General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

NASA TM X= *70988*

SIGNIFICANCE OF MEDIUM ENERGY GAMMA RAY ASTRONOMY IN THE STUDY OF COSMIC RAYS

C. E. FICHTEL
D. A. KNIFFEN
D. J. THOMPSON
G. F. BIGNAMI
C. Y. CHEUNG

SEPTEMBER 1975

GSFC — **GODDARD SPACE FLIGHT CENTER** —
GREENBELT, MARYLAND

Significance of Medium Energy Gamma Ray Astronomy
in the Study of Cosmic Rays

C. E. Fichtel, D. A. Kniffen, D. J. Thompson, and G. F. Bignami*

NASA/Goddard Space Flight Center, Greenbelt, Md.

and

C. Y. Cheung
University of Maryland, College Park, Md.

ABSTRACT

Medium energy (about 10 to 30 MeV) gamma ray astronomy can provide detailed information on the product of the galactic electron cosmic ray intensity and the galactic matter to which the electrons are dynamically coupled by the magnetic field, since for the electrons the bremsstrahlung dominates over other radiation except possibly in a small region at the galactic center. Because high energy (> 100 MeV) gamma ray astronomy provides analogous information for the nucleonic cosmic rays and the relevant matter, a comparison between high energy and medium energy gamma ray intensities can provide a direct ratio of the cosmic ray electrons and nucleons throughout the galaxy. A calculation of gamma ray production by electron bremsstrahlung shows that: (1) bremsstrahlung energy loss is probably not negligible over the lifetime of the electrons in the galaxy; and (2) the approximate bremsstrahlung calculation often used previously overestimates the gamma ray intensity by about a factor of two. Further, as a specific example, expected medium energy gamma ray intensities are

*NAS-NRC Senior Postdoctoral Research Associate.

calculated for the spiral arm model wherein it is assumed that the cosmic ray energy density is proportional to the matter, to which it is tied by magnetic fields. This model has previously had success in explaining the high energy gamma rays. Medium energy gamma ray astronomy will be a valuable tool in galactic research; it should ultimately be possible, for example, to test whether cosmic ray electrons are predominantly primary and produced in the same sources as the nucleonic cosmic rays and whether electrons and nucleons are always produced in the same proportion.

I. INTRODUCTION

The development of gamma ray astronomy has provided new opportunities for research into the nature of our galaxy. As has been recognized for some time (e.g. Morrison, 1958), nuclear cosmic rays in the galaxy inter-act with interstellar matter leading to high energy (> 100 MeV) gamma rays mostly arising from π° mesons formed in the interactions. The high energy gamma radiation formed in this way is distinguishable by its unique energy spectrum which has a maximum intensity at 70 MeV. Further, its intensity (Kraushaar et al., 1972; and Kniffen et al., 1973) is great enough so that it stands out clearly from the diffuse background, which also has a distinctly different energy spectrum (Fichtel et al., 1975a). Thus, high-energy gamma-ray astronomy provides information on the product of the galactic nuclear cosmic-ray intensity and the galactic matter to which the cosmic rays are tied by the magnetic fields.

Several recent theoretical papers (Kniffen et al., 1973; Bignami and Fichtel, 1974; Puget and Stecker, 1974; Schlickeiser and Thielheim, 1974; Solomon and Stecker, 1974; Cowan et al., 1975; Fichtel et al., 1975a; Bignami et al., 1975; Stecker et al., 1975; Paul et al., 1975) have shown that the major features of the observed spatial distribution of galactic high energy (> 100 MeV) gamma radiation are well explained as the result of the decay of neutral pions produced by the interaction of energetic cosmic rays with the interstellar gas. These theories differ in detail - Kniffen et al. (1973); Bignami and Fichtel (1974); and Bignami et al. (1975) have for example argued that on the scale of galactic arms the cosmic rays are preferentially contained in the spiral arms where the gas density is highest. Making the simplest assumption that the cosmic rays vary linearly with the density of that portion of the gas in all forms (atomic, ionized, and molecular) which is tied to the cosmic ray gas by the magnetic fields, the resulting gamma-ray production is proportional to the second power of the relevant gas density, and reasonable agreement is obtained with the experimental data. Paul et al. (1975) extended this model to demand that B^2 also be proportional to the matter density. Since synchrotron radiation is not a major contributor to the radiation above 100 MeV, similar good agreement is obtained. Stecker et al. (1975) and Solomon and Stecker (1974) have assumed that the molecular hydrogen plays a greater role, particularly in a 4 to 5 kpc ring about the galactic center. The results of this work also agree reasonably well with the experimental data if the cosmic-ray density is correlated with the matter density (or indirectly with

3

the matter density through the supernova density), but not as strongly as the first power of the matter density.

Still another approach has been to assume that the distribution of the product of the cosmic-ray density and matter density is best estimated by assuming that this product is proportional to the magnetic field strength to some power, i.e. $n \cdot N \sim H^\beta$, (Schlickeiser and Thielheim, 1975; Fuchs et al., 1975) on the basis that the energy density of the cosmic-ray gas is closely related to the interstellar magnetic field. n is the cosmic ray density and N is the matter density. Reasonable agreement with the observations is obtained for β between 2 and 3. It should be noted that when $\beta = 3$, the theory is essentially equivalent to assuming that the cosmic-ray energy density, the magnetic field energy density and the matter density are all proportional, and hence agreement between the predictions of Schlickeiser and Thielheim (1974) and Bignami et al. (1975) would be expected. An earlier calculation relating the high energy γ-rays to the galactic magnetic field was made by Strong et al. (1973) based on earlier magnetic fields data of Thielheim and Langhoff (1968).

The encouraging success in predicting the observed high-energy ($>$ 100 MeV) gamma-ray distribution makes it interesting to investigate additional observable quantities which can add important new information to the understanding of the origin of cosmic rays, their subsequent propagation, and the overall dynamics of our galaxy. In considering the medium energy (defined here as being between about 10 and 30 MeV) gamma-ray region, the major contributor to the galactic gamma radiation is

the bremsstrahlung radiation resulting from the galactic cosmic-ray electrons penetrating the interstellar gas. By observing this energy range, then, information can be obtained directly on the spatial distribution of > 10 MeV galactic cosmic-ray electrons. The first question of interest is the obvious one of whether or not the electron intensity distribution is similar to the cosmic-ray nuclei distribution. Even if cosmic-ray electrons and nuclei have the same origin, there can be second order differences. Locally the electron flux in the energy region of interest consists of between 7% and 20% positrons (Fanselow et al., 1969; Daugherty et al., 1975; Daniel and Stephens, 1975; Hartman and Pellerin, 1975). Since positrons are generally believed to be of secondary origin, and indeed it can be shown that the intensity of positrons can be explained in terms of cosmic-ray interactions with matter (e.g. Ramaty, 1974), and since there would be an equal number of negatron secondaries, 15% to 40% of the electrons are secondaries. This fraction of the electron component could vary differently with galactic position from that of the primary electron component, as will be discussed below. Additionally the continuum radio emission (making the usual assumption that it is due to synchrotron radiation) provides information on the distribution of the product of the high energy cosmic-ray electron density and the magnetic field strength. Hence, when the medium energy gamma-ray distribution is measured in detail, the combined picture of matter, cosmic-ray gas, and magnetic fields should emerge even more clearly.

5

The two principal aims of this paper will be: (1) to examine the question of the medium energy galactic gamma radiation from electrons, both primary and secondary, and (2) to calculate the expected gamma-ray distribution for the specific model of Bignami et al. (1975), wherein it is assumed that the cosmic rays are correlated with the matter on the scale of galactic arms and that the matter itself is concentrated in spiral arm segments.

II. THE MODEL AND CALCULATIONS

Before discussing a specific model it is important to show that the medium energy gamma rays reveal the presence of galactic cosmic-ray electrons in much the same way that high-energy gamma-rays reveal the distribution of the galactic nuclear cosmic rays. The principal contributors to galactic γ-ray production in the 10-30 MeV energy range are neutral pion decays from cosmic-ray interactions with the interstellar gas, bremsstrahlung γ-rays from energetic cosmic-ray electrons, Compton emission of cosmic-ray electrons interacting with the interstellar photon fields, and the synchrotron radiation of high energy electrons interacting with the interstellar magnetic fields.

Source functions may be calculated for each of these processes in the solar vicinity where the relevant parameters are reasonably well known. The "local" source functions for the processes most likely to contribute to 10-30 MeV galactic gamma radiation are given in Table I. The neutral pion decay source function is taken from the work of Stecker (1973). The bremsstrahlung source function is calculated from cross-

TABLE I - SOURCE FUNCTIONS IN THE SOLAR VICINITY

Source Mechanism	Value of Source Function ($cm^{-3}sec^{-1}$)	
	10-30 MeV	> 100 MeV
Neutral Pion Decay	0.5×10^{-26}	10.0×10^{-26}
Electron Bremsstrahlung	4.1×10^{-26}	0.8×10^{-26}
Compton Scattering (Starlight)	0.6×10^{-26}	0.2×10^{-26}
Compton Scattering (3°K)	1.0×10^{-26}	0.2×10^{-26}
Synchrotron Radiation	1.0×10^{-30}	0.2×10^{-30}

sections given by Koch and Motz (1959), and integrated over the inter-stellar electron spectrum given by Daugherty et al. (1975), and the secondary electron spectrum calculated by Ramaty (1974). It should be noted that many approximate calculations given in the literature give results which are about a factor of two higher than this exact calcula-tion (Kniffen and Cheung, 1975). The Compton scattering and synchrotron source functions are given by Ginzburg and Syrovatskii (1974). An electron spectrum $J(E_e) = K_e E_e^{-\Gamma} (cm^2 sec \ sr \ GeV)^{-1}$ is assumed with $K_e = 6.8 \times 10^{-3}$ and $\Gamma = 1.8$ below 2 GeV and $K_e = 1.4$ and $\Gamma = 2.8$ above 2 GeV. The local total interstellar gas density is taken to be 0.8 equivalent hydrogen atoms cm^{-3} with the starlight energy density .45 eV cm^{-3} corresponding to a temperature of about 6000° (Shukla et al., 1975) and 3°K energy density .25 eV/cm^{-3}.

Table I indicates the shift from a nucleonic mechanism at higher energies to an electron mechanism at the lower energies. This provides a most important and direct means of probing the cosmic-ray electrons as a function of galactic position by making gamma-ray observations in the 8 to 40 MeV energy range. Below about 6 to 8 MeV the problem is complicated by the superposition of nuclear gamma-ray lines and the difficulty of making experimental measurements both because of locally produced background and the inherent problem of relatively poor angular resolution.

In the Table, the importance of the bremsstrahlung mechanism in the 10-30 MeV region for conditions in the solar vicinity is evident, and this feature should remain true throughout the galaxy except for regions where the starlight photon/interstellar gas density ratio $N_{ph}(r,\ell,b)/N(r,\ell,b)$ is much larger than the value in the solar vicinity. If such high photon densities exist at all, they should occur only in the galactic center where the presence of a highly enhanced starlight density might lead to a significant gamma-ray intensity from Compton scattering of energetic cosmic-ray electrons by these photons. The photon density in this region is inaccessible to direct observation in our own galaxy and estimates of its magnitude are highly uncertain.

Since the 3°K blackbody radiation is universal, its photon density is constant over the galaxy and hence is only a significant contributor to the medium energy gamma-ray intensity in regions where the interstellar gas density is much less than its local value.

NOTE: ℓ and b refer to new galactic coordinates.

The dominance of the bremsstrahlung mechanism implies, as in the pion decay model at higher energies, that the gamma-ray distribution is strongly dependent on the distribution of the relevant interstellar gas, and hence the formalism for the two cases is very similar.

In order to calculate the gamma radiation from the galaxy, mass and photon distributions are required. Since information on both these subjects is limited (and indeed should ultimately be enhanced by combining gamma-ray astronomical data with radio, optical and X-ray data), specific models based on the data that are available must be assumed. Then, the gamma-ray contributions can be summed along a given direction to give the expected result as seen by a telescope in the solar vicinity. The gamma-ray intensity as a function of energy and longitude is given by

$$\Phi(E_\gamma, \ell) = \frac{1}{4\pi} \int drdb \; [S_{\gamma n}(E_\gamma, r = 0)g_n(r,\ell,b)$$

$$+ S_{\gamma e_p}(E_\gamma, r = 0)g_{e_p}(r,\ell,b) \tag{1}$$

$$+ S_{\gamma e_s}(E_\gamma, r = 0)g_{e_s}(r,\ell,b)] \; \frac{N(r,\ell,b)}{N(r=0)}$$

where $N(r,\ell,b)$ is the total interstellar gas density at a distance r from the sun in the direction (ℓ,b) and $S_{\gamma n}$ represents the gamma rays produced per second by the decay of pions produced in interactions of nucleonic cosmic rays (with the intensity and spectral distribution in the solar vicinity) with the interstellar gas. $S_{\gamma ep}$ and $S_{\gamma es}$ are similar functions for primary and secondary cosmic ray electrons, respectively. In each case g expresses the spatial variation with galactic position of the ratio of the cosmic ray component to its interstellar value at the sun. Implicit in this approach is the assumption

that the spectral shape of each component is unchanged throughout the galaxy. The assumption is reasonable, as long as the source spectral shape in the solar vicinity is typical of that throughout the galaxy and energy losses remain with certain limits. The latter condition will be shown to be true for the energy region and intensity levels relevant to the model being considered.

In order to proceed, a specific model must now be chosen for the variation of the various g_i with position. The assumption to be made here is that, on the scale of galactic arms, the cosmic rays are enhanced where the gas density is greatest; namely in the galactic spiral arm segments. The arguments in favor of such a hypothesis are discussed in detail by Bignami and Fichtel (1974), Fichtel et al. (1975a or b), and Bignami et al. (1975). As a trial assumption, the cosmic-ray nucleon density is assumed to be directly proportionally to the gas density and hence:

$$g_n \quad = \quad \frac{N(r,\ell,b)}{N(r=0)}$$

where $N(r=0)$ is the interstellar gas density in the vicinity of the solar system. Less severe dependencies on density could also be considered and will be mentioned briefly later. Similar arguments apply for primary electrons which are assumed to be produced in the same source, or sources, with the same spatial distribution as the nucleons; and hence $g_n = g_{e_p}$. It is also assumed that the sources of these primaries, protons and electrons, are distributed with a spatial distribution which varies on a large scale in proportional to the interstellar gas density, as suggested by the approximate linear relation

between supernova remnants and the galactic hydrogen density (Ilovaisky and Lequeux, 1972; Kodaira, 1974; Stecker, 1975).

It is now necessary to consider if the model satisfies the condition that the energy spectral shape does not vary throughout the galaxy and then to determine g_{e_p} and g_{e_s}.

For cosmic-ray electrons the equilibrium transport equation is

$$\frac{\partial}{\partial E}\left[\left(\frac{dE_e}{dt}\right) n_e (r,\ell,b)\right] + \frac{n_e (r,\ell,b)}{\tau_e} = S_e(r,\ell,b). \qquad (2)$$

where τ_e is the total time for escape from the confinement region.

To examine the magnitude of the first term of equation (2) and more specifically dE_e/dt, consider the energy loss mechanisms at the energies most important for gamma-ray production in the galactic spiral arms. The energy loss rates for the three dominant mechanisms satisfy the relationships

$$\left(\frac{dE_e}{dt}\right)_{synch} = \frac{2}{3} c \left(\frac{e^2}{m_e c^2}\right)^2 B_\perp^2 \left(\frac{E_e}{m_e c^2}\right)^2$$

$$\left(\frac{dE_e}{dt}\right)_{comp} = c\sigma_T u_{ph}\left(\frac{E_e}{m_e c^2}\right)^2$$

$$\left(\frac{dE_e}{dt}\right)_{brems} = \frac{cm_H N}{X_o} E_e$$

where $B_\perp$ is the component of the interstellar magnetic field perpendicular to the direction of particle motion, u_{ph} is the energy density of interstellar photons, σ_T is the Thomson Cross Section, m_H the mass of atomic hydrogen and N its gas density, and X_o is the radiation length of interstellar matter.

For local region of the galaxy, it is assumed that $B_\perp = 3 \times 10^{-6}$ gauss, $u_{ph} = 0.7$ eV/cm^3, and $N = .8$ nuclei/cm^3 and $\tau_e = 6 \times 10^6$ years. Using these values and $X_0 = 66$ g/cm^2 yields the following for E_e in MeV:

$$\left(\frac{\tau_e}{E_e} \frac{dE_e}{dt} \right)_{synch} = 0.7 \times 10^{-5} \left(\frac{B_\perp}{3 \times 10^{-6}} \right)^2 E_e \qquad (3)$$

$$\left(\frac{\tau_e}{E_e} \frac{dE_e}{dt} \right)_{comp} = 1.1 \times 10^{-5} \left(\frac{u_{ph}}{0.7 \times 10^{-6}} \right) E_e \qquad (4)$$

$$\left(\frac{\tau_e}{E_e} \frac{dE}{dt} \right)_{brems} = 0.12 \left(\frac{N}{0.8} \right) \qquad (5)$$

It should be noted that a longer escape lifetime would have little effect on the synchrotron and bremsstrahlung loss rates since the path length implied by the cosmic-ray composition measurements would imply more time spent in regions of lower gas density, and since the magnetic fields are correlated with the matter they likewise would be lower. The Compton scattering loss rate could become somewhat more important in this case.

Unless $B_\perp$ or u_{ph} exceeds its local value near the earth by more than an order of magnitude, the energy loss for Compton and synchrotron radiation is negligible in the lifetime of the electrons at least below 1 GeV. The bremsstrahlung energy loss then dominates, or at least certainly in the model being considered here; therefore, it will be assumed that equation (5) may be used for dE_e/dt in equation (2). Making the usual assumption that τ_e is independent of E for the relevant cosmic

ray energy range, equation (2) becomes:

$$\frac{\partial}{\partial E_e} \left[0.12 \ \frac{N(r,\ell,b)}{N(r=0)} \ E_e \ n_e \right] + n_e(r,\ell,b) = \tau_e S_e(r,\ell,b)$$

If a power law equilibrium spectrum is assumed for the electrons, i.e.

$$n_e(r,\ell,b) \ \propto E_e^{-\Gamma},$$

the solution to the transport equation becomes:

$$n_e(r,\ell,b) \ = \ \frac{\tau_e \ S_e(r,\ell,b)}{0.12 \ \frac{N(r,\ell,b)}{N(r=0)} \ (\Gamma - 1) + 1} \tag{6}$$

Utilizing the earlier assumption that the source functions of primary electrons and protons were proportional to the matter on a broad scale,

$$S_{e_p}(r,\ell,b) = S_{e_p}(r=0) \frac{N(r,\ell,b)}{N(r=0)} = S_{e_p}(r=0) g_n(r,\ell,b).$$

It is reasonable to assume that τ_e for the cosmic-ray electrons being considered here is the same as that for the protons, and it is easy to show that τ_e for the protons is a constant independent of position. Since energy loses are negligible for protons, the equilibrium transport equation for protons similar to equation (2) reduces at once to:

$$n_n(E,r,\ell,b) \ \propto \ \tau_e \ S_n(E,r,\ell,b)$$

where τ_e is the escape lifetime and S_n is the source function for cosmic ray production. Since under the assumptions stated above $n_n(E,r,\ell,b) \propto n_n(E,r=0)\frac{N(r,\ell,b)}{N(r=0)}$ and $S_n(E,r,\ell,b) \propto S_n(E)\frac{N(r,\ell,b)}{N(r=0)}$, τ_e is independent of galactic position.

The equilibrium density for primary electrons then becomes

$$n_{e_p}(r,\ell,b) \ = \ n_{e_p}(r=0) g_n(r,\ell,b) \ \frac{0.12 \ (\Gamma-1) + 1}{0.12 \ \frac{N(r,\ell,b)}{N(r=0)} \ (\Gamma-1) + 1} \tag{7}$$

13

From equation (7) it can be seen that

$$g_{e_p}(r,\ell,b) = g_n(r,\ell,b) \frac{0.12(\Gamma-1) + 1}{0.12 \frac{N(r,\ell,b)}{N(r=0)}(\Gamma-1) + 1}$$

For secondary electrons

$$S_{e_s}(r,\ell,b) = \int c\, n_n(r,\ell,b) N(r,\ell,b) \sigma(E_e, E_n)$$

where $\sigma(E_e, E_n)$ is the cross section for the production of secondary electrons of energy E_e by the collision of cosmic ray nucleons of energy E_n with the interstellar gas.

Since

$$n_n(r,\ell,b) = g_n(r,\ell,b)\, n_n(r=0),$$

$$S_{e_s}(r,\ell,b) = g_n^2 \int c n_n(r=0) N(r=0) \sigma(E_e, E_n) = g_n^2\, S_{e_s}(r=0);$$

Substituting into equation (6), the equilibrium density for secondary electrons is

$$n_{e_s}(r,\ell,b) = \frac{\tau_e S_{e_s}(r,\ell,b)}{0.12 \frac{N(r,\ell,b)}{N(r=0)}(\Gamma-1) + 1}$$

$$= n_{e_s}(r=0)\, g_n^2(r,\ell,b) \frac{0.12(\Gamma-1) + 1}{0.12 \frac{N(r,\ell,b)}{N(r=0)}(\Gamma-1) + 1}$$

(8)

and hence

$$g_{e_s}(r,\ell,b) = g_n^2(r,\ell,b) \frac{0.12(\Gamma-1) + 1}{0.12 \frac{N(r,\ell,b)}{N(r=0)}(\Gamma-1) + 1}.$$

The contribution of the electron component to the galactic gamma-ray intensity is given by

$$\Phi_e(E_\gamma,\ell) = \frac{1}{4\pi} \int dE_e\, dr\, db\, c\, n_e(E_e, r,\ell,b) \sigma(E_\gamma, E_e) N(r=0) g(r,\ell,b)$$

$$= \frac{1}{4\pi} \int dr\, db \int dE_e\, c\, n_e(E_e, r=0) \sigma(E_\gamma, E_e) N(r=0) g(r,\ell,b) \frac{0.12(\Gamma-1)+1}{0.12\frac{N(r,\ell,b)}{N(r=0)}(\Gamma-1)+1}$$

where $\sigma(E_\gamma, E_e)$ is the cross section for the bremsstrahlung production

of gamma rays of energy E_γ, produced by electrons of energy E_e and

velocity β. Defining $S_{\gamma_e} = \int dE_e\ \beta c N_e(E_e, r=0)\ \sigma(E_\gamma, E_e) N(r=0)$ and using

equations (2) and (3) the total electron contribution becomes

$$\Phi(E_\gamma, \ell) = \frac{1}{4\pi} \int dr\, db\ [S_{\gamma_{e_p}}(E_\gamma, r=0)\ g_n^2(r, \ell, b) + S_{\gamma_{e_s}}(E_\gamma, r=0)$$

$$g_n^3(r, \ell, b)]\ \frac{0.12(\Gamma-1) + 1}{0.12\frac{N(r, \ell, b)}{N(r=0)}(\Gamma-1) + 1}$$

where $S_{\gamma_{e_p}}$ and $S_{\gamma_{e_s}}$, the local source functions for gamma ray production

by the bremsstrahlung process are given in Table I. The total expres-

sion for the galactic gamma intensity therefore becomes $\Phi(E_\gamma, \ell) =$

$\frac{1}{4\pi}\int dr\, db [S_{\gamma_n}(E_\gamma, r=0)\ g_n^2(r, \ell, b) + \{S_{\gamma_{e_p}}(E_\gamma, r=0) g_n^2(r, \ell, b) + S_{\gamma_{e_s}}(E_\gamma, r=0)$

$g_n^3(r, \ell, b)\}\ \dfrac{0.12(\Gamma-1) + 1}{0.12\frac{N(r, \ell, b)}{N(r=0)}(\Gamma-1) + 1}]$. Since $g_n \propto N$, this relation-

ship shows that primary cosmic ray protons and electrons (related to the

first and second terms respectively) contribute to the gamma ray pro-

duction approximately in proportion to N^2, while the secondary cosmic ray

electrons contribute approximately as N^3 and hence become more significant

in high density regions.

Following the approach of Bignami et al. (1975), the integral of

this equation is performed numerically in discrete steps along the line

of sight for a given galactic longitude and latitude and summed over a

specified interval in latitude centered on the galactic equator. It is

now necessary to assume a specific model for the relevant matter distri-

bution. Following the work of Bignami et al. (1975), it is assumed that

the relevant gas is distributed in spiral arm segments deduced from the

density wave theory and 21 cm observations in accordance with the work of Simonson (1975). All the relevant gas, atomic, molecular, and ionized is assumed to obey this spiral pattern and the specific matter distribution used is that of Bignami et al. (1975).

A crucial aspect of the matter distribution is the extent to which it is coupled to the cosmic rays through magnetic fields and hence participates strongly in gamma-ray production. In particular, the relative roles of molecular and atomic hydrogen will be discussed in view of the papers by Puget and Stecker (1974), Stecker et al. (1975) and Fuchs et al. (1975) mentioned earlier which appeared after that of Bignami and Fichtel (1974). It is worth repeating and reemphasizing here the fundamental assumptions to clarify the hypothesis regarding molecular hydrogen. First, the cosmic rays are assumed to be galactic and that, as shown by Parker (1969), the cosmic rays and magnetic fields can only be contained by the mass of the gas through which the magnetic fields penetrate, and, hence, are tied to this matter. The galactic cosmic-ray energy density cannot substantially exceed that of the magnetic field, or the cosmic-ray pressure will push a substantial bulge into the fields which will ultimately allow the cosmic rays to escape. This local energy density of the cosmic rays is about the same as the estimated energy density of the average magnetic field and the kinetic motion of matter. This feature together with others discussed in the earlier papers (Bignami and Fichtel, 1974; and Bignami et al., 1975) suggest that the cosmic-ray density may generally be as large as would be expected under quasi-equilibrium conditions. Therefore, it was

16

assumed that the energy density of the cosmic rays is larger where the relevant matter density is larger, and, as the simplest and more likely assumption, the cosmic-ray density was taken to be proportional to the density of matter to which it was tied by the magnetic fields on the scale of galactic arms and normalized to the local galactic value. All of the atomic hydrogen is assumed to be relevant (i.e. dynamically coupled to the cosmic rays) to the dynamic balance between the expanding pressures of the cosmic rays, the magnetic fields, and the kinetic motion of matter and the gravitational attraction of the matter--or at least to the same degree that the atomic hydrogen is locally. The ionized hydrogen is taken to be small in comparison to the atomic hydrogen.

It is further assumed that the molecular hydrogen that is relevant to the containment of cosmic rays has the same distribution as the atomic hydrogen and that the mass ratio of this component of the molecular hydrogen to the atomic hydrogen was one in the inner galaxy. Scoville and Solomon (1975) on the basis of CO line measurements have suggested that the total molecular hydrogen density is large in certain regions of the inner galaxy. However, on the basis of the observations that exist it seems reasonable to assume that much of this molecular hydrogen is in the form of dense clouds in which the cosmic-ray density is not expected to be particularly high. These clouds at most then contribute gamma rays at a much reduced rate and almost not at all if the magnetic fields are generally isolated from them. In a recent paper, Wentzel et al. (1975) present several arguments to show that most of the molecular hydrogen is dynamically independent of the atomic hydrogen and cosmic

rays. Therefore, in view of this situation and present uncertainties, the position of the present paper will be that only a modest amount of molecular hydrogen is tied to the magnetic fields and is therefore relevant, and that the molecular hydrogen density which is relevant is the same by mass as the atomic hydrogen density in the inner part of the galaxy, as in the previous papers on high energy gamma rays (Bignami and Fichtel, 1974; Bignami et al., 1975; and Fichtel et al., 1975a).

The essence of the result can be seen from the spectral distribution for the direction $\ell = 335°$, $b = 0°$ shown in Fig. 1. The strong shift from the bremsstrahlung mechanism at lower energies to the pion decay mechanism at higher energies is evident in the principal model. The resulting longitude distribution, disregarding detector resolution, is presented separately for bremsstrahlung and pion decay components in the 10-30 MeV and greater than 100 MeV energy ranges in Fig. 2. It can be seen that the galactic spiral arm features appear in both energy ranges, but the primary source mechanism has changed. It should be noted that the model discussed here assumes the same height distribution for electrons as for nuclear cosmic rays, which may or may not be the same as that for the matter distribution. In fact, continuum radio measurements suggest the scale height for cosmic-ray electrons may exceed that for the matter distribution. Bignami et al. (1975) have, however, shown that the longitude distribution is insensitive to the scale height over a wide range of distributions, for an intensity normalized to the galactic equator.

The radio observations also give qualitative support to the

concept of enhanced > 100 MeV cosmic-ray electrons in the $300° \leq \ell^{II} \leq$ 60° galactic longitude interval with concentration in the spiral arms (Webber, 1968; Cummings et al., 1973; Cowsik and Mittledorf, 1973; Price, 1974), but uncertainties in interpretation of the observations do not allow a definitive determination of the electron intensities involved.

III. DISCUSSION

One of the more revealing aspects of this result is the energy spectrum which would be observed. The calculated spectrum typical of regions near the galactic center is presented in Fig. 1. The spectrum indicates the dramatic shift from a predominately cosmic-ray nucleonic mechanism at higher energies to a cosmic-ray electron mechanism at the lower energies. While the calculations are made for a specific model, the results should be similar for any reasonable model of galactic dynamics. This provides a most important and direct means of probing the cosmic-ray electrons as a function of galactic position by making gamma-ray observations in the few to 40 MeV energy range.

Although the model calculations have been summed over a 20° galactic latitude interval for comparison with the previous calculations for 100 MeV gamma rays, a narrower 10° interval would give relatively little change in distribution or the energy spectrum and so the diffuse background, which is only poorly known in the 10-30 MeV energy interval, should contribute $< 5 \cdot 10^{-5}/cm^2$ sec rad (Fichtel et al., 1975a), a value well below the model predictions. However, this background makes it desirable to make such observations with an instrument with angular resolution of a few degrees or better.

The specific model developed in the last section assumed that the fraction of the electrons which were not believed to be secondaries had the same origin as the nuclear cosmic rays and were proportionate to them, as well as having a similar life time. Whereas this has been the traditional assumption, it is quite possible that their having a common origin and especially their having a uniformly constant ratio is not entirely correct. We now know that electrons are being accelerated to cosmic-ray energies in a pulsar long after a supernova (Thompson et al., 1975), but it is not necessarily true that protons are. However, if the protons are being accelerated, their rate of energy loss in a pulsar may be much different. Thus, it is possible that the cosmic-ray electrons and protons may have very different distributions in the galaxy. The comparison of medium and high energy gamma-ray measurements provides the opportunity to determine their relative density because the gamma rays in the two energy intervals result from cosmic-ray electrons and protons, respectively, interacting with the same matter distribution. Hence, no assumption need be made about the relative variations of fields and matter, fields and photons, and photons and matter, or even the exact amount of matter or its distribution in order to deduce the cosmic-ray electron to cosmic-ray proton ratio.

The model of Bignami et al. (1975) which has been extended here gave results which reproduced the essential features of the SAS-2 high energy gamma-ray longitude distribution reasonably well. When extended to lower energies, where electron bremsstrahlung dominates at least away from the galactic center, the calculations here show that medium energy

gamma-ray astronomy should provide an important probe for the distribution of > 10 MeV galactic cosmic-ray electrons. By comparing the medium energy observations with the high energy (> 100 MeV) nucleonic induced gamma radiation, it may be possible to test whether the hypothesis that cosmic-ray electrons are predominantly primary in origin and produced in the same sources as the nucleonic cosmic rays, and always in the same proportion, is correct or not.

REFERENCES

Bignami, G. F. and Fichtel, C. E. 1974, Ap. J. Letters 189, L65.

Bignami, G. F., Fichtel, C. E., Kniffen, D. A., and Thompson, D. J. 1975, Ap. J. 199, 54.

Cowan, J. J., Kafatos, M., and Rose, W. K. 1975, Ap. J. 195, 47.

Cowsik, R. and Mittledorf, J. 1973, Proc. 13th Int. Cosmic Ray Conf. (Denver) 1, 414.

Cummings, A. C., Stone, E. C. and Vogt, R. E. 1973, Proc. 13th Int. Cosmic Ray Conf. (Denver) 1, 335.

Daniel, R. R. and Stephens, S. A. 1974, Reviews of Geophysics and Space Physics 12, 233.

Daugherty, J. K., Hartman, R. C. and Schmidt, P. J. 1975, Ap. J. 198, 493.

Fanselow, J. L., Hartman, R. C., Hildebrand, R. H. and Meyer, P. 1969, Ap. J. 158, 771.

Fichtel, C. E., Hartman, R. C., Kniffen, D. A., Thompson, D. J., Bignami, G. F., Ögelman, H. B., Özel, M. E. and Tümer, T. 1975a, Ap. J. 198, 163.

Fichtel, C. E., Hartman, R. C., Kniffen, D. A., Thompson, D. J., Bignami, G. F., Ögelman, H., Özel, M. E. and Tümer, T. 1975b, Proc. 14th Int. Cosmic Ray Conf. (Munich) 1,

Fuchs, B., Schlickeiser, R. and Thielheim, K. O. 1975, Proc. 14th Int. Cosmic Ray Conf. (Munich) 1, 83.

Ginzburg, V. L. and Syrovatskii, S. I. 1964, The Origin of Cosmic Rays, Oxford, Pergamon Press.

Hartman, R. C. and Pellerin, C. J. 19 , submitted to Ap. J.

Ilovaisky, S. A. and Lequeux, J. 1972, Astron. and Astrophys. 18, 169.

Kniffen, D. A. and Cheung, C. Y. 1975, "Medium Energy Gamma Ray Pro-
    duction by Interstellar Cosmic Ray Electrons", preprint.

Kniffen, D. A., Hartman, R. C., Thompson, D. J., and Fichtel, C. E.
    1973, Ap. J. (Letters) 186, L105.

Koch, H. W. and Motz, J. W. 1959, Rev. Mod. Phys. 31, 920.

Kodaira, K. 1974, Publ. Astron. Soc. Japan 26, 255.

Kraushaar, W. L., Clark, G. W., Garmire, G. P., Borken, R., Higbie, P.,
    Leong, V., and Thorsos, T. 1972, Ap. J. 177, 341.

Morrison, P. 1958, Nuovo Cimento 7, 858.

Parker, E. N. 1969, Space Sci. Rev. 9, 654.

Paul, J., Casse, M., and Cesarsky, C. J. 1975, Proc. 14th Int. Cosmic
    Ray Conf. (Munich) 1, 59.

Price, R. M. 1974, Astron. and Astrophys. 33, 33.

Puget, J. L. and Stecker, F. W. 1974, Ap. J. 191, 323.

Ramaty, R. 1974, in High Energy Particles and Quanta in Astrophysics,
    ed. F. B. McDonald and C. E. Fichtel, MIT Press, Cambridge, Mass.

Ramaty, R. and Lingenfelter, R. E. 1966, J. Geophys. Res. 71, 3687.

Schlickeiser, R. and Thielheim, K. O. 1974, Astron. and Astrophys.
    34, 167.

Scoville, N. Z. and Solomon, P. M. 1975, Ap. J. (Letters) 199, L105.

Shukla, P. G., Casse, M., Cesarsky, C. J. and Paul, J. 1975, Proc.
    14th Int. Cosmic Ray Conf. (Munich) 1, 65.

Simonson, S. C. III 1975, CNRS Paris Colloquium 1974 Sept., ed.
    L. Weliachew, in press.

Solomon, P. M. and Stecker, F. W. 1974, Proc. ESLAB Symp. on the

    Context and Status of Gamma Ray Astronomy, ESRO SP-106.

Stecker, F. W. 1973, Ap. J. <u>185</u>, 499.

Stecker, F. W. 1975, Phys. Rev. Lett. <u>35</u>, 188.

Stecker, F. W., Puget, J. L., Strong, A. W., and Bredekamp, J. H.

    1974, Ap. J. Letters <u>188</u>, L59.

Stecker, F. W., Solomon, P. M., Scoville, N. Z., and Ryter, C. E. 1975,

    Ap. J., in press.

Strong, A. W., Wdowczyk, J. and Wolfendale, A. W. 1973, <u>Gamma Ray</u>

    <u>Astrophysics</u> (ed. F. W. Stecker, and J. I. Trombka), U. S. Gov't.

    Printing Office, Washington, D. C., 259.

Thielheim, K. O. and Langhoff, W. 1968, J. Phys. A (Proc. Phys. Soc.)

    Ser 2, <u>1</u>, 694.

Thompson, D. J., Fichtel, C. E., Kniffen, D. A. and Ögelman, H. 1975,

    submitted to Ap. J. Letters.

Webber, W. R. 1968, Aust. J. Phys. <u>21</u>, 845.

Wentzel, D. G., Jackson, P. D., Rose, W. K. and Sinha, R. P. 1975,

    Ap. J. (Letters), in press.

FIGURE CAPTIONS

Fig. 1 -- Expected gamma ray spectrum above 10 MeV for $\ell = 335°$, b = 0°. Dashed curve includes total of contributions from cosmic-ray nucleon--interstellar gas interactions and bremsstrahlung emission from primary and secondary cosmic-ray electrons. The general features of this spectrum are expected to exist anywhere in the galactic plane with the possible exception of a small region near the galactic center where there may be a substantial Compton component.

Fig. 2 -- Longitude distribution of the galactic gamma ray emission deduced from the spiral arm model, summed from -10° to +10° in galactic latitude, for each of two energy ranges: photon energies greater than 100 MeV, and 10-30 MeV photon energies. In each figure, the dashed line represents the contribution from cosmic ray nucleon--interstellar gas interactions ($\pi°$ decay) and the solid line represents the contribution from bremsstrahlung emission from primary and secondary cosmic ray electrons. The scale for the 10-30 MeV distribution has been expanded relative to the > 100 MeV distribution in order to show the detail.
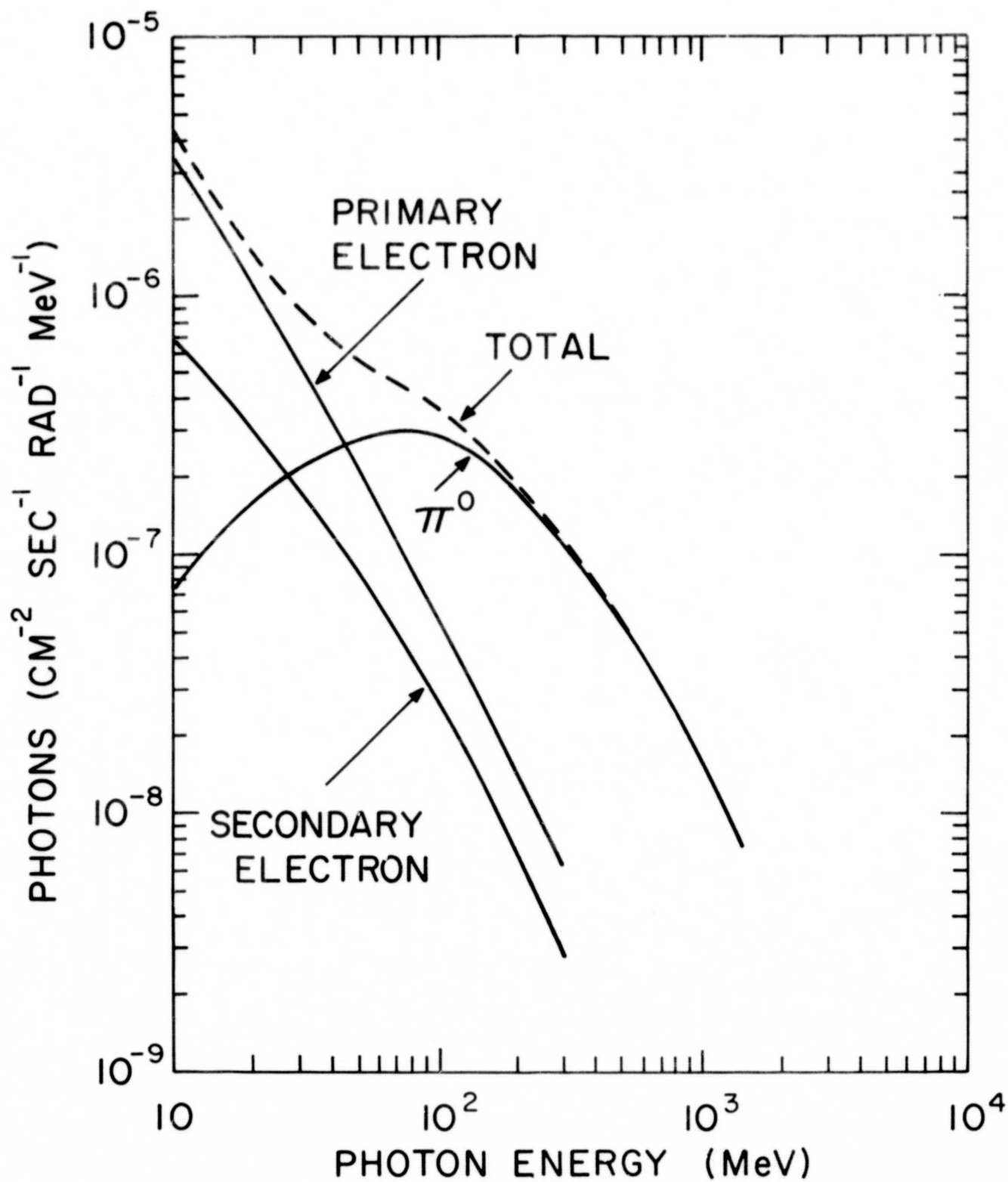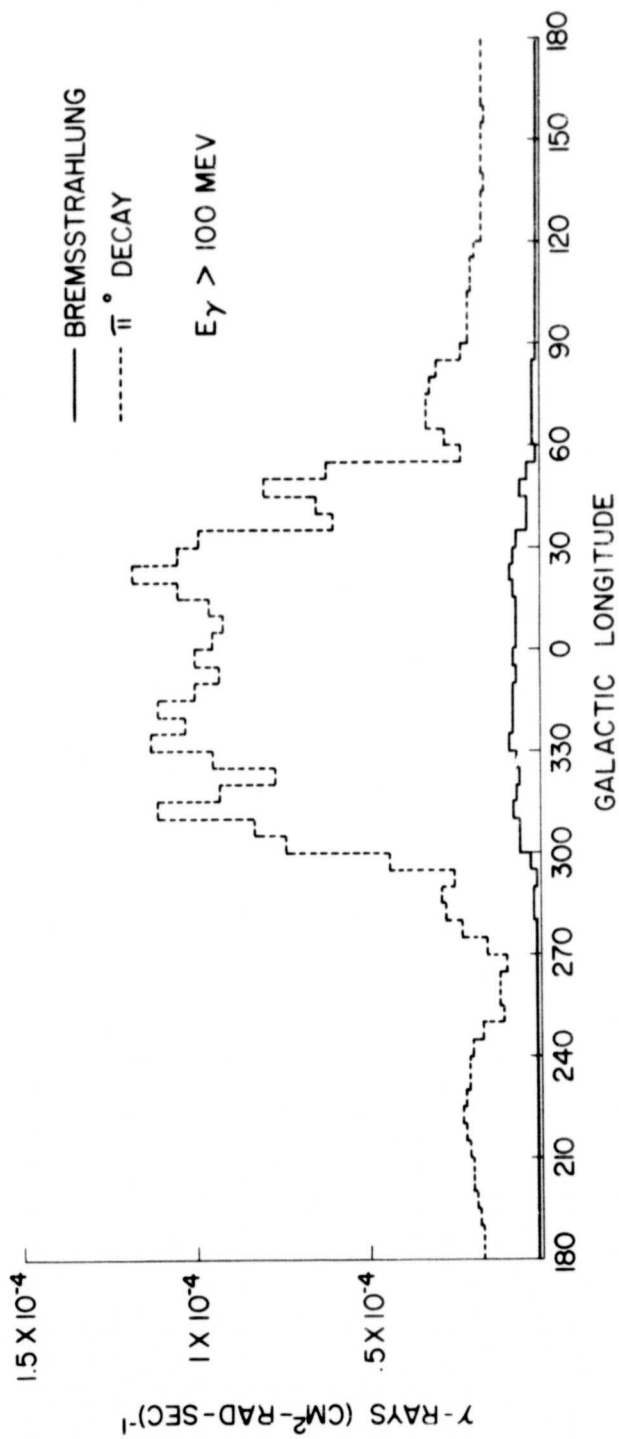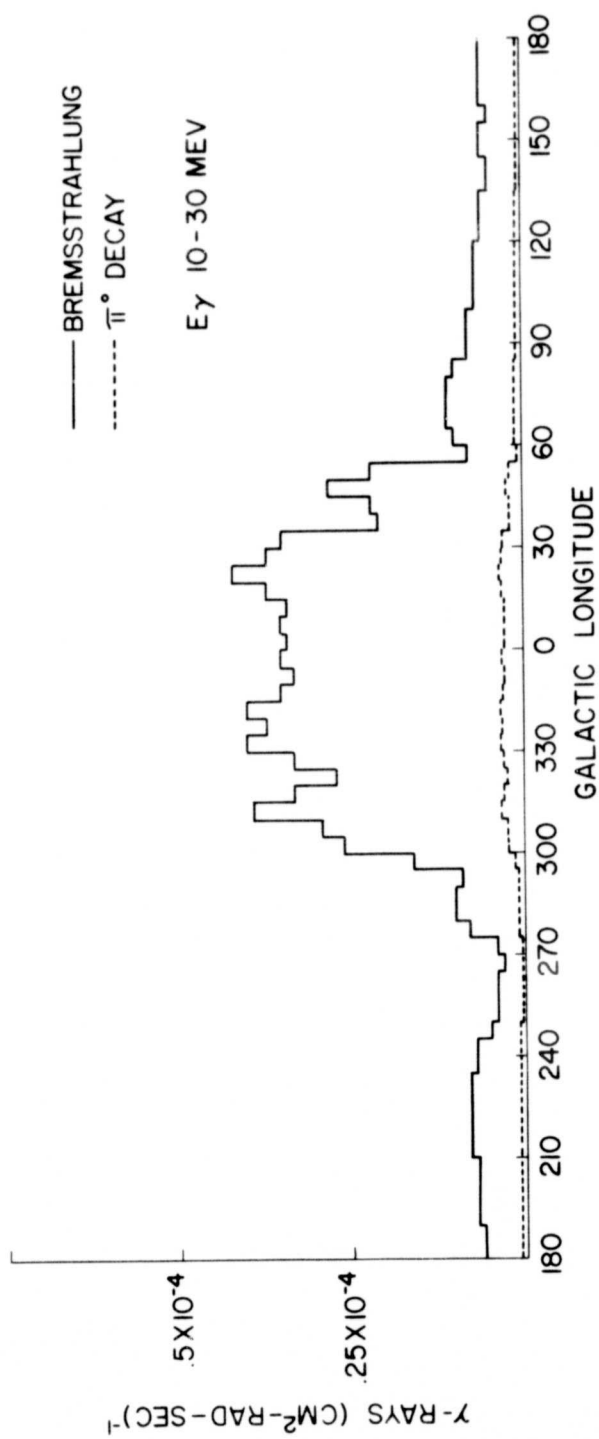
Fig. 1

Fig. 2