ence of exchange on lattice parameter of opposite sign ($\beta$ negative) would not yield (for an antiferromagnetic ground state) negative thermal expansion behavior since the exchange magnetostriction term would give rise to a contraction at $T=0$. It may thus be that the observation of negative thermal expansion in solid $He^3$ is auxiliary evidence for the supposed dependence of exchange upon lattice parameter.

I have benefited from communications with Professor H. Primakoff on the subject of this note, the kernel of which originated in a more general problem on magnetic phase transitions done in conjunction with C. P. Bean.

---

[1]H. Primakoff, Bull. Am. Phys. Soc. 2, 63 (1957).

[2]H. Meyer, E. D. Adams, and W. M. Fairbank, Proceedings of the Seventh International Conference on Low-Temperature Physics, September, 1960 (University of Toronto Press, Toronto, 1960), p. 339.

[3]N. Bernardes and H. Primakoff, Phys. Rev. Letters 2, 290 (1958).

[4]N. Bernardes and H. Primakoff, Phys. Rev. Letters 3, 144 (1959).

[5]N. Bernardes and H. Primakoff, Phys. Rev. 119, 968 (1960).

[6]E. Grilly, S. Sydoriak, and R. Mills, in Helium 3, edited by J. G. Daunt (Ohio State University Press, Columbus, Ohio, 1960).

[7]C. P. Bean and D. S. Rodbell, Bull. Am. Phys. Soc. 6, 159 (1961).

[8]C. P. Bean and D. S. Rodbell (to be published).

[9]L. Goldstein, Ann. Phys. 8, 390 (1959).

[10]This condition results from evaluating $|\sigma d\sigma/dT|$ at its maximum ($\sigma\rightarrow 0$) from the Brillouin function for $j=1/2$ where $\lim_{\sigma\rightarrow 0}|\sigma d\sigma/dT|=3/2T_0$. The effect of modifying the Brillouin function as occurs in this treatment will raise this value; we have therefore evaluated the lower bound of this exchange magnetostriction.

[11]Estimating $\alpha_l$ from the high-temperature measurements to be less than $10^{-2}/°K$ while $K\sim 5\times 10^{-9}$ $cm^2/dyne$.

[12]N. Bernardes, in Helium 3, edited by J. G. Daunt (Ohio State University Press, Columbus, Ohio, 1960).

[13]A transition of this type may be appreciably affected by externally applied magnetic fields and may be understood through the magnetic analog of the Clausius-Clapeyron relation, e.g., $\Delta T/T=H\Delta M/L$; for latent heat, $L$, a transition temperature change $\Delta T$ will result for an applied field $H$; $\Delta M$ is the difference in net magnetization per unit volume between the ferromagnetic and antiferromagnetic states. If the latent heat is largely due to changes in the spin system entropy, then $L$ may be small and $\Delta T$ large.

[14]Note added in proof. M. J. Klein and R. D. Mountain [Phys. Rev. Letters 5, 363 (1960)] have pointed out that the thermal expansion must change sign when the transition from antiferromagnetism to ferromagnetism occurs. This is also evident in our Eq. (3) when $\phi$ changes from $\pi$ to 0.

---

# FLUX AND ENERGY SPECTRA OF THE PROTONS IN THE INNER VAN ALLEN BELT

J. E. Naugle and D. A. Kniffen
National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland
(Received June 8, 1961)

In this experiment, for the first time, the flux and energy spectrum of the trapped protons in the inner Van Allen belt were measured as a function of position in the belt. Previous measurements[1,2] of the proton energy spectrum have been made in emulsions which integrated over the entire flight paths of intercontinental ballistic missiles flown from Cape Canaveral.

On September 19, 1960, a research rocket with a special nose cone developed for the exposure and recovery of emulsions was flown along a trajectory which closely corresponded to a magnetic meridian. The rocket payload was designed to permit a four-inch cylinder to be extended out through the front end of the nose cone, thereby reducing the amount of material surrounding the emulsion container to a minimum. Time resolution of the spectrum was obtained by exposing sections of a cylindrical emulsion stack to the ambient radiation through a port in the tungsten emulsion container. Figure 1 shows the experimental arrangement. A point on the periphery of the stack was behind the port for approximately 80 seconds. During the rest of the flight that point was shielded by 30.6 $g/cm^2$ of tungsten. Therefore, the track population at such a point is made up of particles which came in through the port during the 80-second exposure and a background of particles which passed through the tungsten during the remaining 900 seconds the payload was in flight. A portion of the stack which did not pass behind the port has been used to measure the background. Protons of energy $\geqslant 8$ Mev were able to penetrate

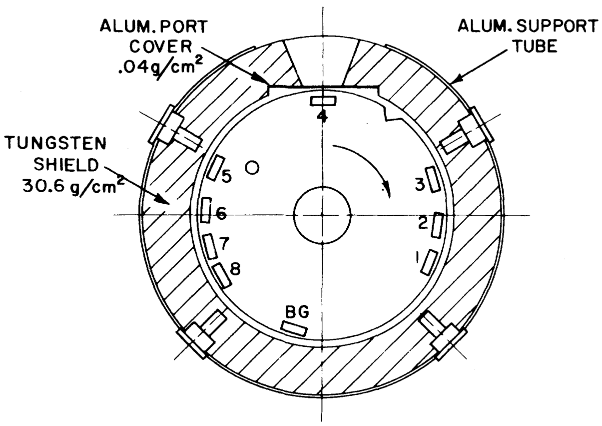


FIG. 1. Film position at apogee. 25 circular G-5 and G-0 nuclear emulsions were contained in a tungsten cassette. The numbered points around the periphery of the stack refer to the sections of the emulsion which are being analyzed.

the aluminum port cover and be detected, whereas only protons with $E \geqslant 145$ Mev were recorded in the emulsion after passing through the tungsten shield.

Figure 2 shows the trajectory of the rocket payload. The numbered points along the trajectory indicate the locations at which the corresponding points on the stack were behind the port. Table I gives the pertinent data regarding the three points 3, 4, 5, which have been analyzed to date.

A "line scan" was made around the periphery of the emulsions at points 3, 4, and 5. The scan was made approximately 500 microns from the edge of the emulsions. It was not possible to scan closer to the edge of the emulsion because of blackening. All particles which, at the scan line, were within ±25° of a radius vector and ±45° of the plane of the emulsion were recorded.

The portion of the emulsion which was not exposed behind the port was also scanned, with the same criteria, to obtain an integral flux averaged over the entire flight and also to obtain a background correction for the other sections of the stack.

In order to obtain the differential energy spectrum, all particles in the scans which had a possible residual range in the emulsion, at the scan line, of at least 2.5 mm were followed until they either ended, interacted, or left the stack. The energies and mass of these particles were then determined from range, ionization, and scattering measurements.

In the analysis to date, no evidence has been found for particles other than protons crossing the scan line. However, the mass measurements do not rule out a small component of singly-charged particles heavier than protons. The thickness of the blackened edge of the emulsion varies around the periphery of the stack and is consistent with electrons of energy up to about 600 kev stopping in the emulsion. There is a high background of grains for another 500 microns in from the black edge, due possibly to the presence of soft x rays.

The number of protons with energy greater than 100 Mev crossing the scan lines was ap-

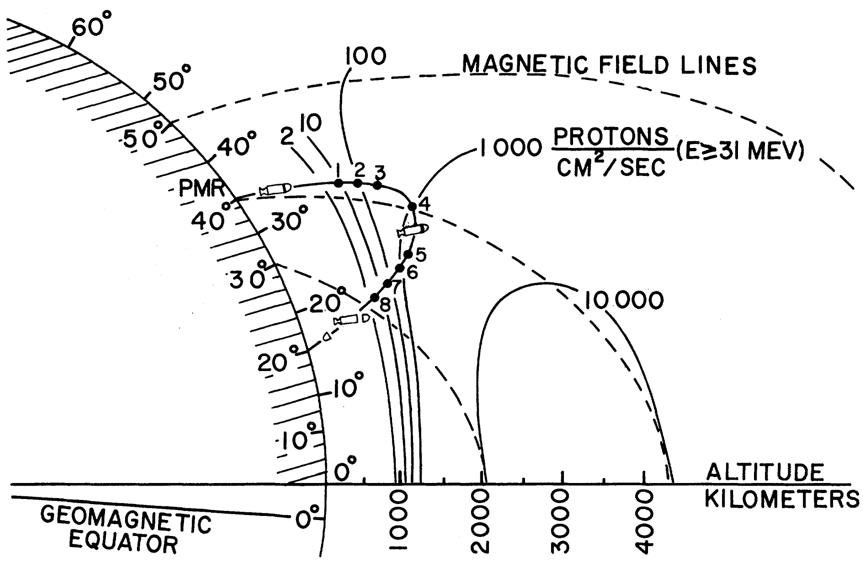


FIG. 2. Meridian section of the earth showing the trajectory of the rocket payload relative to the magnetic field and the radiation belt.

Table I. Summary of results.

| | | |
|---|---|---|
| Point 3: | | |
| | 1600 km<br>28.4°N lat.<br>237.7°W long.<br>$B = 0.231$ gauss<br>$I = 1.67\,r_e$ | $J(E \geq 31) = 70 \pm 15$ protons/cm$^2$ sr sec<br>$4\pi J(E \geq 31) = 900 \pm 200$ protons/cm$^2$ sec<br>$J_0(E \geq 31)^a = 220$ protons/cm$^2$ sec |
| | $J(E) = (3.2 \pm 0.6) \times 10^6 / E^{4.5 \pm 0.5}$ protons/cm$^2$ sec sr Mev; $10 \leq E \leq 50$ Mev | |
| Point 4: | | |
| | 1884 km<br>25.2°N lat.<br>236.5°W long.<br>$B = 0.198$ gauss<br>$I = 1.34\,r_e$ | $J(E \geq 31) = 120 \pm 20$ protons/cm$^2$ sr sec<br>$4\pi J(E \geq 31) = 1500 \pm 250$ protons/cm$^2$ sec<br>$J_0(E \geq 31)^a = 1000$ protons/cm$^2$ sec |
| | $J(E) = (6.8 \pm 0.3) \times 10^6 / E^{4.5 \pm 0.2}$ protons/cm$^2$ sec sr Mev; $10 \leq E \leq 50$ Mev | |
| Point 5: | | |
| | 1600 km<br>21.5°N lat.<br>235.4°W long.<br>$B = 0.209$ gauss<br>$I = 0.946\,r_e$ | $J(E \geq 31) = 190 \pm 40$ protons/cm$^2$ sr sec<br>$4\pi J(E \geq 31$ Mev$) = 2400 \pm 500$ protons/cm$^2$ sec<br>$J_0(E \geq 31$ Mev$)^a = 1290$ protons/cm$^2$ sec |
| | $J(E) = (1 \pm 0.5) \times 10^3 / E^{1.7 \pm 0.3}$ protons/cm$^2$ sec sr Mev; $40 \leq E \leq 100$ Mev | |
| | Integral flux behind 30.6 g/cm$^2$ of tungsten, averaged over trajectory. | |
| | $J(E \geq 145$ Mev$) = 16 \pm 3$ protons/cm$^2$ sr sec | |

[a]Integral omnidirectional proton flux at point based on satellite data.[5]

proximately equal to the number in the background area in the same energy range. Therefore, it is not possible, with the statistics available at this time, to make reliable measurements of the spectrum above about 100 Mev.

The spectra obtained at the three points are shown in Fig. 3.

Three things are apparent from these results: (1) At the higher latitudes, the slope of the spectrum below 40 Mev is very steep compared to

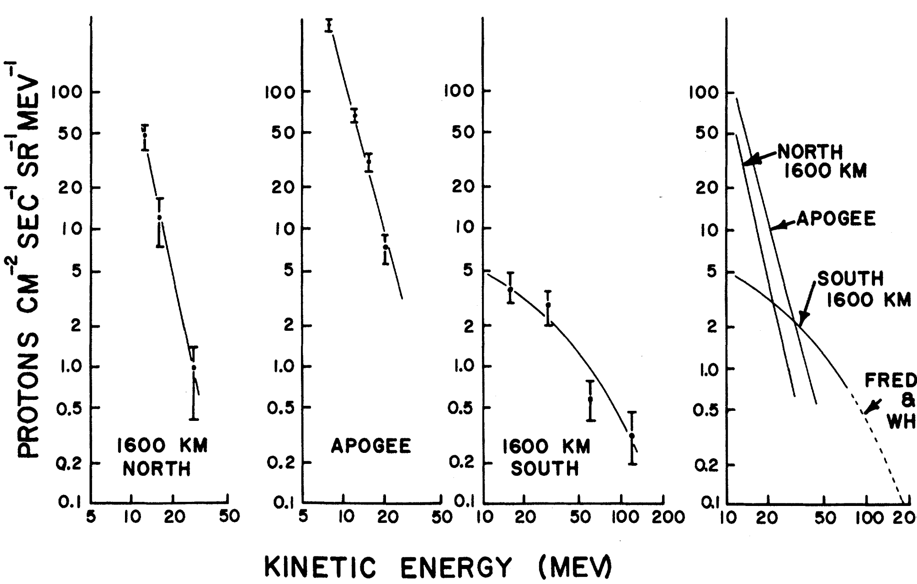


FIG. 3. The differential energy spectra obtained at points 3, 4, and 5 on the trajectory, together with the three spectra superimposed for purposes of comparison.

predictions from galactic cosmic-ray neutron albedo theory.[3] (2) The shape of the spectrum and the flux change with latitude. Points 3 and 5 are at the same altitude and geomagnetic longitude. (3) At a comparable position in the belt (point 5) the flux and shape of the spectrum agree with the previous data.

Singer[4] has predicted a change in the slope of the spectrum at higher energies with a change in latitude based on the assumption that the maximum energy of the trapped protons decreases with altitude due to the breakdown of the adiabatic invariance of the magnetic moment. It is also possible that the change in the spectrum at lower energies is due either to solar protons trapped in the geomagnetic field or to protons produced by the decay of albedo neutrons produced in nuclear interactions of solar protons over the polar cap. In either case there would be a preferential trapping of low-energy particles at the higher latitudes.

It is not clear which of these mechanisms is responsible for the change in the spectrum. Further analysis will be made in these emulsions to determine the maximum energy at which protons can be trapped at a given point. Additional flights are scheduled in late 1961 to determine if there is a time variation. Assuming that the low-energy protons are associated with solar activity, their flux should decrease as the number of solar proton events per year decreases during the solar cycle. Changes in the spectrum after a large flare have been reported by Armstrong et al.[2]

The unidirectional integral flux, $J$, for protons with $E \geqslant 31$ Mev is given in Table I. In order to compare this flux with the measurements in satellites, the assumption has been made that the flux is isotropic so that the integral omnidirectional flux is obtained by multiplying $J$ by $4\pi$. The values obtained in this way are listed in Table I together with the best value of the flux at the three points based on the analysis of the satellite data.[5] The quoted errors are large due to the effects of the background on the integral flux. The agreement is quite good considering the errors. The unidirectional flux, assuming isotropy, is consistently higher than the omnidirectional flux at all three points, indicating that the assumption is not valid.

The nose cone was spin stabilized nearly parallel to the magnetic field lines, and the unidirectional flux in the emulsion was measured primarily at angles near 90° with respect to the field lines. At low altitudes, where there is a high density of mirror points, the flux should not be isotropic but should be higher at 90° angles as observed.

The solution of the problems associated with the exposure and recovery of emulsions at 1880 km required outstanding and unique contributions from a number of people. These efforts are gratefully acknowledged by the authors. In particular, the shot would not have been successful without the work over and above his normal responsibility by Project Engineer Charles E. Campbell, of the Goddard Space Flight Center.

---

[1] S. C. Freden and R. S. White, Phys. Rev. Letters 3, 9 (1959).

[2] A. H. Armstrong, F. B. Harrison, H. H. Heckman, and L. Rosen, J. Geophys. Research 66, 351 (1961).

[3] S. C. Freden and R. S. White, J. Geophys. Research 65, 1399 (1960); S. F. Singer, Phys. Rev. Letters 1, 141, 181 (1958); W. N. Hess, Phys. Rev. Letters 3, 11 (1959).

[4] S. F. Singer, Space Research (Interscience Publishers, Inc., New York, 1960), p. 797.

[5] C. E. McIlwain and J. A. Van Allen (private communication).