TUUCN 05-03 rcnp.talk3.tex, rcnp.pulse.f

RCNP Workshop: Physics with Spallation UCN

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How to Use the Spallation UCN The Case of RCNP, 2004

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Abstract

This note is a consideration how to use the spallation UCN, based on our experience at the RCNP. Two types of operation are possible. (i) an intermittent high UCN pulse, and (ii) distributed UCN in time.
RCNP に適した具体的パラメーターを section 9 に示す。

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1. Spallation UCN source

We have succeeded to produce UCN (Ultra-Cold Neutrons) in the liquid helium from the spallation neutrons [Ref-1], at the Research Center for Nuclear Physics, Osaka University (RCNP) by using the spallation UCN source developed at KEK. It is a promissing device to achieve a very strong UCN flux and to open a new generation of physics using the UCN.
Fig.1 shows our spallation UCN source. The proton beam, (400MeV and $< 2\mu A$), hits a lead taget and produces the spallation neutrons. The fast neutrons are cooled down to Very-Cold Neutrons (VCN) by the 300K D_2O water and 10K D_2O ice. Finally VCN of their wave length 9 Angstromes are converted to UCN in the helium-II cryostat by the phonon interactions below 1.2 K. The produced UCN are stored in the cryostat and upper guide tube part, and decay gradually with a stored life time of τ .
In the November 2004 run at RCNP, we used the following parameters.

case (a),

proton kinetic energy = 400 MeV

proton current = 0.2 μ A, peak energy: W1 = 80 watts
proton beam width, t1= 40 sec integ. energy: W1.t1 = 3.2 k joules
period , t2 = 100 sec
measured life , τ = 18 sec
cryostat temperature = 1.2 K .

Fig.2 is a time vs. UCN-count plot in the November run, where the UCN counters were in the same height with that of the cryostat. It shows that the experimental room was full of fast neutrons and counters were completely saturated during the 40 seconds of proton pulse. After the proton beam pulse, counters started the UCN counting. The logarithmic scale of Fig.2 showed the exponential decay of UCN. We provided two UCN counters in parallel, one was bare and another covered by a Germanium filter. It is seen that there is a slight difference between two decay curves in Fig.2, which indicates the life time of slow UCN below the critical velocity of Germanium, 4.3 m/s, is longer than that of faster ones.
The production and use of UCN are repeated, and this periodic operation is a characteristic feature of the spalltion UCN source.

Fig.1, 2,

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2. UCN production

First, we will review the production of UCN. As there exist a production and a loss of UCN in a closed system, the UCN density per cc is given by

$$dN(t) = (po.W1).dt - (1/\tau).N(t).dt . \qquad \text{Eq.1}$$

where N(t) : UCN space density, per cc
po.W1 : UCN produced by the incident proton power of W1 watts, per cc, per sec
1/ τ : UCN loss probability, and τ is the stored life time in sec.

The solution is given as a function of proton irradiation time, t1, and the life time, τ,

$$N(t1) = (po.W1).\ \tau .(1 - \exp(- t1/\tau)) \qquad \text{Eq.2}$$

$$N(t1) = (po.W1.t1).\ F2 \qquad \text{Eq.3}$$
where $F2 = (\tau/t1).(1 - \exp(-t1/\tau))$

Fig.3 shows the growth of UCN density, Eq.2. It shows an exponential approach to a saturation value, po.W1. τ. The Eqs.1 and 2 are exactly same with those for the activation of radioactivities by the beam irradiation.
In Eq.3, (po.W1.t1) is the ideal UCN production proportional to the proton input power of (W1.t1) joules. Therefore, the F2 is an efficiency factor to reduce the real UCN density N(t1) from the ideal production. F2 is a function of $t1/\tau$, Fig.4.
After the proton beam, the UCN density decreases exponentially with the life time of storage, τ.

Fig.3, 4

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3. RCNP 2004 Run

Since the November run was the first test after the improvement of the cryostat in 2004, the parameters above mentioned, case (a), were not optimized. They were just those used in the previous run of 2003. The UCN was measured by a UCN counter with 1 cm^2 effective area. The peak count of 3.94 cps corresponds to the space density of UCN, 0.47/cc approximately. The measured life time of the system (cryostat + guide tube + valves + detector), 20 sec, is shorter than the expectation. It might be due to the relatively high temperature of the cryostat.

The curve (a) in Fig.3 shows the time evolution of UCN density for the above case (a), parameters of Nov'04. The parameters are suitable for the estimation of the production rate and stored life time. However, the expression of Eq.2 is somewhat misleading. Some one will think, the saturation value is (po.W1. τ), and the longer the t1, the larger the UCN density. The pulse length, $t1/\tau \geq 2$ is desired. However, it is not correct in general. It is correct only for the case of limitted low proton-peak-power, W1.

4. Radiation problem

The activation of the target area by the spallation neutrons caused a serious problem in our RCNP run. For example, after two hours operation, we had to wait about five hours to enter the experimental area under the present condition of shielding. It must be improved by a better handling of the activated target, however, this radioactive activation is an essential problem in the spallation UCN source.

The pile up of radioactivity is proportional to the average proton power, (W1.t1/t2), where the t1/t2 is the proton duty cycle. On the other hand, the time average of the produced UCN is N(t1)/t2. The number of UCN per residual radiation is proportional to

$$\begin{aligned} &\text{UCN/radiation} \\ &\propto (N(t1)/t2)/(W1.t1/t2) \\ &= (po.W1.t1.F2/t2)/(W1.t1/t2) \\ &= po.F2 . \qquad \text{Eq.5} \end{aligned}$$

Therefore, parameters giving a large F2 or a short width, $t1/\tau \leq 0.2$, are a good choice from the view of radiation. Since the F2 is the efficiency factor to reduce the UCN density from the proton input power, a large F2 is good for both the production of UCN and residual activity.

Fig.5

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5. High density UCN pulses

If we shorten the proton pulse width t1 from 40 sec (case a) to 4 sec (case b) keeping the total proton power in the 100 sec, the UCN production in 100 sec UCN100 increases from 1.383 to 2.90 more than twice, Table I. The improvement of UCN production is remarkable. The sharp rise at t1=4 sec in Fig.5 is this narrow pulse case (b). The maximum proton peak power (watt) and short pulse in addition of long τ, ($t1/\tau$ <0.2), result in a highest density of UCN peak.
Some experiments like the measurement of neutron life time or neutron electric dipole moment require an intermittent supply of dense UCN pulses, therefore, there is no essential problem for this long period operation.

Table I program: rcnp.pulse.f, $\tau = 20$ sec
Proton current = 2 μ A (except 0.2 μ A(a))
Total proton power per 100 s = 3.2 kjoules
Proton power per pulse = 3.2/n kjoules
UCN100=3.2kj.F2, UCNpp=UCN100/n

Case	cycle n	period t2 sec	ppower kjoule	pulse t1 sec	t1/ τ	F2	ucn/pulse UCNpp $\propto$ UCN/cc	ucn/total UCN100 $\propto$ UCN/cc	pile
(a)	1.	100.00	3.20	40.00	2.000	.432	1.38	1.38	1.01
(b)	1.	100.00	3.20	4.00	.200	.906	2.90	2.90	1.01
	2.	50.00	1.60	2.00	.100	.952	1.52	3.05	1.10
(c)	4.	25.00	.80	1.00	.050	.975	.78	3.12	1.40
	8.	12.50	.40	.50	.025	.988	.40	3.16	2.15
(d)	16.	6.25	.20	.25	.0125	.994	.20	3.18	3.74

6. Ditributed UCN, Ripple and Pile

Table I also shows the UCN production for the change of the repetition cycle in 100 sec, where the life τ, and total proton power in 100 sec W1.t1.n, were fixed.
We have discussed the case (b) of one cycle. It is suitable for an experiment which requests high density pulses intermittently. However, the time structure of one pulse per 100 sec is too rough for many other experiments in practice. For such experiments, we will discuss to divide the protons to many short periods.

The (c) and (d) in Table I and Fig.3 are the cases of 4 and 16 cycles in 100 sec and the period of 25 and 6.25 sec respectively. There, the total production of UCN in 100 sec, UCN100, is almost saturated as 3.12 and 3.18 as seen in Table I, however, the periodic fluctuation of density defined by the following Ripple, is much smaller than that in case (b).

$$\text{Ripple} = (\max - \min)/(\max + \min)$$
$$= (1 - \exp(-(t2 - t1)/\tau))/(1 + \exp(-(t2 - t1)/\tau)) \qquad \text{Eq.6}$$

Furthermore, if the period t2 is much shorter than the life time τ, the next

production of UCN comes before the decay of previous UCN and they overlap. This overlap rises the number of UCN in the following cycles as seen in Fig.3 (d). The increase factor, Pile, is given by a superposition of decay tails,

$$\begin{aligned} \text{Pile} &= 1 + \exp(-t2/\tau) + \exp(-2^*t2/\tau) + \exp(-3^*t2/\tau) + \ldots \\ &= 1/(1 - \exp(-t2/\tau)) \qquad \text{Eq.7} \end{aligned}$$

$$\sim 1. \quad \text{for } t2 \gg \tau$$
$$\sim \tau/t2 \quad \text{for } t2 \ll \tau .$$

In case (d) with t2=6.25 sec, the pile factor is 3.7 and Ripple 0.15. It is suitable for experiments such as the measurement of the velocity spectrum of UCN.
It is noted that such repetition of short period pulses gives the maximum production of UCN in time average, UCN100 in Table I.
The proton current producing the spallation neutrons fluctuates with time, therefore, it is neessary to provide an incident flux monitor in an experiment which does not measure the incident flux directly such as the measurement of UCN spectrum by using a gravitational spectrometer.

7. Continuous UCN flow

The UCN stored life time is generally short (loss is large) in an experimental box, and the ripple of UCN in the source propagates to the experimental box directly. If a more stable UCN beam is required, a muffler cavity or buffer volume with a long life time should be located in front of the experimental box, in addition of the short period operation like (d).

8. Extrapolation from the November'04 run

The proton energy used in the November '04 run, case (a), was

392 MeV x 0.185 μ A x 40 s
= 72 W x 40 s
= 2.9 kjoules/pulse ,

and the temperature of cryostat was 1.2 K. These are not optimized conditions but they gave the UCN density of 0.47 UCN/cc. Table II is a simple extrapolation from this November run, for the UCN density vs. necessary proton power, for two views

of the peak and time average of UCN, where all parameters are kept in constant except the proton power. We assume a density of 40 UCN/cc for the ILL UCN system, though it is hard to define the UCN space density in the ILL system, Table II is an extrapolation from a non-optimized condition. Further improvement of factor ten may be not so difficult by improving the following points,

temperature of cryostat,
decay life time τ ,
choice of proton pulse width, t1
fast-neutron reflector,
and etc..

9. Reccomended operations for RCNP

A. 単発型実験

まず行なわれる、UCN 生成後の系の life τ の測定には Table III の (b) が良い。November'04 の (a) に比べ生成は約 2 倍になる。RCNP での過去の測定は再現性にかけるので、ヘリウム温度にたいする確実なデータをとる必要がある。統計を 4 倍にする kp=72 (計 2 時間) がよい。

B. 連続型実験

Table III の (d) が基準。UCN 強度を更に増したいときには、(d') のように proton current を増し、且、pulse width を増すというようにする。
Eq.5 に示したように (生成 UCN /放射能) = F2 であるので、一度 t1 を小にし F2 を大にした後は、放射能は常に生成 UCN に比例することに注意。
F2、Pile, Ripple に使われる寿命 τ は実測しなければ判らないが、15 ー 50 sec 程度と考えておけばよい。

Reference

Y.Masuda,T.Kitagaki,K.Hatanaka,M.Higuchi,S.Ishimoto,Y.Kiyanagi,K.Morimoto, S.Muto,M.Yoshimura, Phys.Rev.Lett.Vol.89,No.21 (2002) 284801-1-4

Table II Extrapolation from a not optizized run of Nov'04.
Proton power vs. UCN density

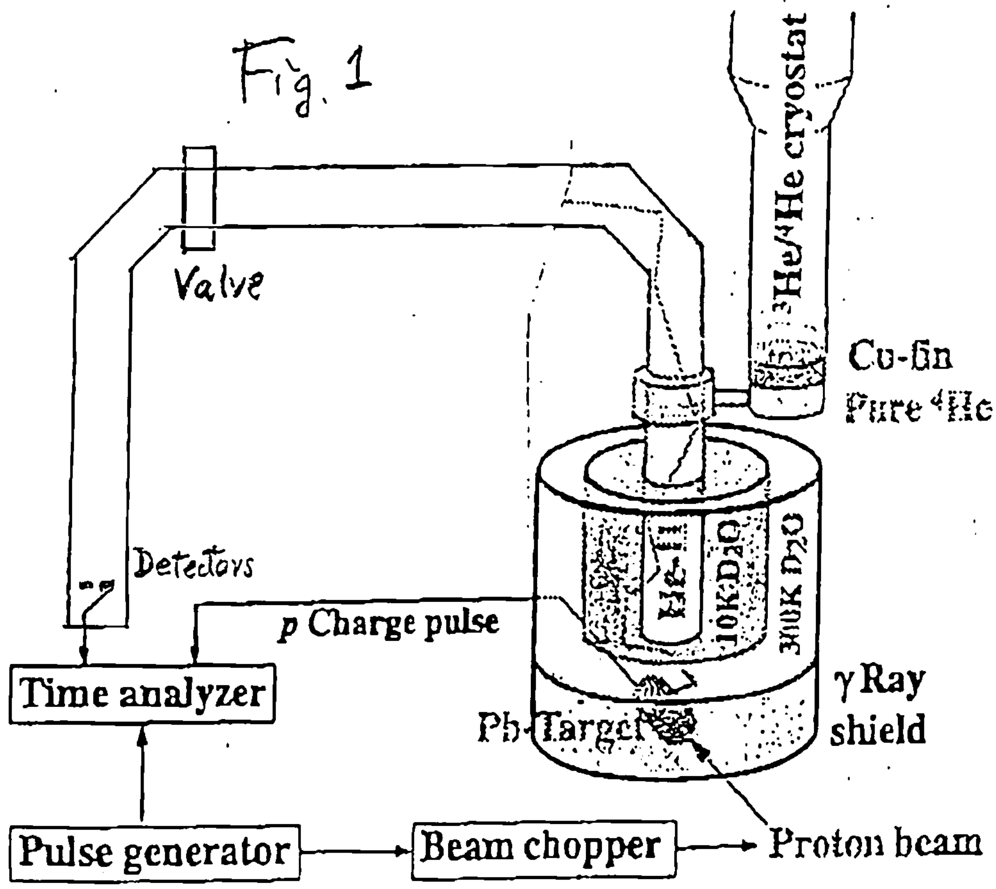
	proton power kW x sec	peak UCN UCN/cc	average UCN UCN/cc
RCNP Nov'04	0.072 x 40	0.47	0.09
RCNP	0.80 x 40 *	4.7	0.90
ILL		40	40
To be the same	6.1 x 40	40	7.6
with ILL	32 x 40	210	40
To be 100 times	610 x 40	4,000	760
of ILL	3200 x 40	21,000	4,000

* RCNP; 400 MeV x 2 μA = 0.80 kW.

Table III RCNP 用運転 Recommended operations

		(a)	(b)	(d)	(d')
	unit	Nov'04	Source sdy	UCN spect	UCN-2
proton current, ip	μ A	0.18	2.0	2.0	4.0
pulse width, t1	sec	40	4.0	0.25	0.50
proton peak power	kW	0.072	0.8	0.8	1.6
proton power,/pulse	kJ	2.9	3.2	3.2/16	12.8/16
period, t2	sec	100	100	6.25	6.25
duty cycle, t1/t2	%	40	4	4	8
放射能、比		0.9	1	1	4
生成 UCN					
計数(小カウンター)	cps	3.94	8.28	9.11	36.4
UCN 密度	/cc	0.47	0.99	1.09	4.36
pile (τ 20)		1.01	1.01	3.74	3.74

Fig. 1


Valve
$^3He/^4He$ cryostat
Cu-fin
Pure ^4He
He-II
10K D_2O
300K D_2O
Detectors
p Charge pulse
Time analyzer
γ Ray shield
Pb Target
Pulse generator
Beam chopper
Proton beam

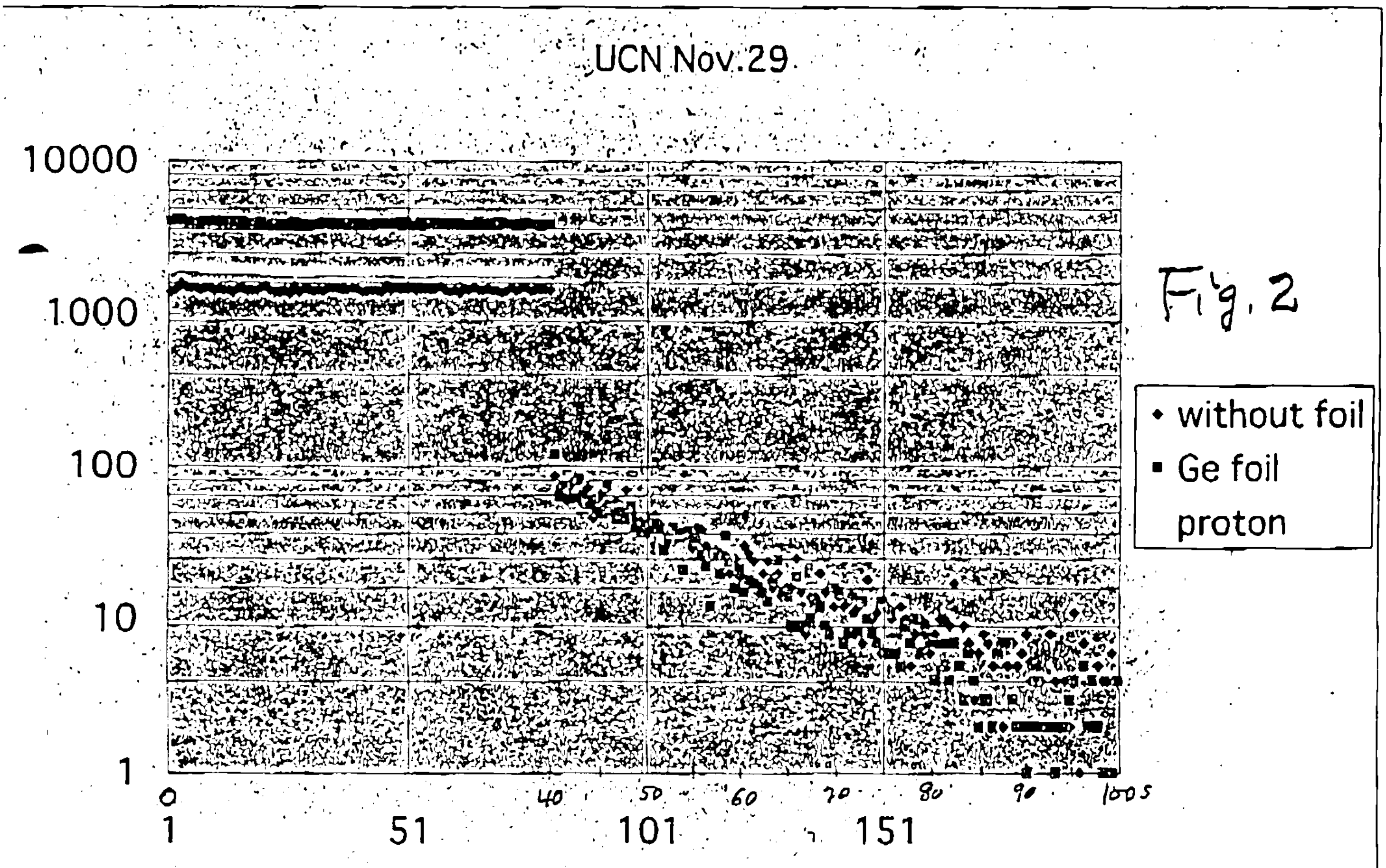

UCN Nov.29
10000
1000
100
10
1
0
40
50
60
70
80
90
100s
1
51
101
151
without foil
Ge foil
proton

Fig. 2

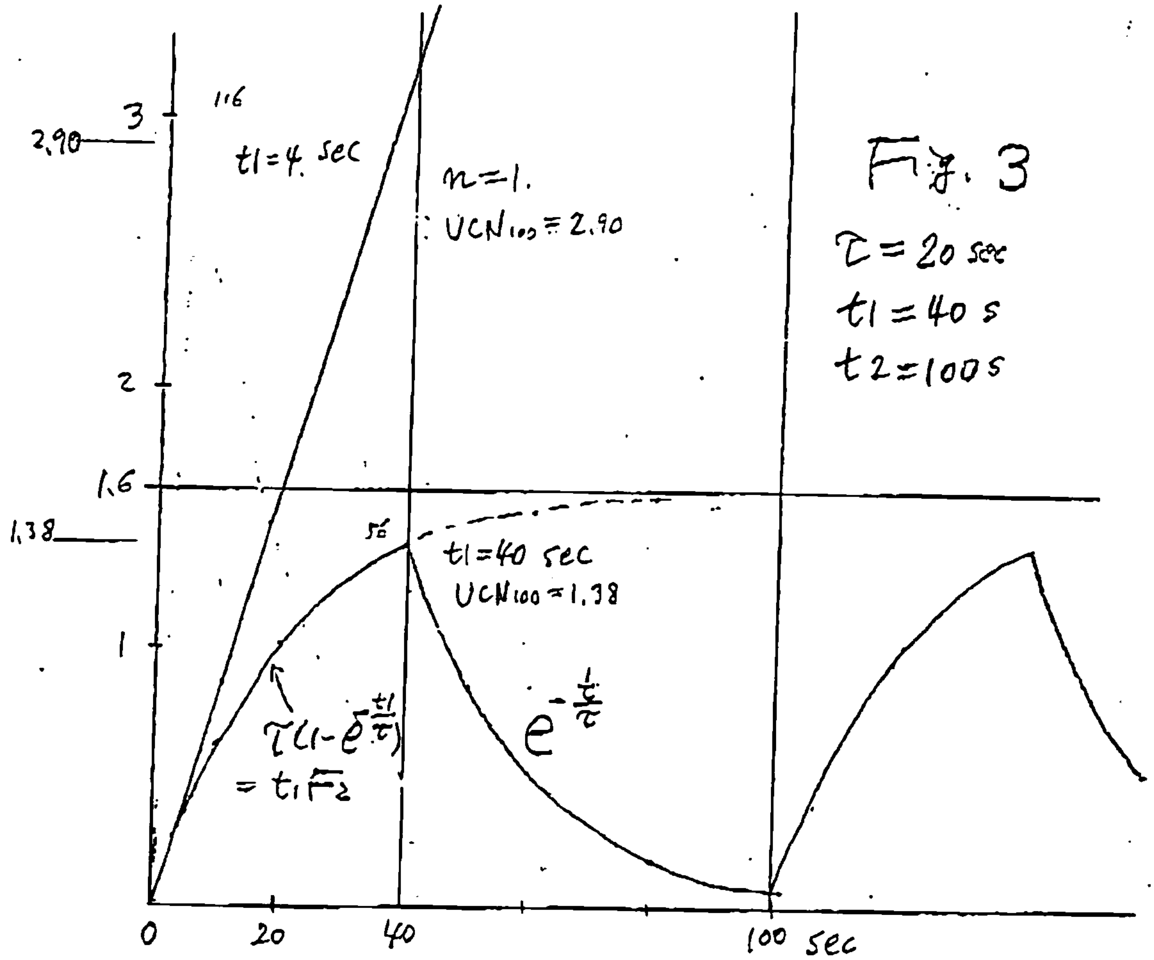

2.90
3
1.6
t1=4 sec
n=1.
∴ UCN100 = 2.90
2
1.6
1.38
1.56
t1=40 sec
UCN100 = 1.38
1
τ(1-e^(-t1/τ))
= t1F2
e^(-t/τ)
0
20
40
100 sec
τ = 20 sec
t1 = 40 s
t2 = 100 s

Fig. 3

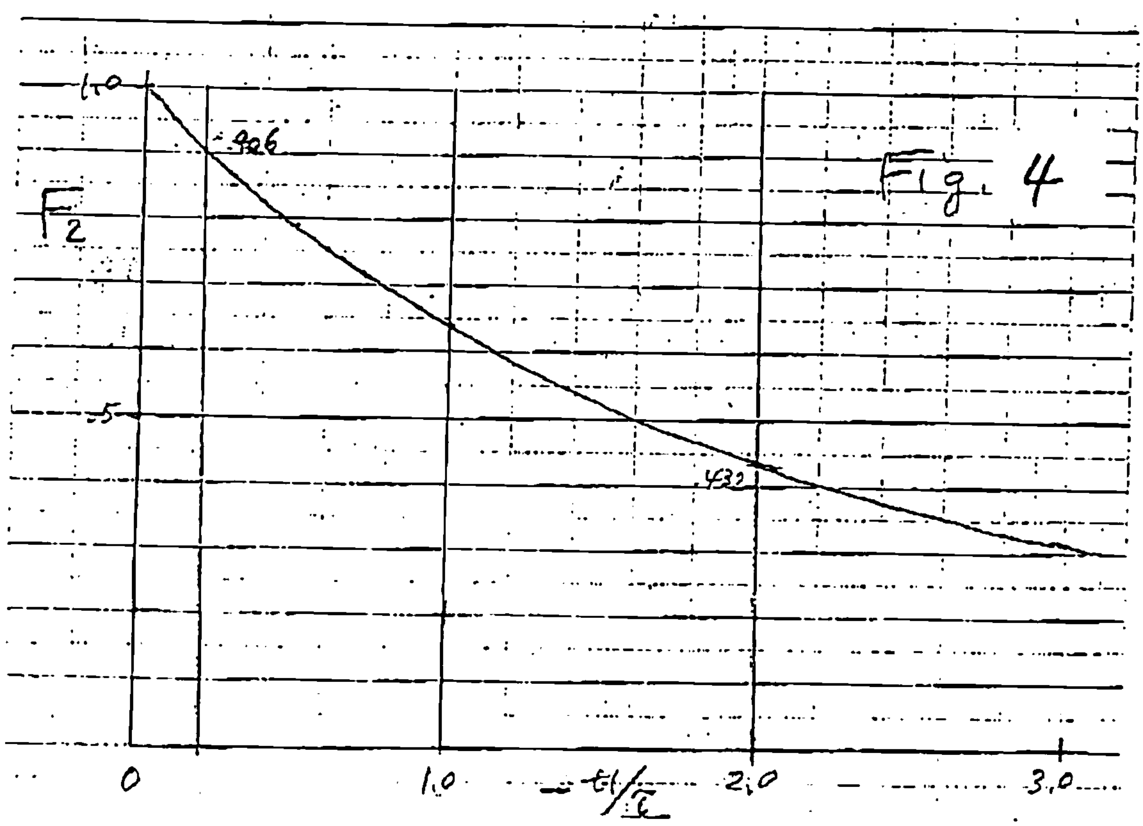

1.0
.906
F2
.5
.432
0
1.0
t1/τ
2.0
3.0

Fig. 4

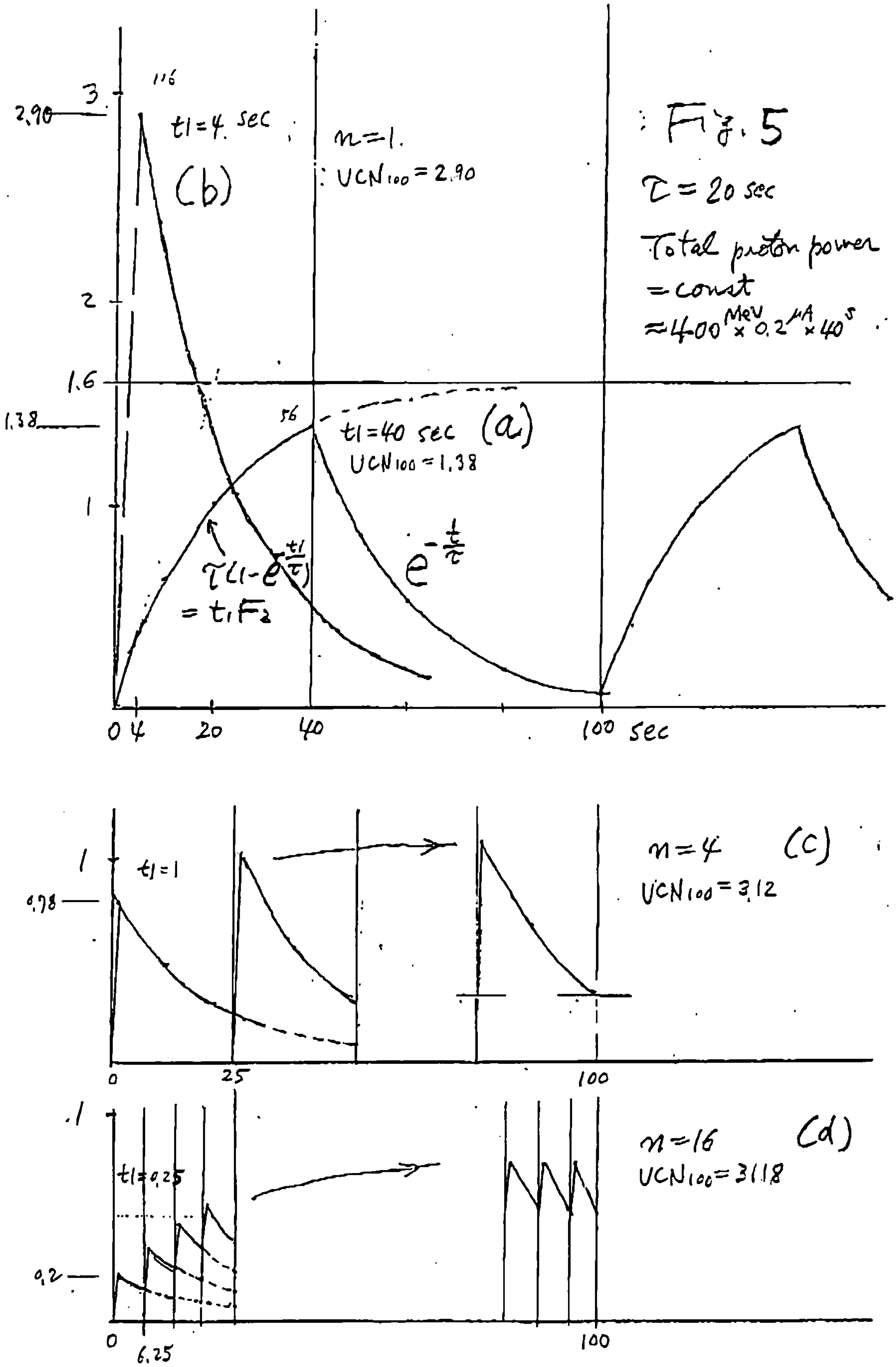


Fig. 5
τ = 20 sec
Total proton power
= const
≈ 400 MeV × 0.2 μA × 40 s
2.90
3
116
t1 = 4 sec
(b)
n = 1.
UCN100 = 2.90
2
1.6
1.38
56
t1 = 40 sec
(a)
UCN100 = 1.38
1
τ(1-e^(-t1/τ))
= t1F2
e^(-t/τ)
0
4
20
40
100 sec
1
t1 = 1
0.78
n = 4
(c)
UCN100 = 3.12
0
25
100
.1
t1 = 0.25
0.2
n = 16
(d)
UCN100 = 3.18
0
6.25
100