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HELIUM-3 NEUTRON POLARISERS

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1. INTRODUCTION

The attractive features of polarised 3He as a broad-band polarising filter for thermal and epithermal neutrons has been recognised for over two decades (1). The cross-section for neutron capture σ_c is large (5327b atom^{-1} at 25.3 meV, decreasing inversely with neutron velocity), and the ratio of the cross-section for antiparallel spin capture to the total cross-section has been experimentally determined to be 1.010 + 0.032 (2). In common with all other resonance absorption polarising filters (3), the properties of polarised 3He are dominated by the capture cross-section, and any non-resonant capture and scattering can be ignored.

The most obvious method for polarising solid 3He is to cool the nuclear moments in a large applied magnetic field ('Brute Force' polarisation). In principle a 3He nuclear polarisation P_{He-3} ~ 55% is achievable at 10mK in a 10T field, however the neutron beam heating due to capture makes this method non-viable in high flux beams (4). The recent resurgence of interest in using polarised 3He as a neutron polariser follows the discovery of an optical pumping method which can provide high nuclear polarisations (P_{He-3} ~ 70%) in high pressure gaseous samples (5). This new technique utilises the spin transfer from optically pumped Rb vapour, and is undergoing extensive development in the USA and France. The interest for the neutron scattering community is twofold: a cell containing highly polarised 3He can be used as an efficient broad-band polarising filter at neutron energies up to 1eV and beyond, and there is also the possibility of combining the polarisation and detection properties of 3He to provide a spin analyser-detector as a single instrument component.

The main objective of this paper is to examine the polarised 3He cell parameters, ie polarisation and gas pressure, required for the neutron polariser and spin analyser-detector applications. Optimised values for the design parameters are derived and used to calculate the neutron energy dependences of various efficiency parameters which define the effectiveness of the polariser and spin analyser-detector.

2. DYNÁMIC POLARISATION IN Rb/3He MIXTURES

High pressure polarised 3He gas is most readily achieved in gas mixtures containing an alkali metal vapour where the 3He nuclei are polarised by spin exchange with the laser-pumped alkali metal vapour. The alkali metal, normally Rb, contains a fully polarised valence electron spin, and the spin exchange is a consequence of the hyperfine interaction between this electron spin and the 3He nuclear spin during binary collisions. In the experimental set-up of Coulter et a (5), 3He gas at pressures up to several atmospheres was contained in a glass cell together with a Rb droplet and ~100 Torr of nitrogen as a buffer gas to assist the optical pumping process. The cell was heated to approximately 200°C and the Rb component of the gas first polarised by illumination with D_1 resonance light (795nm). The 3He-Rb spin exchange probabilities were sufficiently large to produce 3He polarising times of a few hours, with 3He polarisation relaxation times of about 40 hours. 3He polarisations greater than 70% were achieved in a volume of 6cm3 at a density of 3×10^{20} at cm^{-3} (10 atm at STP).

3. NEUTRON POLARISER PARAMETERS

In this section we define the parameters of a polarised ^{3}He cell which determine its effectiveness as both a neutron polarising filter and as a spin analyser-detector. The underlying principle by which they operate is the large difference in the neutron capture cross-sections for neutron spins parallel (σ_+) and antiparallel (σ_-) to the nuclear polarisation, which, for the pure (I-½) resonance absorption in ^{3}He is given by

$$\sigma_\pm = \sigma_c (1 \mp P_{He\text{-}3}) \tag{3.1}$$

where σ_c is the unpolarised beam capture cross-section, and $P_{He\text{-}3}$ is the ^{3}He nuclear polarisation. The transmittances $T_\pm$ of ($\pm$) spin neutrons are given by $\exp-(\sigma_\pm Nt)$, where Nt is the ^{3}He atomic thickness (at.cm^{-2}), and these have a significant neutron energy dependence consequential to the energy dependence of the capture cross-section σ_c.

3.1 Neutron Polarisers

The three relevant polarising filter parameters are the polarising efficiency:

$$P = (T_+ - T_-)/(T_+ + T_-) = \tanh(\sigma_c P_{He\text{-}3} Nt), \tag{3.2}$$

the unpolarised beam transmittance,

$$T = (T_+ + T_-)/2 = \exp(-\sigma_c Nt) \cosh(\sigma_c P_{He\text{-}3} Nt) \tag{3.3}$$

and the polariser quality factor

$$Q = P\,T^{1/2} \tag{3.4}$$

3.2 Spin Analyser-Detectors

The corresponding quantities which determine the effectiveness of spin analyser-detectors are the spin analyser efficiency:

$$P_A = (T_- - T_+)/[2-(T_+ + T_-)]$$
$$= \sinh(\sigma_c P_{He\text{-}3} Nt)/[\cosh(\sigma_c P_{He\text{-}3} Nt) - \exp(\sigma_c Nt)], \tag{3.5}$$

the detector efficiency for unpolarised neutrons,

$$\eta = 1 - T \tag{3.6}$$

and the spin analyser-detector quality factor,

$$Q_A = P_A \eta^{1/2} \tag{3.7}$$

In contrast to the polariser, the analyser efficiency decreases with increasing atomic thickness Nt and a further useful spin analyser parameter is its maximum efficiency $P_A(\mathrm{Max})$ which is given by the $\sigma_c Nt \rightarrow 0$ approximation of eqn (3.5):

$$P_A(\mathrm{Max}) = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-) = -P_{He\text{-}3} \tag{3.8}$$

3.3 Commmon Relationships

For polarised ^3He neutron polarisers P, T and η are always positive whereas P_A is negative, and these are interrelated as follows:

$$PT = -P_A\eta \tag{3.9}$$

In discussing spin analyser efficiencies and quality factors we shall generally simply use their moduli $|P_A|$ and $|Q_A|$.

These efficiencies are related to the quality factors as follows:

$$|Q/Q_A| = |P/P_A|^{1/2} = (\eta/T)^{1/2} \tag{3.10}$$

4. PERFORMANCE OF ^{3}He NEUTRON POLARISERS AND SPIN ANALYSERS

The most useful starting point for discussing the properties of filter polarisers and spin analysers is to use the defining equations given in section 3 to calculate universal 'constant polarisation' curves (6). For ^{3}He neutron polarisers, once P is fixed, $\sigma_c Nt$ and P_{He-3} are related through eqn (3.2), and the complete series of polariser and analyser parameters are calculable as a function of P_{He-3} (or $\sigma_c Nt$). In this section we present two sets of polariser and analyser parameter curves for ^{3}He neutron polarisers with widely different polarising efficiencies. We then proceed to use the results of these calculations to evaluate the neutron energy dependences of the efficiency parameters for ^{3}He polarisers and spin analysers with optimised values for the ^{3}He atomic thickness Nt and nuclear polarisation P_{He-3}.

4.1 Universal Curves

Figure 1 shows the polariser transmittance T, spin analyser polarising efficiency $|P_A|$, and analyser detection efficiency η for a ^{3}He filter with constant polarising efficiency $P = 0.95$ (or equivalently $\sigma_c P_{He-3} Nt = 1.832$), as a function of the helium polarisation P_{He-3} and absorption parameter $\sigma_c Nt$. These are suitable design parameters for a ^{3}He filter used as a polariser in neutron scattering experiments where the need for a high polarising efficiency is extremely important. The polariser transmittance rises sharply as P_{He-3} increases, and combining this with the requirement that any effective polarising filter should ideally have $T > 0.3$, we conclude that for the polariser application we need an optically polarised ^{3}He cell with nuclear polarisation $P_{He-3} \simeq 0.80$ and absorption parameter $\sigma_c Nt \simeq 2.3$. Neutron scattering applications require the filter to operate at neutron energies $\sim$ 1eV (and beyond), where $\sigma_c \sim$ 830b atom^{-1}, and this determines the ^{3}He atomic thickness to be $Nt \sim 2.76\text{x}10^{21}$ atom cm^{-2}. This atomic thickness can, for example, be achieved with a 10 atm (at 300K) ^{3}He cell which has a length $t \simeq 11.3$cm. The specification compares reasonably favourably with the currently achievable $P_{He-3} \simeq 0.70$ in a 10 atm cell of length 5cm.

The spin analyser efficiency $|P_A|$, in contrast to P, rises sharply with decreasing absorption parameter $\sigma_c Nt$, and the values in Fig 1 fall significantly short of the diagonal line representing $|P_A(Max)| = P_{He-3}$. We conclude that the behaviour of a filter with absorption parameters $\sigma_c Nt$ in the 2-10 range departs significantly from the low $\sigma_c Nt$ limit represented by eqn (3.8), and that this filter is too absorbent for the spin analyser application, unless ^3He polarisations in excess of 95% can be achieved.

To produce an effective spin analyser we therefore require a lower atomic thickness Nt, but must retain a usefully large absorption parameter to give an acceptable detector efficiency. Figure 2 shows the filter parameters T, $|P_A|$, and η where $\sigma_c Nt$ has been reduced to one tenth of the values of Figure 1; these curves correspond to constant polarisation curves where P = 0.181, or $\sigma_c P_{He-3} Nt = 0.183$. It is immediately evident that $|P_A|$ now approaches $|P_A(Max)|$, and is in fact within 90% of $|P_A(Max)|$ for all P_{He-3} values greater than ~ 0.5. It is also clear that there is a significant increase in $|P_A|$ towards larger P_{He-3} values, and we conclude that for the spin analyser-detector application it is important to achieve ^3He polarisations approaching unity.

The data of Figure 1 and 2 have also been used to calculate universal curves for the polariser quality factor Q and spin analyser quality factor $|Q_A|$; these are shown in Figure 3. The plots confirm a) that the polariser application requires the more absorbent filter ($\sigma_c P_{He-3} Nt = 1.832$) and b) that for ^3He polarisations up to $\sim$ 75%, the lower density filter has the more effective performance as a spin analyser. It is also apparent that the spin analyser quality factors $|Q_A|$ will in general always be lower than the best polariser quality factors Q obtained with a highly absorbing filter.

4.2 Neutron Energy Dependences

Universal curves provide a powerful method for assessing the properties of neutron polarising filters and polarisation analysers. In practice, however, an operational filter always has a fixed P_{He-3} (ie the maximum value attainable) and a fixed atomic thickness Nt chosen by the filter designer to optimise the performance over the neutron energy range (or equivalently the σ_c range) corresponding to the demands of the neutron experiments. For condensed matter physics scattering experiments we can regard the useful neutron energy band to be 0-1 eV. The neutron experimentalist requires good filter characteristics over as large a part of this energy range as possible, and it is essential to know how the filter parameters vary over this energy band.

We now present calculated values of the neutron energy dependences of P, T, $|P_A|$ and η for two gaseous polarised ^3He filters. The filter parameters were chosen on the basis of the results described in Section 4.1; the first is suitable as a filter polariser and the second as a spin analyser-detector. For the polariser we have selected a filter with P_{He-3} = 0.80, ^3He atomic density N=2.45x10^{20} atom cm^{-3} (this corresponds to 10 atmospheres of gas pressure at 300K), and a thickness t = 5cm; this is designated Filter A. For the spin analyser-detector we have retained the ^3He polarisation value P_{He-3} = 0.80, but have reduced the atomic density to N=0.49x10^{20} atom cm^{-3} (ie ~ 2 atmos. gas pressure at 300K) and the cell thickness to t=2.5cm; this is designated Filter B.

The neutron energy dependences of the polarising efficiency P, transmittance T, and polariser quality factor Q for Filter A are shown in Figure 4. The overall performance is very satisfactory over the entire 10-1000meV range; note that the polarising efficiency at energies less that 100 meV is essentially 100%, and that the lowest polarising efficiency is P=0.67 at 1eV.

The neutron energy dependences of the spin analyser efficiency $|P_A|$, detector efficiency η, and analyser quality factor $|Q_A|$ for Filter B are shown in Figure 5. The overall performance of this filter as a spin-analyser is very good over the whole energy range, however it should be noted that $|P_A|$(Filter B) < P(Filter A) and $|Q_A|$(Filter B) < Q (Filter A) over most of this range. Thus, in general, a filter of this type will have a better performance as a polariser than as a spin analyser.

5 CONCLUSIONS

Generalised curves have been presented to illustrate the performances of gaseous polarised ^3He cells when they are used as neutron polarisers and spin analyser-detectors. The efficiency parameters of the devices are strongly dependent on the ^3He polarisation and atomic thickness in both applications. The main conclusions are that for neutron scattering experiments in the 0.01-1 eV energy range:

a) it is important to improve the currently achievable ^3He polarisation from P_{He-3}=0.70 to P_{He-3} = 0.80 (or greater),

b) it is necessary to increase the effective area of the cell to accommodate ~ 6 cm^2 beams in the case of the polariser and ~10cm^2 scattered beams for the spin analyser, and

c) there is no compelling reason to develop the optical pumping technique to accommodate gas pressures in excess of 10 atmospheres; the recommended optimum gas pressures are ~10 atmos in a cell length ~ 5cm for the polariser, and ~ 2 atmos in a cell length ~ 2.5 cm for the spin analyser. The shorter cell thickness of the spin analyser is necessary to preserve resolution in neutron time-of-flight experiments, e.g. when it is used as a detector in a pulsed neutron source spectrometer.

REFERENCES

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FIGURE CAPTIONS

Figure 1

Universal curves showing the polariser and spin analyser parameters for a polarised ^{3}He filter with $P=0.95$ or $\sigma_c P_{He-3} Nt=1.832$, as a function of ^{3}He polarisation and the absorption parameter $\sigma_c Nt$.

Figure 2

Universal curves showing the polariser and spin analyser parameters for a polarised ^{3}He filter with $P=0.181$ or $\sigma_c P_{He-3} Nt=0.183$, as a function of ^{3}He polarisation and the absorption parameter $\sigma_c Nt$.

Figure 3

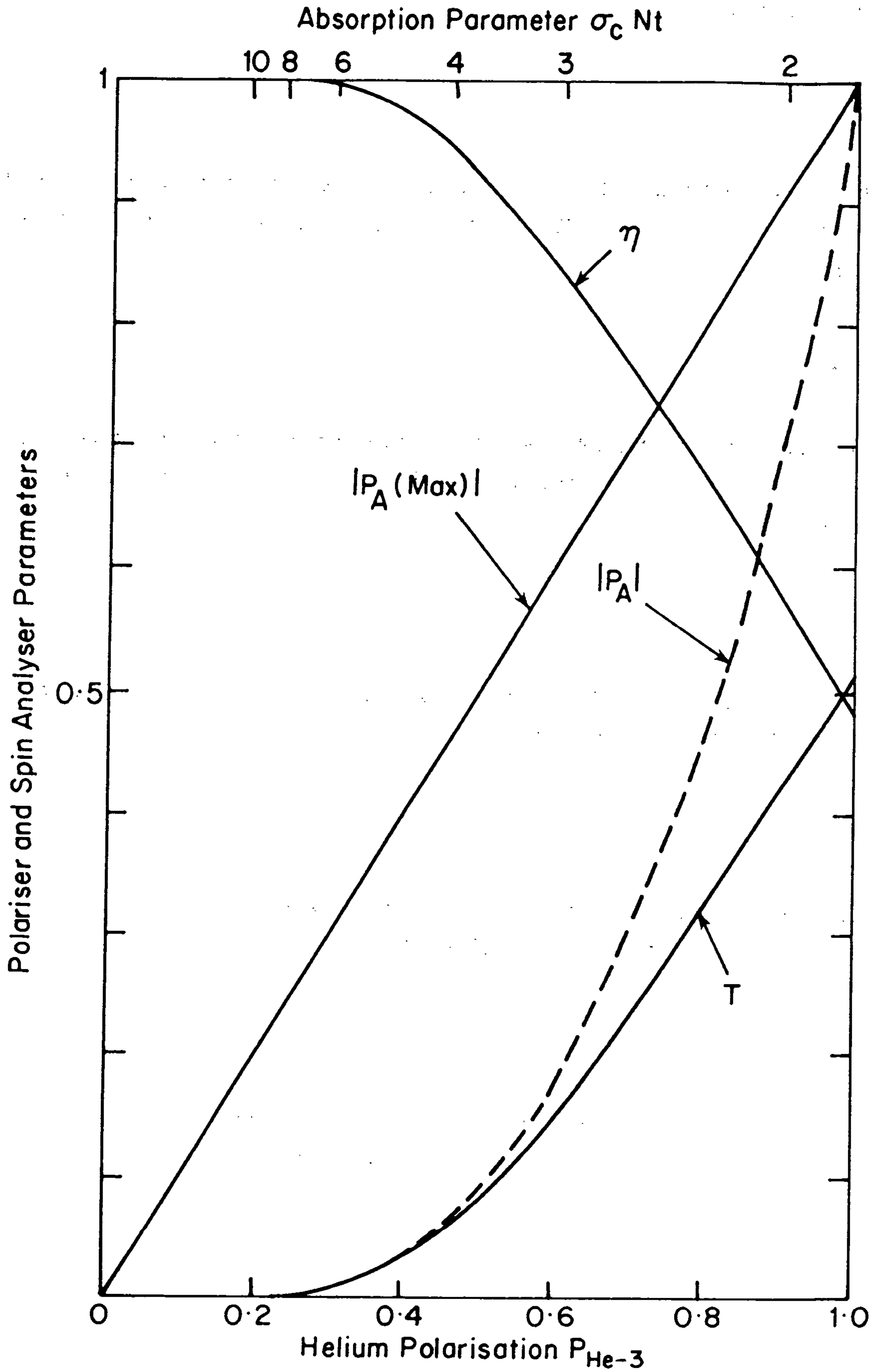
Universal curves for the quality factors Q and $|Q_A|$ of the polarised ^{3}He filters described in Figs 1 and 2 as a function of ^{3}He polarisation.

Figure 4

Neutron energy dependences of the polariser parameters P, T, and Q for a polarised ^{3}He filter with 80% ^{3}He polarisation and atomic thickness $Nt=1.225\times10^{21}$ at.cm^{-2}.

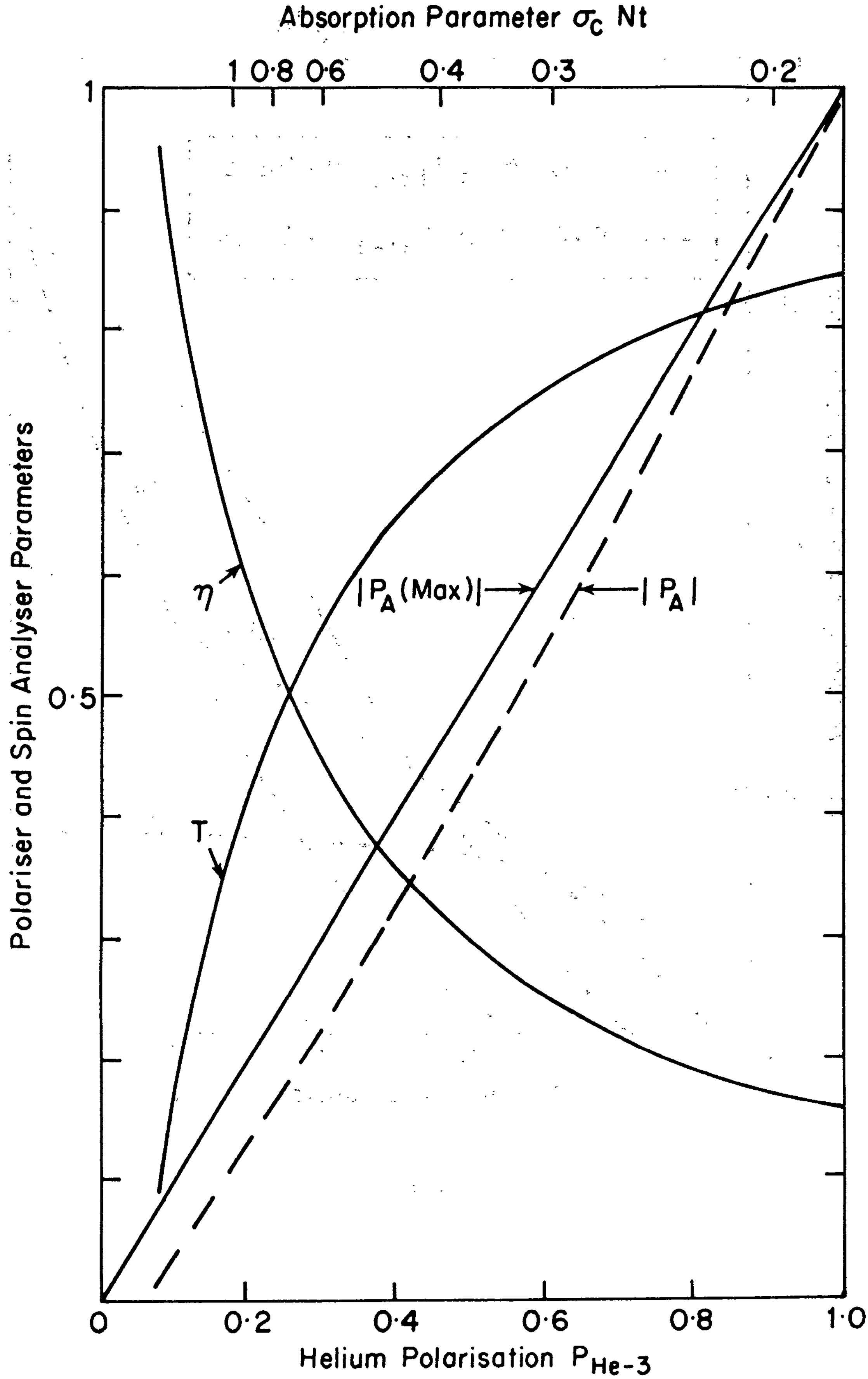
Figure 5

Neutron energy dependences of the spin analyser-detector parameters $|P_A|$, η, and $|Q_A|$ for a polarised ^{3}He filter with 80% ^{3}He polarisation and atomic thickness $Nt = 1.225 \times 10^{20}$ at.cm^{-2}.



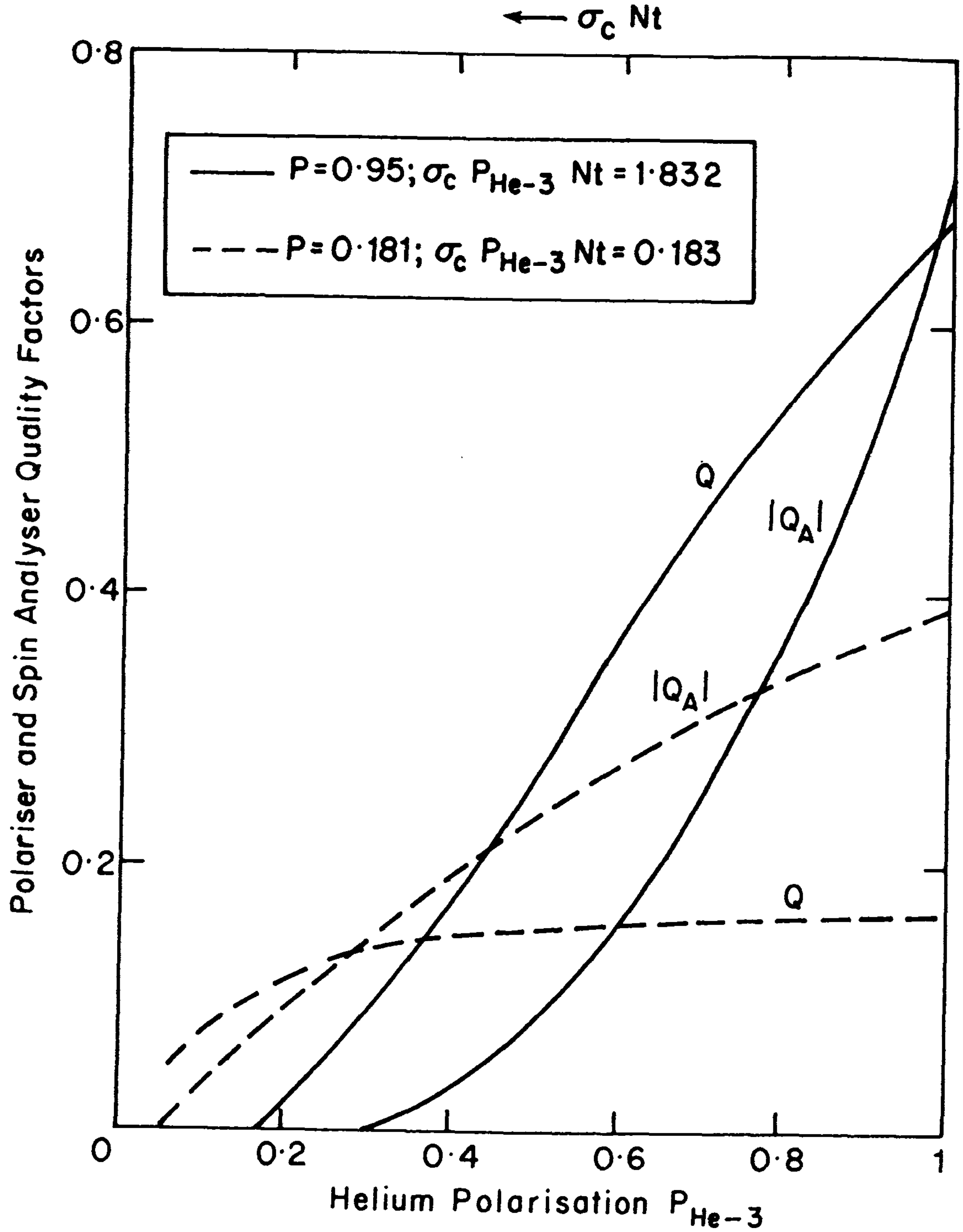
Absorption Parameter σ_c Nt
10 8 6 4 3 2
1
0·5
0
Polarisation and Spin Analyser Parameters
η
$|P_A\,(Max)|$
$|P_A|$
T
0·2 0·4 0·6 0·8 1·0
Helium Polarisation P_{He-3}

Fig. 1



Absorption Parameter σ_C Nt
1 0·8 0·6 0·4 0·3 0·2
1
0·5
0
0·2 0·4 0·6 0·8 1·0
Polariser and Spin Analyser Parameters
Helium Polarisation P_{He-3}
η
T
$|P_A(\mathrm{Max})|$
$|P_A|$

Fig.2



← σc Nt
P=0·95; σc PHe-3 Nt = 1·832
P=0·181; σc PHe-3 Nt = 0·183
Q
|QA|
|QA|
Q
0·8
0·6
0·4
0·2
0
0·2
0·4
0·6
0·8
1
Polariser and Spin Analyser Quality Factors
Helium Polarisation PHe-3

Fig.3

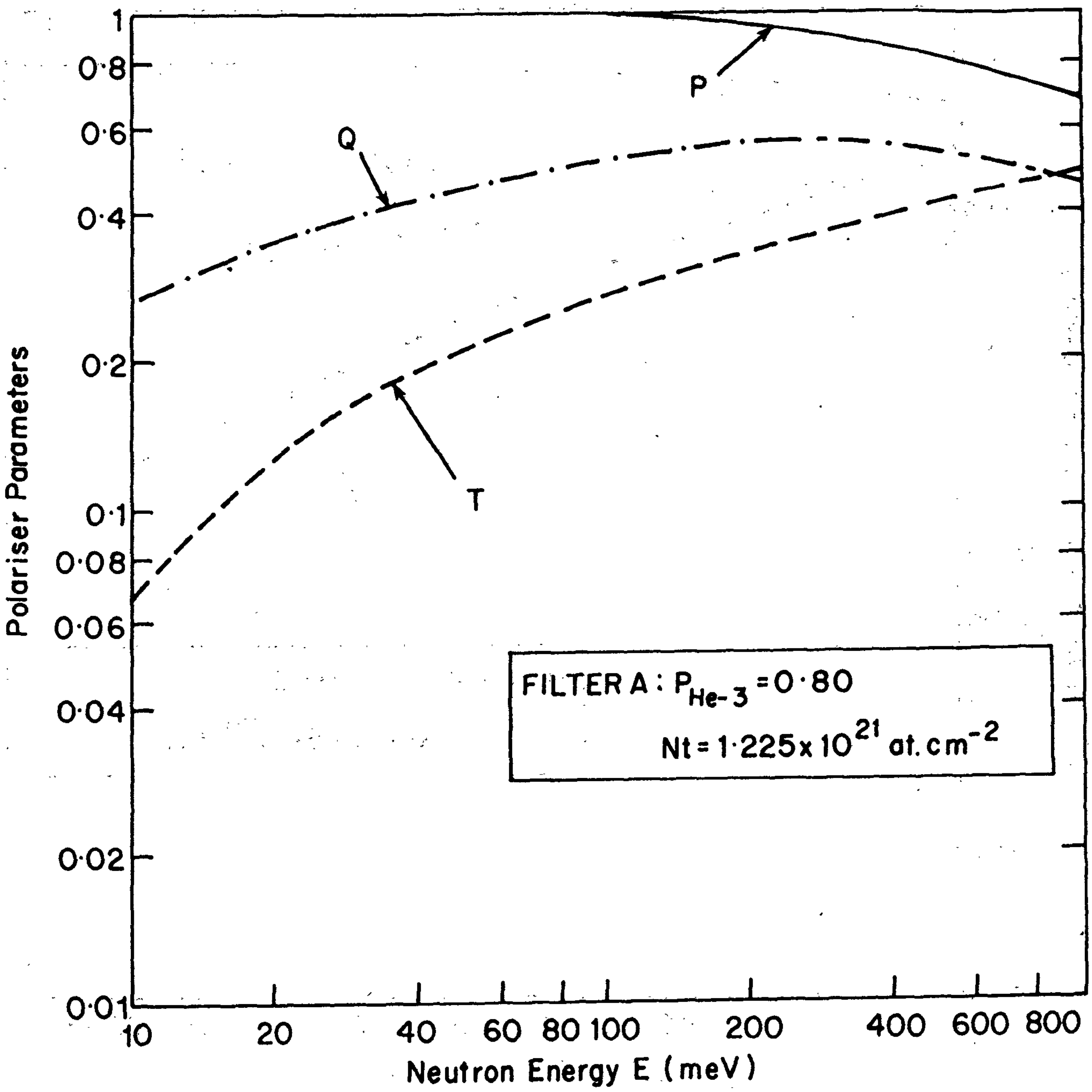

Polariser Parameters
1
0·8
0·6
0·4
0·2
0·1
0·08
0·06
0·04
0·02
0·01
P
Q
T
FILTER A : P_{He-3} = 0·80
Nt = 1·225 x 10^{21} at. cm^{-2}
10
20
40
60
80
100
200
400
600
800
Neutron Energy E (meV)

Fig. 4

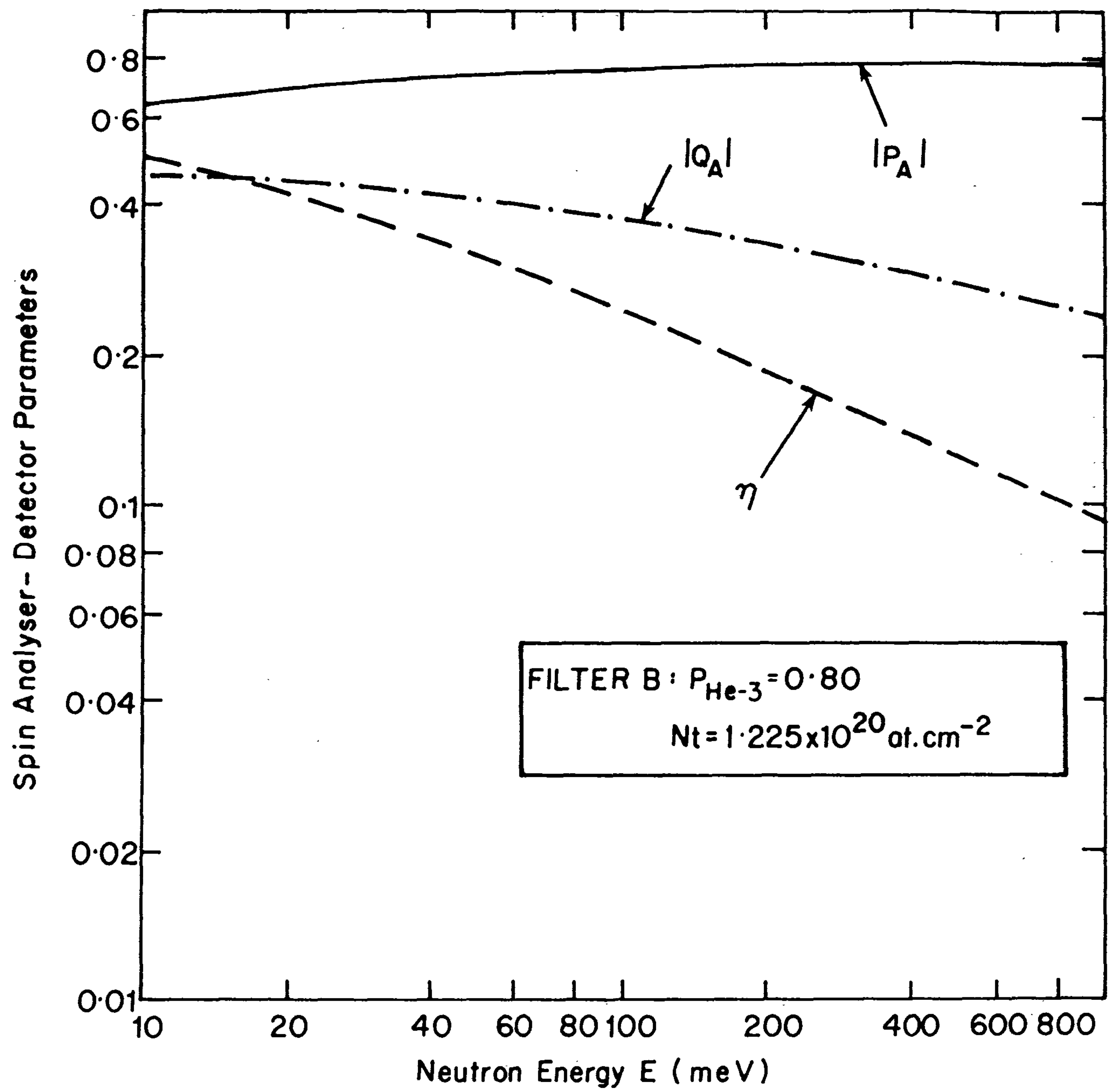

0·8
0·6
0·4
0·2
0·1
0·08
0·06
0·04
0·02
0·01
10
20
40
60
80
100
200
400
600
800
Neutron Energy E (meV)
Spin Analyser - Detector Parameters
|Q_A|
|P_A|
η
FILTER B : P_He-3 = 0·80
Nt = 1·225x10^20 at.cm^-2

Fig. 5