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STATISTICAL THEORY OF NON-ADIABATIC MAGNETIC TRAPS

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STATISTICAL THEORY OF NON-ADIABATIC MAGNETIC TRAPS

by

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ABSTRACT

In this paper we consider the trapping and containment of particles injected into a non-adiabatic magnetic mirror trap. The results of numerical orbit calculations are compared with the statistical theory which is shown to give essentially identical results. This statistical theory leads to simple expressions for the mean containment time and the mean density of trapped particles. These results indicate that the most significant factors in the non-adiabatic trapping process are the width of the acceptance cone (i.e. the solid angle in velocity within which the injected particles have a finite chance of capture) and the angular spread of the input beam. Optimum trapping requires that these two quantities be appropriately matched. When this is done the density approaches a limiting value (which is generally below the usually quoted 'Liouville limit') and the build-up time is a minimum. Provided this matching can be achieved there appears to be no special merit in using resonant non-adiabatic traps over any other form.

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CONTENTS

I. INTRODUCTION

The adiabatic invariance of the magnetic moment, usually regarded as a sine qua non for particle confinement in a mirror machine, makes it difficult (in a stationary field system) to trap particles which have been injected through one of the mirrors. However the magnetic moment is not a true constant and if it varies sufficiently during one transit externally injected particles may be temporarily trapped and significant particle densities may be accumulated; such an arrangement has been called a 'non-adiabatic trap'.

Most attention has hitherto been given to systems in which particles are injected parallel to the field and acquire a large magnetic moment on their first transit by <u>resonant</u> interaction with a spatially-periodic modulation of the central field of the machine; the modulation may either be axially symmetric[1,2,3] or produced by helical windings[4,5,6,7]. The lifetime of particles in such a trap is determined by successive encounters with the modulations which eventually reduce the magnetic moment sufficiently for escape through the mirrors.

Although there has been considerable theoretical and experimental work on these systems no clear understanding of the factors which lead to optimum containment in them has emerged, probably because particle behaviour is complicated by the resonant nature of the non-adiabatic interaction with the field. In this paper we begin by considering a very simple type of non-adiabatic trap in which the field perturbation is non-resonant. We examine the trapping and containment properties of this system, firstly by numerical calculation of particle orbits, and secondly by the application of statistical mechanics. From the statistical treatment we are led to conclusions which are applicable to more general systems, both resonant and non-resonant, and which clarify the basis of 'non-adiabatic trapping'. These results imply that there is no special advantage in resonant trapping over any other form of non-adiabatic trapping and that other features, such as the proper relationship of the beam and trap parameters, are of much greater significance than the form of the non-adiabaticity.

II. THE STOCHASTIC TRAP

We consider a mirror machine with a long, uniform central field of magnitude $1-h$, where $h \ll 1$. At each end there is a small discontinuity in the field strength, which rises abruptly to value unity, and beyond the discontinuities there are magnetic mirrors with maximum field values R (Fig.1). The mirrors are assumed to be adiabatic, that is, they reflect particles without change of magnetic moment. Passage of a particle through the field discontinuity is non-adiabatic and changes the magnetic moment, so the combined effect of the mirror and the field step is similar to that of a slightly non-adiabatic mirror with the step height h controlling the degree of non-adiabaticity. In this model it is possible to calculate particle orbits algebraically[3], thus avoiding the accumulation of errors which inevitably occurs when integrating equations of motion over many transits in 'real' fields[8].

The field is symmetrical about the z-axis so that the particle motion has two constants: the total velocity v and the canonical angular momentum p_θ. At any axial position z, only two quantities are needed to define the position and velocity of the particle: we will take these to be the normalised magnetic moment $\xi = v_\perp^2/v^2$ and the phase of the particle in its Larmor orbit φ.

Orbits are calculated as follows: we start in unit field outside one of the mirrors with a particle having $\xi = \xi_0$. Provided $\xi_0 < 1/R$ the particle enters the trap and arrives at the first field step with $\xi = \xi_0$ but with a phase φ which we assume is by then uncorrelated with its initial phase. This phase is therefore chosen at random and the change in ξ at the field step is calculated in the manner of ref. 3. It is also assumed that the distance L between the steps is long enough for us to disregard correlations between the phase with which the particle leaves one step and the phase with which it arrives at the other, so we again use a random number for φ at the second step. If now $\xi < 1/R$ the particle will escape through the end mirror; if $\xi > 1/R$ it will be reflected, and again we assume the phase is randomised. We follow a particle in this way through successive reflections until it eventually escapes and by computing the orbits of a large number of particles we build up a statistical picture of containment. On account of the use of random phase at each step this system is known as a stochastic trap: the assumption of phase randomisation by magnetic mirrors has been discussed by several authors[3,6,9].

III. NUMERICAL CALCULATIONS

Particles injected with $\xi_o = \xi_m = 1/R$ will enter the trap, and on their first transit acquire a spread in ξ above and below ξ_m. If $\xi'_{min} = \xi_m - \Delta\xi$ is the lowest value reached, then, because of the symmetry of the field and the time-reversal properties of the orbits, ξ'_{min} must also be the lowest value of initial ξ for which a particle can achieve ξ_m on its first transit. Thus by calculating $\Delta\xi$ for a group of particles having $\xi_o = \xi_m$ we find the 'acceptance band' $\xi_m \geqslant \xi \geqslant \xi_m - \Delta\xi$ within which particles have a chance of capture, but outside which they will either not enter the trap or will pass straight through. Within this band the probability of capture $p(\xi)$ varies from just over 0.5 at $\xi = \xi_m$ to zero at $\xi = \xi_m - \Delta\xi$: the calculated capture probability is shown in Fig.2a for a system with $R = 2$, $h = 0.01$, and particles with $v = 1$, $p_\theta = 2$ (mass and charge are taken as unity).

We now take several values of initial ξ uniformly spaced within the acceptance band and for each value obtain a mean containment time $t(\xi)$ by calculating the orbits of 5000 particles for each ξ. Only the time spent in the region between the field steps is recorded; this makes the calculation independent of the shape of the mirrors (which are simply introduced as a test on the value of ξ). Furthermore, when, as occasionally happens, a particle with large ξ is reflected from the field step, this is no different from a reflection at a mirror. The containment times are measured in units of L/v, the 'unit transit' time and $t(\xi)$ for the example quoted above is shown in Fig.2b.

The mean time spent in the trap by particles injected uniformly within the acceptance band is

$$T = \frac{1}{\Delta\xi} \int_{\xi_m - \Delta\xi}^{\xi_m} t(\xi)\, d\xi \qquad \ldots (3.1)$$

This quantity is found by integrating Fig.2b. Since T includes a contribution from particles which pass straight through the system without being trapped, each of which contributes a time $(1-\xi)^{-\frac{1}{2}}$, the mean time for which particles are actually trapped (i.e. with $\xi > \xi_m$), again averaged over the acceptance band is

$$T^* = T - \frac{1}{\Delta\xi} \int [1-p\ (\xi)]\ \ [1-\xi]^{-\frac{1}{2}}\, d\xi \qquad \ldots (3.2)$$

or if $\Delta\xi$ is small

$$T^* = T - (1-f)\ (1-\xi_m)^{-\frac{1}{2}} \qquad \ldots (3.3)$$

Here f is the fraction of particles in the band which are reflected at least once, and can be found by integrating Fig.2a. Because the containment time of the trapped particles greatly exceeds the "straight through" transit time $(1-\xi)^{-\frac{1}{2}}$, the difference between T and T^* is normally small.

T^* is of importance because if I is the current of particles being injected within the band $\Delta\xi$, the line density N_t of particles in the trap is, in the steady state

$$N_t = \frac{I}{v}\, T^* \qquad \ldots (3.4)$$

and therefore

$$\frac{N_t}{N_b} = T^*\ (1-\xi_m)^{\frac{1}{2}} \qquad \ldots (3.5)$$

where N_b is the line density in the beam. This ratio is a measure of the effectiveness of the trap.

In Table 1 we present the results of calculations for $R = 2$ and values of h between 0.01 and 0.05. All particles have $v = 1$, $p_\theta = 2$ (with these constants, when $\xi = 1$ the particles have unit Larmor radius, and when $\xi = 0$ they travel along field lines at radius $r = 2$). The most significant result is that, within the accuracy of the calculation, $T^* \Delta\xi$ is a constant independent of h, i.e.

independent of the degree of non-adiabaticity in the trap. The value of this constant depends on the mirror ratio. In Table 2 we summarise the results obtained at different mirror ratios, taking $h = 0.01$ in each case.

IV. APPLICATION OF STATISTICAL MECHANICS

In order to apply statistical mechanics to the problem of injection into the stochastic trap, we first consider the equilibrium state which would result if the trap were part of a closed system (we might, for example, regard the given mirror machine as one of a large number of identical units spaced end-to-end around a torus).

Since the particles are assumed to be non-interacting we can regard each as a member of an ensemble, all members having definite energy U and definite canonical angular momentum $p_\theta = P$. The appropriate ensemble distribution function for the equilibrium state of our closed system is then just the micro-canonical distribution:

$$F\,(\underline{r},\,\underline{p}) = \delta[p_r^2 + p_z^2 + (\frac{p_\theta}{r} - A_\theta)^2 - 2U]\;\delta[p_\theta - P]\,. \qquad \ldots\ (4.1)$$

Where the mass and charge of the particles are taken as unity and $\underline{A}$ is the vector potential of the axisymmetric mirror field. The Hamiltonian is

$$\mathcal{H} = \tfrac{1}{2}\left\{p_r^2 + p_z^2 + (\frac{p_\theta}{r} - A_\theta)^2\right\} \qquad \ldots\ (4.2)$$

and

$$\begin{aligned} p_r &= v_r = \dot{r} \qquad p_z = v_z = \dot{z} \\ p_\theta &= r\,(v_\theta + A_\theta) = r^2\dot{\theta} + rA_\theta \end{aligned} \qquad \ldots\ (4.3)$$

In this (hypothetical) equilibrium state of the closed system the fraction of particles which are in any region of phase space is found by integration of (4.1) over the appropriate domain. We will, for example, be interested in the fraction of particles whose velocity vector lies within a cone of semi-angle ψ about the z-axis. To calculate this it is convenient to carry out the integration over velocity rather than over momentum. The fraction of particles with their velocity vector in the cone ψ is then

$$q(\psi) = K \int_{-\infty}^{\infty} r\, dr\, dz\, d\theta\, dv_r\, dv_\theta \int_{(2U)^{1/2}\cos\psi}^{V} dv_z\, \delta[v_r^2 + v_z^2 + v_\theta^2 - 2U]\, \delta[rv_\theta + rA_\theta - P] \quad \ldots (4.4)$$

where K is the normalizing factor obtained by integrating over all v_z instead of only over the values $v_z > (2U)^{1/2}\cos\psi$.

For the stochastic trap considered in Section 2, the field is uniform over most of the trap so that we can put $A_\theta = rB/2$: we shall also consider only particles with positive P (these are particles whose orbits do not encircle the axis). The integrations over z and θ then merely change the normalization and the remaining integrations can be carried out as follows: we transform from r to $\rho \equiv r + v_\theta/B$ when

$$q(\psi) = K \int (\rho - V_\theta/B) d\rho\, dv_r\, dv_\theta \int_{(2U)^{1/2}\cos\psi} dv_z \delta[v_r^2 + v_z^2 + v_\theta^2 - 2U]\, \delta[B\rho^2/2 - P - v_\theta^2/2B] \quad \ldots (4.5)$$

The term involving v_θ/B will vanish by symmetry and the ρ integration then yields

$$q(\psi) = \tfrac{1}{2}K \int dv_r\, dv_\theta \int_{(2U)^{1/2}\cos\psi} dv_z\, \delta(v_r^2 + v_z^2 + v_\theta^2 - 2U) \quad \ldots (4.6)$$

The final integration may be performed by introducing polar co-ordinates in velocity space and gives, after normalisation:

$$q(\psi) = (1 - \cos\psi) \quad \ldots (4.7)$$

We see, therefore, that in the steady state the fraction of particles with their velocity vectors in a cone of semi-angle ψ is proportional to the solid angle subtended by this cone, just as for a uniform distribution in velocity space. It should be emphasized, however, that this result has been obtained only after integration over the volume of the trap; with this micro-canonical ensemble it is certainly <u>not</u> true that the velocity distribution is uniform at each point in space.

We now return to the steady state in which particles injected from a beam are captured into a mirror trap by non-adiabatic effects and lost at the same rate by the inverse of the capture process. We do this by regarding the steady state as part of the equilibrium described above.

The number of particles in the trapped domain ($\psi > \psi_m$) is, by (4.7)

$$N_t = \cos \psi_m \qquad \dots (4.8)$$

and the number of particles in the region $\psi_m > \psi > \psi_m - \Delta\psi$, which we take as the acceptance cone filled uniformly by the beam, is

$$N_b = \int_{\psi_m - \Delta\psi}^{\psi_m} \sin\psi \, d\psi \qquad \dots (4.9)$$

A particle in the acceptance cone has a probability $p(\psi)$ of being deflected by non-adiabatic effects into the trapped region in a single transit of the system, that is in a time $L/v_{\parallel}$. If $\bar{T} . \frac{L}{v}$ is the mean time which particles spend in the trapped region, then by balancing rate of injection with rate of loss we have

$$\frac{v}{L} \int_{\psi_m - \Delta\psi}^{\psi_m} \cos\psi \sin\psi \, p(\psi) \, d\psi = \frac{\cos \psi_m}{\bar{T}} \cdot \frac{v}{L} \qquad \dots (4.10)$$

and if $\Delta\psi$ is small this becomes

$$\bar{T} f \, \Delta\psi = \frac{1}{\sin \psi_m} \qquad \text{where } f = \frac{1}{\Delta\psi} \int_{\psi_m - \Delta\psi}^{\psi_m} p(\psi) \, d\psi \qquad \dots (4.11)$$

and since, with the notation of the previous section

$$f \, \bar{T} = T^* \qquad \dots (4.12)$$

we have

$$T^* \, \Delta\psi = \frac{1}{\sin \psi_m} \qquad \dots (4.13)$$

or if we work with $\Delta\xi$ instead of $\Delta\psi$

$$T^* \, \Delta\xi = 2(1 - \xi_m)^{\frac{1}{2}} = 2 \cos \psi_m \qquad \dots (4.14)$$

One consequence of equation (4.14) is that the product $T^* \Delta\xi$ is independent of the degree of non-adiabaticity: it has already been observed in Section 3 that this is borne out by the numerical results. However, equation (4.14) also predicts the numerical value of $T^* \Delta\xi$ and its dependence on the mirror ratio. This is compared with the numerical calculations in Fig.3 where $T^* \Delta\xi$ (as found in Section 3) is plotted as a function of the cosine of the mirror angle; this shows good agreement with equation (4.14).

V. DISCUSSION

In a simple non-adiabatic trap we have shown that if one assumes phase randomisation at mirror reflections then the results of numerical orbit calculations are identical with those obtained by direct application of statistical mechanics. It is noteworthy that the randomisation of Larmor phase alone is sufficient to ensure that the particles sample all the phase-space available to them. The statistical arguments are clearly independent of the exact mechanism of non-adiabatic trapping and so can be applied directly to any axisymmetric trap, stochastic or resonant, provided only that the acceptance cone $\Delta\xi_t$ is appropriately defined.

In applying the statistical arguments we have assumed that the spread of the beam, $\Delta\xi_b$, is such that it just fills the acceptance cone $\Delta\xi_t$. In this case the containment time is

$$T^* = \frac{2(1-\xi_m)^{\frac{1}{2}}}{\Delta\xi} \qquad \dots (5.1)$$

and from (3.5), the density ratio is

$$\frac{N_t}{N_b} = \frac{2(1-\xi_m)}{\Delta\xi} \qquad \dots (5.2)$$

where N_t and N_b are the <u>line</u> densities in the trap and beam respectively, and $\Delta\xi = \Delta\xi_b = \Delta\xi_t$.

If however the trap has an acceptance cone which is narrower than the beam, $(\Delta\xi_t < \Delta\xi_b)$, then only a fraction of the beam is utilized - the remainder passes straight through the system and may be disregarded. If the beam is uniform in ξ then the preceding formulae can be applied to the useful fraction $\Delta\xi_t/\Delta\xi_b$, which fills the acceptance cone $\Delta\xi_t$. The mean containment time <u>of this useful fraction</u>

is thus

$$T_t^* = \frac{2(1-\xi_m)^{\frac{1}{2}}}{\Delta\xi_t} \qquad \ldots (5.3)$$

while the mean containment time of the whole beam is

$$T_b^* = \frac{2(1-\xi_m)^{\frac{1}{2}}}{\Delta\xi_b} \qquad \ldots (5.4)$$

Similarly the density ratio is

$$\frac{N_t}{N_b} = \frac{2(1-\xi_m)}{\Delta\xi_b} \qquad \ldots (5.5)$$

where N_b is here the total (useful plus wasted) beam density. We see, therefore, that provided the input beam at least fills the whole acceptance cone ($\Delta\xi_b \geqslant \Delta\xi_t$) the trapped density is independent of $\Delta\xi_t$ and so of h, the degree of non-adiabaticity. The containment time of the captured particles can be increased by decreasing $\Delta\xi_t$ (equation 5.3) but correspondingly less of the beam is captured so that N_t is unaffected; the most economical use of the beam is thus when $\Delta\xi_t = \Delta\xi_b$.

If, on the other hand, $\Delta\xi_b < \Delta\xi_t$ so that the beam does not fill the acceptance cone the density and mean containment time will depend on how $\Delta\xi_b$ is disposed within $\Delta\xi_t$. However, the density reached in the trap will always be less than that given by (5.5) because all routes by which particles can enter the system are not being used while all escape routes are still available. This situation usually occurs in resonant trapping systems where, in addition to the special resonant entry orbit, there are generally other possible entry orbits, for example orbits close to the loss cone for which the system acts like a stochastic trap. Unless these orbits are also used for injection the density ratio given by (5.5) cannot be achieved. Thus, while resonant trapping is at first sight attractive because it captures the entire beam on the first transit, it can only attain the maximum accumulation efficiency if the resonant orbits are the sole entry and escape routes of the system. This in turn can only be achieved by using very large mirror ratios so that the acceptance cone coincides with the mirror loss cone and $\frac{1}{R} = \xi_m \simeq \Delta\xi \ll 1$. Then (5.1) reduces to

$$T^* = 2R \qquad \ldots (5.6)$$

which is in good agreement with earlier numerical results[3] for a five-period resonant trap at large mirror ratios.

In this discussion we have so far compared <u>line</u> densities in the beam and trap. When all the injected particles have the same p_θ, the input beam has an annular cross-section of thickness $2v \sin \psi_m/B$, whereas the trapped particles extend over an annulus of thickness $2v/B$. The ratio of the mean volume densities is therefore less than the ratio of line densities by a factor $\sim \xi_m^{1/2}$. However, if the beam has a large spread in p_θ and so is many Larmor radii wide, the cross-sections of beam and trap are more nearly equal and the ratio (5.2) will apply to the volume densities as well as line densities. If we combine these circumstances with the condition $\xi_m \simeq \Delta\xi \ll 1$ and in addition make one mirror effectively infinite so that the system is single-ended (this will double T^*) we obtain as the maximum possible density ratio the value $\frac{4}{\Delta\xi} = \frac{16}{(\Delta\psi)^2}$. This will be recognised as the oft-quoted 'Liouville limit'[10] which we see can only be attained in very special circumstances.

VI. CONCLUSIONS

We have shown that the calculation of containment in a non-adiabatic trap by statistical mechanics and by numerical orbit calculations leads to essentially the same results: we therefore conclude that non-adiabatic effects enable a beam of particles to fill a mirror trap to the limit set by conservation of density in phase-space. However it is important to observe that this statistical limit can only be achieved when the input beam completely fills all the acceptance cone(s) of the trap. Furthermore for the example we have considered, and for most cases likely to be set up in practice, this limit is lower than the 'Liouville limit' usually quoted.

In simple, axisymmetric stochastic traps the matching of the trap to the beam can readily be achieved by controlling the degree of non-adiabaticity h, and providing one can ensure that $\Delta\xi_t \leqslant \Delta\xi_b$ then the trap to beam density ratio

N_t/N_b is independent of $\Delta\xi_t$ and so of h. We should therefore expect stochastic trapping to be possible in any mirror system. The only effect of h is to determine the time to reach the steady state density; this time increases as h is decreased in accordance with equation (5.3).

In resonant traps the individual particle orbits are much more complicated, but the same basic considerations apply; the acceptance cones may occupy several separate regions in velocity space, and the requirement that they should all be filled by the beam may be difficult to satisfy in practice. For systems without axial symmetry, such as those with helical or spiral modulations, p_θ is no longer a constant and particles may enter and leave the system in diverse ways, including radially, and the complete filling of all entry cones is even more difficult. Consequently there appears to be no special advantage to be gained by using resonant trapping over stochastic trapping. It is more important to obtain a well collimated beam and then to optimise the trap to match its acceptance cone $\Delta\xi_t$ to the beam spread, $\Delta\xi_b$, thereby achieving simultaneously the maximum trapped density and the minimum build-up time.

VII. ACKNOWLEDGEMENTS

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TABLE 1

Effect of Varying h

$R = 2,\ (\xi_m = 0.5),\ v = 1,\ p_\theta = 2.$

h	0.01	0.02	0.03	0.04	0.05
$\Delta\xi$	0.0293	0.0585	0.0865	0.1141	0.1406
T	52.7	26.1	18.9	15.0	12.5
T^*	51.7	25.1	18.0	14.0	11.5
$T^*\Delta\xi$	1.53 ± 0.07	1.47 ± 0.08	1.56 ± 0.07	1.60 ± 0.04	1.62 ± 0.05

TABLE 2

Effect of Varying Mirror Ratio

$h = 0.01,\ v = 1,\ p_\theta = 2.$

R	1.023	1.067	1.140	1.333	2.00	5.00
ξ_m	0.9775	0.9375	0.8775	0.75	0.50	0.20
$\Delta\xi$	0.0436	0.0426	0.0409	0.0373	0.0296	0.0180
T	11.9	15.9	21.6	28.4	52.7	101.0
T^*	7.3	12.9	18.1	27.3	51.7	100.5
$T^*\Delta\xi$	0.32 ± 0.002	0.55 ± 0.02	0.78 ± 0.03	1.02 ± 0.03	1.53 ± 0.07	1.81 ± 0.17

VIII. REFERENCES

1. SINELNIKOV, K.D., FEDORCHENKO, V.D., RUTKEVICH, B.N., CHERNYI, B.M. and SAFRONOV, B.G., Zh. Tekhn. Fiz., 30, 256, (1960). [English Translation: Soviet Phys. - Tech. Phys., 5, 236, (1960).]

2. LAING, E.W. and ROBSON, A.E., J. Nuclear Energy Part C, 3, 146, (1961).

3. DUNNETT, D.A., LAING, E.W., ROBERTS, S.J. and ROBSON, A.E., J. Nuclear Energy Part C, (1965) (in press).

4. WINGERSON, R.C., Phys. Rev. Letters, 6, 446, (1961).

5. DREICER, H., KARR, H.J., KNAPP, E.A., PHILLIPS, J.A., STOVALL, E.J. and TUCK, J.L. Nuclear Fusion 1962 Supplement, Part 1, 299, (1962).

6. WINGERSON, R.C., DUPREE, T.H. and ROSE, D.J., Phys. Fluids, 7, 1475, (1964).

7. DEMIRKHANOV, R.A., KURSANOV, Yu.V., BARATOV, D.G. and KHARIN, G.V. Zh. Tekhn. Fiz., 34, 60 (1964). [English Translation: Soviet Phys. - Tech. Phys., 9, 45, (1965).]

8. GARREN, A., RIDDELL, R.J., SMITH, L., BING, G., HENRICH, L.R., NORTHROP, T.G. and ROBERTS, J.E., Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 31, 65, United Nations, N.Y. (1958).

9. GRAD, H. and VAN NORTON, R., Nuclear Fusion 1962 Supplement, Part 1, 61, (1962).

10. HUBERT, P. Rapport EUR - CEA - FC. No.239, (1964)

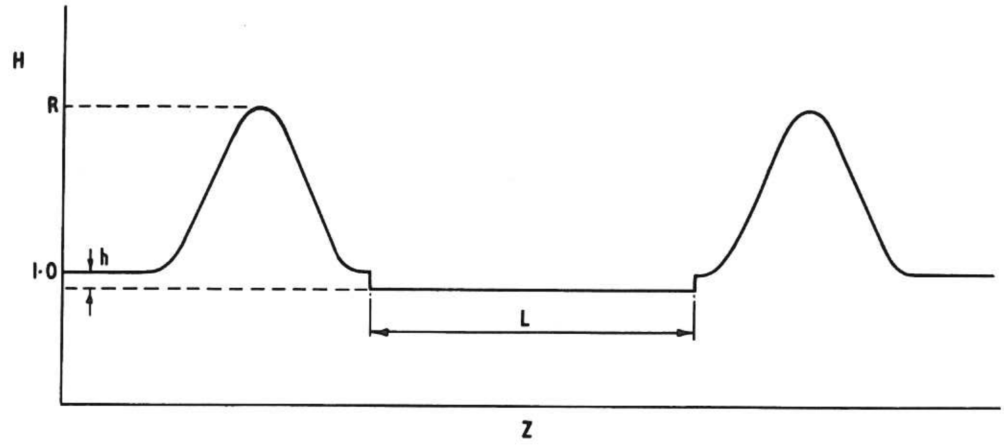

Fig. 1 Stochastic trap (CLM-P77)

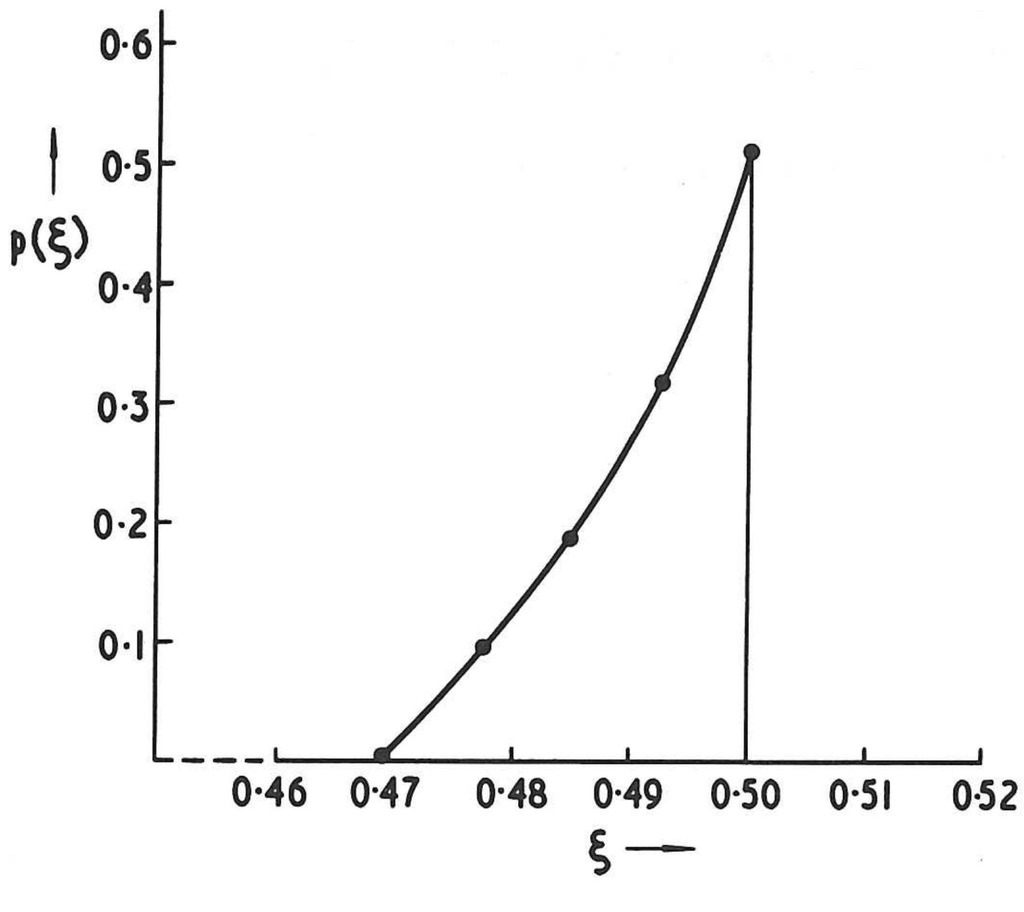

Fig. 2(a) (CLM-P77)
Capture probability as a function of ξ

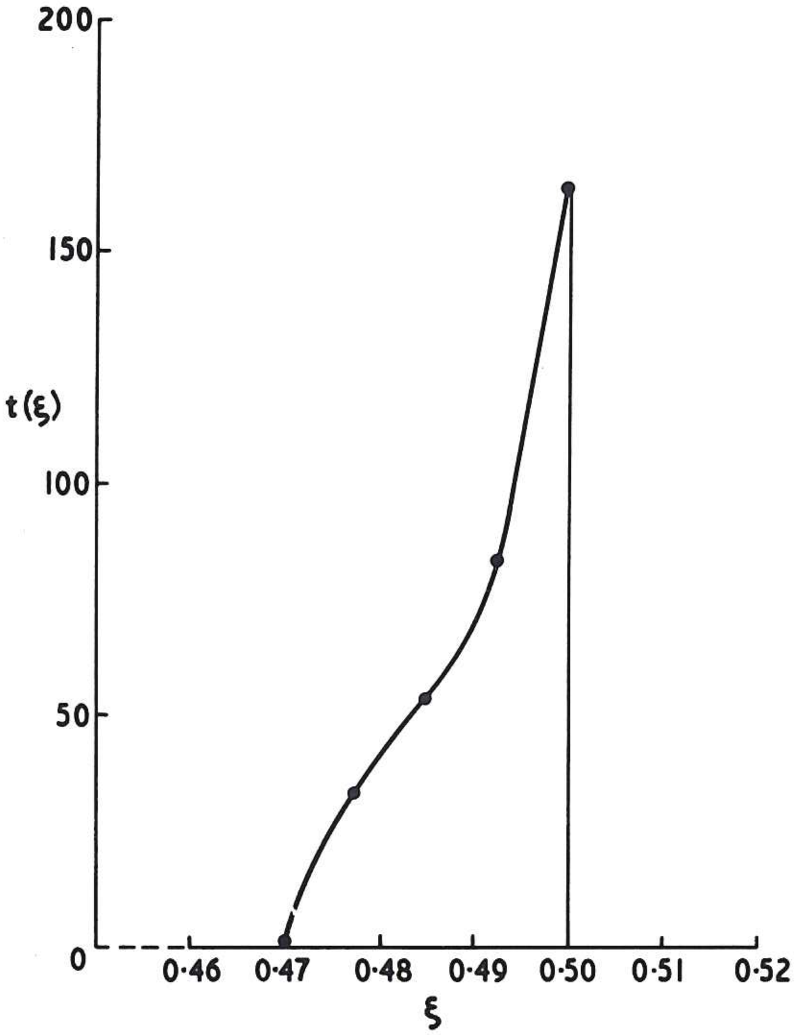

Fig. 2(b) Mean lifetime as a function of ξ (CLM-P77)

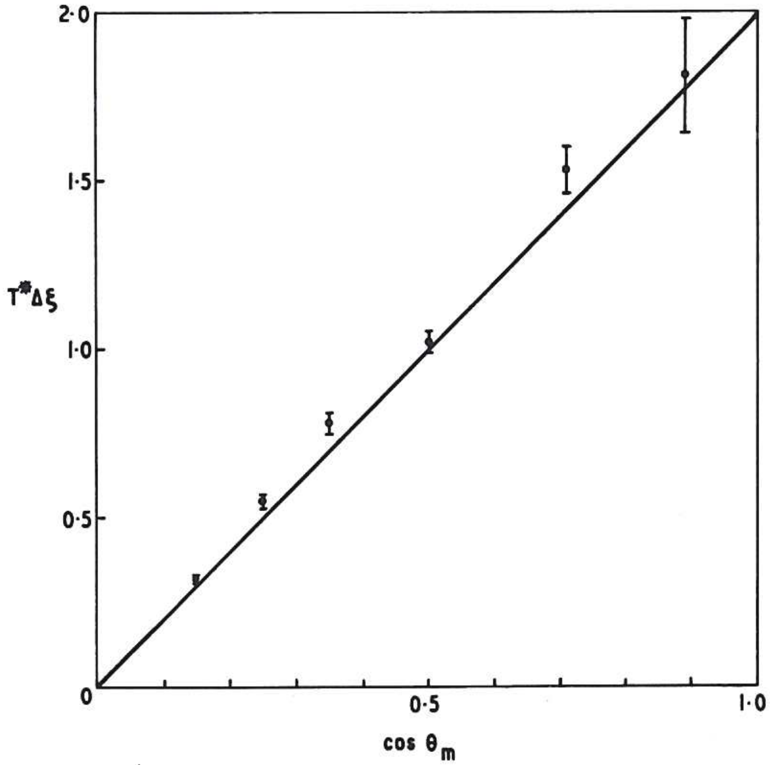

Fig. 3 $T^*\Delta\xi$ as a function of $\cos\theta_m$ (CLM-P77)