversion efficiency of the hydrogenated target. Typical values of the conversion efficiency are of the order of $10^{-3}$.

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In this work a new PRT detector is presented featuring an extended dynamical range and good resolution, which makes it useful in several applications.

2. The proton recoil telescope design

The lay-out of the PRT detector described in this work is shown in Fig. 1, whereas pictures of the detector are reported in Fig. 2. An active multilayer of segmented plastic scintillators is adopted as neutron to proton converter. Since the plastic scintillator array is position sensitive, it is used to determine the conversion point of the neutron. Two silicon strip detectors allow to track the recoil proton direction measuring the energy losses. Finally, a $3 \times 3$ CsI(Tl) scintillator, with a photomultiplier read-out, measures the residual proton energy.

The active converter, the silicon strip detectors and the entrance face of the CsI(Tl) scintillator are contained in a vacuum chamber, including a stainless steel box housing the converter, hermetically connected to a tube housing the silicon detectors, 25.3 cm long, with 7.5 cm internal radius. The neutron beam entrance window is made by a 2 mm thick aluminium layer. The overall length of the PRT is 49 cm.

The neutron converter consists of five planes, each of them made by four EJ212 plastic scintillator strips, 12 mm wide, 50 mm long and 0.4 mm thick with photomultiplier read-out through cylindrical plexiglas light guides. The distance between the planes is 10 mm.

The strips of the first four planes are mounted orthogonally to the axis of the detector, in vertical ($y$) and horizontal ($x$) directions alternatively, determining the coordinate information of the proton impact position. The strips of the fifth plane, the one facing the first silicon detector, are mounted horizontally so that the $y$-coordinate of the proton impact position is given by the hit strip, whereas the $x$-coordinate is reconstructed from the analysis of the light signals collected at both ends of each strip.

The silicon strip detectors are two double-sided totally depleted DC silicon strips mounted along the axis of the detector on a rigid frame. They feature a thickness of 0.3 mm, a total active area of $50 \times 50$ mm divided into 16 strips (3 mm wide each) in the junction (front) side and 16 strips, orthogonally oriented with respect to the front side, in the ohmic (rear) side. Consequently, each silicon strip detector provides both the $x$- and $y$-coordinates information on the proton impact position. The first silicon detector is mounted at 6.5 cm from the neutron converter whereas the distance between the first and second silicon detector is 24.5 cm.

The main advantages in the present PRT design are obtained by the adoption of the active multilayer converter. On one side, the $z$-coordinate of the conversion point of the neutron inside the 2 mm thick segmented converter is identified with 0.4 mm accuracy, improving the evaluation of the energy lost by the proton inside the converter itself. On the other side, in addition to the information on the proton trajectory given by the silicon strip detectors, the $x$- and $y$-coordinates of the conversion point are measured, even if with reduced accuracy. This improves the pattern recognition efficiency and the angular resolution of the proton direction. Moreover, the direction of the lowest energy protons that stop in the first silicon strip detector can be reconstructed too, thus lowering the detection threshold. As a result, the range of the detected neutron extends from 2 to 160 MeV, keeping a fair energy resolution, from about 20% [FWHM] at low energy to 2% [FWHM] at the highest energies, and reasonable global detector efficiency, of the order of $10^{-5}$. The evaluation of these latter quantities is described in the next section, devoted to Monte Carlo simulations of the whole apparatus.

3. Monte Carlo simulations

To study the performances of the PRT, extended Monte Carlo simulations have been performed using the GEANT3 [15], MICAP
[16] and SRIM [17] codes. Two different sets of simulations have been performed to evaluate separately: (i) the energy threshold and the energy resolution as a function of the incident neutron energy; (ii) the detection efficiency as a function of the incident neutron energy.

In the first set of simulations, protons with fixed energy values or randomly extracted in suitable energy range are generated uniformly in the entire volume of the multilayer segmented converter.

Their directions are randomly assigned inside the solid angle aligned with the detector axis and covering the different PRT sub-detectors: first and second strip detectors and final CsI(Tl) scintillator. The reconstructed neutron energy $E_n$ is calculated by assuming that the initial neutron direction is parallel to the PRT axis and using Eq. (1), where $\theta$ is the angle between the incident neutron and the recoil proton directions and $E_p$ is the reconstructed proton energy.

In order to evaluate the neutron energy threshold and the energy resolution of the PRT, events have been classified into three categories, depending on the stopping position of the recoil proton.

The first category (type I events in the following) includes those events where the recoil proton has enough energy to cross the neutron converter layers, to pass through the two silicon strip detectors and to reach the CsI(Tl) detector. The energy of these protons is reconstructed accounting for the residual energy released by the proton in the CsI(Tl) detector as well as the energy lost in the two silicon strip detectors and by evaluating the energy lost by the proton in crossing the converter layers. The direction of the trajectory of the proton is obtained with a linear fit of the hit strips in the $(x;z)$ and $(y;z)$ planes of the two silicon strip detectors as well as of the scintillator slabs in the active multilayer converter.

The second category (type II events in the following) includes those events where the recoil proton stops in the second silicon strip detector. The energy of these protons is reconstructed measuring the residual energy released in the second silicon strip detector and the energy lost in the first silicon strip detector, and evaluating the energy lost by the proton in the converter layers. The direction of the trajectory of the protons is reconstructed as in the previous case.

Finally, the events for which the recoil proton stops inside the first silicon strip detector are assigned to the third category (type III events in the following). For these events the energy of the protons can be reconstructed accounting for the residual energy released in the first silicon strip detector and evaluating the energy lost by the proton in the neutron converter. The direction of the protons in this category of events can be reconstructed anyway, using the information on the $x$- and $y$-coordinates of the proton crossing position on the multilayer segmented converter. It is worth recalling that the events belonging to this category correspond to the lowest energy neutrons detectable by the PRT.

The energy ranges of the neutrons belonging to the three categories of events have been evaluated by Monte Carlo calculations. The neutrons corresponding to type I events are characterized by energies in the range 9–160 MeV, the lower limit being determined by the energy needed to a proton to cross the fifth layer, the thickness of the two silicon strip detectors and to enter the CsI(Tl) detector. The upper energy limit is essentially determined by the thickness of the CsI(Tl) crystal.

The energy range of neutrons corresponding to type II events spans from about 6 up to 16.5 MeV. It is worth noting that this range is partially overlapping with the previous type of events one, since recoil protons with the same energy may stop either in the CsI(Tl) scintillator or in the second strip detector, depending on the layer of the active converter where it is generated.

Finally, the energy range of neutrons corresponding to type III events spans from about 2 to 13.2 MeV. The lower value is the minimum recoil proton energy needed to stop in the first silicon strip detector and represents the energy threshold of the PRT detector for incident neutrons.

The energy resolution of the PRT is defined as the FWHM of the distribution of the differences $E_n-E_o$, where $E_n$ and $E_o$ are the incident and the reconstructed neutron energy, respectively.

The fluctuation of the reconstructed energy of a mono-energetic neutron is a complicated function of the intrinsic energy resolution of the detectors (CsI(Tl) and the silicon strip detectors), of the error in reconstructing the proton trajectory and, consequently, the $\theta$ angle, and of the systematic error introduced by the correction for the energy released by the recoil proton inside the multilayer active converter.

The correction for the energy loss inside the scintillation converter is calculated in the following way: the layer of the active converter in which the neutron conversion took place is identified looking to the recorded hit distribution. However, the exact $z$-coordinate of the conversion point inside the 4 mm scintillator thickness is not known. Consequently, this quantity is chosen randomly with a flat distribution inside the conversion layer. The systematic error introduced by this assumption in the proton energy calculation is statistically smeared in the neutron energy distribution of samples with a large number of events. Knowing the conversion point, the total thickness traversed by the proton can be estimated. Taking into account this thickness and the reconstructed proton energy after the converter, the initial energy of the recoil proton $E_p$ is determined.

The different contributions to the fluctuation of the reconstructed energy of a given neutron have different weights depending on the neutron energy and, consequently, on the classification of the event. Monte Carlo simulations have been used to estimate the energy resolution of the PRT as a function of the incident neutron energy. To this end, the intrinsic energy resolutions of the detectors were folded in the simulations. For the CsI(Tl) detector, an intrinsic resolution of 5.5% [FWHM] measured at 5.49 MeV with alpha particles is scaled in proportion to the square root of the incident energy. For the silicon strip detectors, an intrinsic resolution of 1.0% [FWHM] measured with the same source is kept constant for all incident proton energies. The contribution to the energy resolution given by the reconstruction of the proton trajectory and, therefore, of the proton $\theta$ angle is accounted for by reconstructing the proton direction using a linear fit of the positions of the hits in the silicon strips in the $(x;z)$ and $(y;z)$ planes.

In Fig. 3, the different contributions to the PRT energy resolution, evaluated with Monte Carlo calculations, are reported as a function of the incident neutron energy. Generally, the overall energy resolution is a decreasing function of the incident neutron energy, ranging from 20% [FWHM] at about 10 MeV, to less than 2% [FWHM] at the highest energies of about 150 MeV. For incident neutron energies lower than 10 MeV, the events are mostly of type III, with the neutron conversion occurring inside the fifth layer of the converter and the recoil proton stopped in the first silicon detector. For such events, the error in the reconstructed proton energy due to the uncertainty in the position of the neutron conversion point in the scintillator layer is large.

Looking to the different contribution to the energy resolution, it is worth mentioning that it is dominated by the systematic error due to the evaluation of the energy lost inside the multilayer converter up to about 40 MeV incident neutron energy. The contribution due to the intrinsic energy resolution of the energy sub-detectors, silicon strip detectors and CsI(Tl) scintillator, reaches the maximum value of 2% [FWHM] at about 20 MeV and decreases smoothly to about 1% [FWHM] at the highest energies. It is clear that events below 20 MeV belong mostly to type II and
Ill that do not feel the effects of the energy resolution of the CsI(Tl) detector. The contribution due to the proton direction reconstruction is less than 1% [FWHM] and decreases with energy increase, since the proton trajectory is less affected by the multiple scattering.

A second set of simulations was devoted to the evaluation of the PRT efficiency. To this end, neutron beams with different energies were generated, perpendicularly incident on the entrance PRT aluminium window and uniformly distributed on the neutron converter surface.

The neutron elastic scattering on the hydrogenated converter, as well as all other hadronic interactions C(n,X) on carbon nuclei are simulated by using MICAP [16]. Protons coming from (n,p) elastic scattering that enter in the PRT acceptance and are reconstructed following the procedures described above are recorded for each incident neutron energy. The ratio between the number of reconstructed protons and the total number of incident neutrons provides the PRT overall efficiency, i.e. the conversion efficiency of the converter, the geometrical acceptance of the detector and the proton reconstruction efficiency. It is worth mentioning that the conversion efficiency of the neutron converter ranges from about 2% for 2–3 MeV neutrons to 0.2% for 40 MeV neutrons.

The calculated overall efficiency of the PRT is shown in Fig. 4 as a function of the neutron energy. The errors account for the statistical and systematic uncertainties. The latter takes into account the event selection procedure for each category and has been estimated to be 5% below 20 MeV and 2% above this energy. The overall efficiency ranges from about 0.2 × 10−5 to about 4.7 × 10−5 with a maximum at 15 MeV incident neutron energy, and is of the same order of magnitude of the typical values for the PRT previously reported [18]. The discontinuity at about 20 MeV is due to the differences in the treatment of the type of events.

4. Experimental tests

The PRT sub-detectors have been tested with radioactive sources. A final test of the complete system was performed at the Laboratori Nazionali del Sud (LNS) in Catania (Italy), by using a 40 MeV deuteron beam delivered by the Superconducting Cyclotron. The deuteron beam was used to bombard an infinitely thick 13C target. The target was as a compressed graphite powder having density ρ=0.58 g/cm3, 82% enriched in 13C and housed in the chamber described in Ref. [5]. The PRT was placed at θ=30° with respect to the beam direction at a distance of 200 cm from the target, so that the angular acceptance of the detector was Δθ<1°. The PRT read-out was organized as follows:

(i) The 16 signals of the first 4 scintillator planes of the active converter (4 strips each plane) are sent through a fast amplifier CAEN N979 to a 16 channel CAEN CFD C208 module. The OR output of the CFD output contributes to the trigger logic. The individual CFD output signals are then delayed and sent to the stop inputs of two 8 channel TDC Lecroy 2228A.

(ii) For the fifth (the inner one) scintillator plane of the active converter, two signals are collected at the left and right side of each strip. The 8 signals are first formed with a pre-amplifier and then to a Silena 761F amplifier. The pulse height signals are then sent to an 8 channel ADC Ortec AD811, fast logic left and right outputs of each strip are used to build a left-right coincidence. The OR signal of the four left-right coincidences contributes to the trigger logic.

(iii) The 16 signals of each silicon strip detector (8 for the “front” x-side and 8 for the “rear” y-side, since the strips are read two by two) are formed with an eV-5094 pre-amplifier and sent to a 16 channel Silena 761F amplifier. The pulse height signals are sent to two 8 channel ADC Ortec AD811. Additionally, the 8 output signals of the “front” x-side are sent to a CAEN CFD C208. The OR output of the latter module contributes also to the trigger logic.

(iv) The signal of the CsI(Tl) stop detector is properly formed by a Silena 761F amplifier and then to the input of an ADC Ortec AD811 module.

The acquisition trigger was built requiring that at least one of the layers of the active converter planes is fired in coincidence with the first silicon strip detector. The acquisition and control system was based on the commercial platform KMAX [19]. 1.5 × 106 events were collected.

4.1. Data analysis

In a first stage the recorded data were used to study the sub-detector response.
Concerning the active multilayer converter a study of the detection efficiency of single scintillator layers has been performed. As an example, we considered a set of events triggered by the first scintillation layer of the converter and when signals from both silicon strip detectors were recorded. In these events the proton, generated in the first layer, crossed the full multilayer converter before reaching the silicon strip detectors. Looking to the response for those events of the layers in between the trigger and strip detector, the single layer detection efficiency can be inferred. This procedure is repeated including different scintillation layers in the trigger. As a result, measured efficiency values are $87 \pm 1\%$ for the layer number 2, $90 \pm 1\%$ for the layer number 3, $94 \pm 1\%$ for the layer number 4. The fifth layer of scintillators has different characteristics when compared to the other ones, because of the different read-out scheme. Indeed, the detection efficiency of this layer has been evaluated to be of the order of about 50%.

As far as the silicon strip detectors, the energy calibration was performed off-line with a Pu–Am–Cm $\alpha$ source, independently for each pixel [18]. The data were used also to check the uniformity of response of the detectors. The overall detection efficiency has been evaluated to be not far from 100%.

The CsI(Tl) detector was also calibrated in energy with a $^{241}$Am $\alpha$ source.

In Fig. 5a, the experimental scatter plot of the energy loss in the first silicon strip detector $\Delta E_1$ as a function of the energy loss in the second silicon strip detector $\Delta E_2$ is shown. The upper band corresponds to protons crossing the first silicon strip detector and stopping inside the second one (i.e. events of the type II in the adopted classification scheme), while the lower band corresponds to protons with enough energy to cross both silicon strip detectors (i.e. type I events). Scattered events out of the correlation bands are considered to be background. A quantitative analysis of the scatter plot reveals the presence of a second correlation band due to deuterons emitted by the $^{12}$C(n,$d$) reaction in the multilayer converter. The deuteron events cannot contaminate the neutron spectra since they can easily be separated by the proton ones in the $\Delta E_1 - \Delta E_2$ scatter plot. The experimental scatter plot has been very well reproduced with a Monte Carlo calculation, as shown in Fig. 5b. In both experimental and calculated plots of Fig. 5 the average energy values of the protons entering in the first silicon strip detector are marked.

4.2. Energy spectra

The reconstruction of the neutron incident energy $E_n$ is performed by applying Eq. (1) with measured values for the energy of the recoil proton $E_p$ and the $\theta$ angle between the incident neutron and the recoil proton. As mentioned in the previous paragraphs, the trajectory of the proton is reconstructed fitting with straight lines in the ($x$,$z$) and ($y$,$z$) planes the recoil proton hits on the different tracking detectors. The $x$- and $y$-coordinates used in the fit are associated to the position of the centre of the hit plastic or silicon strips, the associated uncertainty being related to the strip width. The multiple scattering in the plastic and silicon strip detectors, especially for low energy protons, may introduce large errors in the reconstruction of the proton direction. Therefore, proton tracks suffering large multiple scattering angles are singled out by checking the values of the fit residuals and the corresponding events are discarded from the sample.

Once the direction of the proton track has been confidently reconstructed, the events are assigned to one of the three different categories in order to reconstruct the proton energy. For type III events, besides the multilayer converter only the first silicon strip detector is interested. To be sure that the proton track has actually stopped in the first silicon strip detector without continuing its trajectory inside the vacuum chamber, the extrapolation of the reconstructed track must cross the second silicon strip detector, which assumes the role of an anticoincidence. Events belonging to type III, but not responding to this geometrical requirement, cannot be accepted for the analysis and are discarded. The effect of this requirement has been evaluated by Monte Carlo calculation and has been accounted for in the PRT efficiency calculation of Fig. 4.

With these event selection criteria, the geometrical acceptance for the recoil proton is limited to about 10$^\circ$ around the detector axis. This condition limits the PRT efficiency but, considering the reconstruction formula (1), reduces the uncertainty in the measurement of the $\theta$ angle on the reconstruction of the neutron energy $E_n$.

The reconstruction of the total energy of the recoil proton is performed by evaluating the energy of the proton at the exit point from the neutron converter, i.e. the energy of the proton incident on the first silicon strip detector. For type III events, it coincides with the residual energy released by the proton in the first silicon strip detector. For type II events it is obtained adding up the
residual energy released by the proton in the second silicon strip detector and the energy lost in the first silicon strip detector. For type I events it is given by the sum of the energy released by the proton in the final CsI(Tl) scintillator and the energy lost inside the two silicon strip detectors.

The correction for the energy lost by the proton in crossing the converter layers is evaluated following the procedure previously described.

In Fig. 6 the neutron spectrum, in arbitrary units, without (a) and with (b) correction for efficiency, is shown. Moreover, in panel (a) the contributions of the three different types of events are highlighted. The type I and II events span from neutron energy of about 9 MeV to the maximum of about 40 MeV and from about 6 to about 17 MeV, respectively. As already noted, the overlap between those two categories is due to the conversion point of the neutron inside the multilayer converter. The low energy threshold of the detector for events of type III is around 2 MeV corresponding to a neutron converted in the fifth layer. However, due to the measured low efficiency of this layer, Fig. 6 reports events with conversion in the previous layers (3 and 4), resulting in an increase of the low energy threshold. Consequently, the type III events range from about 5 MeV up to about 15 MeV neutron energy. This category of events accounts for the bulk of the statistic in the neutron spectrum.

An evaluation of the background contamination of the neutron spectrum can be performed by Monte Carlo calculations. This background may have two main sources. The first one is due to interactions of neutrons with the carbon nuclei of the plastic converter material giving origin to protons entering the PRT acceptance. These events are indistinguishable from events of (n,p) elastic scattering of the neutrons inside the converter. The second one is due to background events generated by interactions of the neutron beam with the structural material of the PRT, giving correlated signals firing the trigger and reproducing a fake event in one of the three event categories. Certainly these events have less chance to fire the trigger and to be reconstructed, however one has to recall that the PRT structure and its mechanical support were not shielded at all and were fully immersed in the neutron beam coming from the target.

Extended Monte Carlo calculations have been performed to evaluate the possible contamination of the reconstructed neutron spectrum by these two sources of background. For this purpose, not only the PRT structure, but also its mechanical support was simulated. As a result, protons produced after neutron interactions on \(^{12}\text{C}\) nuclei have a huge low energy component and hardly exit from the neutron converter and reach the first silicon strip detector. Moreover, the probability that a neutron collision in the structural materials of the PRT or its support structure might generate the trigger condition and, at the same time, a recognizable configuration on the tracking sub-detectors, is very low. In both cases the spectrum contamination due to these sources of background has been evaluated to be < 1% in the full neutron energy range.

Finally, the spectrum of Fig. 6 has been normalized by using the known accumulated beam charge. In Fig. 7, the double differential neutron yield for the reaction \(^{13}\text{C}(d,n)\) at 40 MeV deuteron beam is shown as measured with the PRT at \(\theta=30^\circ\) in
the laboratory and compared with the data of the reaction $^{13}\text{C}(p,n)$ at 40 MeV proton energy for the same laboratory angle, collected with time-of-flight and activation methods [5]. The shape of the distributions obtained with the deuteron beam appears to be similar to the one with the proton beam. The total neutron yield in the range 6–40 MeV for the deuteron beam results about $2.0 \times 10^{-3} \text{n/d/sr}$, whereas the one for the proton beam results to be $0.8 \times 10^{-3} \text{n/p/sr}$. As expected, the yield value measured with the deuteron beam is higher than the value obtained with the proton beam at the same energy.

5. Conclusions

A new proton recoil telescope characterized by a multilayer active converter has been designed and experimentally tested by using the reaction $^{13}\text{C}(d,n)$ at 40 MeV.

The general performances of the PRT have been determined by using Monte Carlo calculations for neutrons up to 160 MeV. The overall efficiency is in the range $10^{-5}$, due to the conversion efficiency as well as the telescope acceptance and reconstruction conditions. The energy resolution spans from 20% to 2% in going from few MeV to about 160 MeV kinetic energy.

The low energy threshold should be defined by the thickness of the last layer of the converter $E_{th}=2 \text{ MeV}$. In this first experiment, more converter layers have been used to compensate the low efficiency of this layer. Consequently, the energy spectrum is limited to 5 MeV at low energy. This problem will be avoided in future measurements by improving the read-out of the last converter layer.

The experimental results obtained so far indicate that the PRT can be useful in several applications when a neutron spectrum extending at high energy need to be measured.

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