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B. Sadoulet, J. Rich, M. Spiro, and D.O. Caldwell

July 1987

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# Testing the WIMP Explanation of the Solar Neutrino puzzle with Conventional Silicon Detectors[1]

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Abstract

We point out that ionization silicon detectors are sensitive enough to allow the search for weakly interacting dark matter particles, with proton or neutron number coherent interactions for masses between 4 and 10 GeV/$c^2$. These are the properties necessary to explain the deficit of solar neutrinos by the cooling of the sun core by trapped dark matter particles.

## 1 Introduction.

One of the most fundamental questions in Astrophysics and in Cosmology is the nature of the "Dark Matter" which pervades the universe. At least 90% of the mass in the universe does not emit or absorb electromagnetic radiation, and its existence is inferred only through its gravitational interactions. It is difficult to prevent ordinary matter from radiating in an astrophysical environment [1], and primordial nucleosynthesis[2] limits the density of the baryons to a fraction of what seems necessary to account for the dark matter. This has led many authors [3] to doubt that dark matter is made out of ordinary matter. Among the other possibilities (primordial black holes, exotic objects), the idea that it could be made out of the lowest (stable) member of another (unknown) family of particles is fairly attractive. Many current particle physics theories need such a family in order to be singularity-free; the most familiar example is Supersymmetry[4].

Another puzzle of Astrophysics, is the apparent deficit of $^8$B neutrinos [5] coming from the sun. It has been proposed recently [6] that this could also be explained by weakly interacting massive particles (WIMPs) constituting the dark matter . They could be trapped by the sun and they may be able to transport energy from the core of the sun to larger radii and therefore to cool slightly the center. With the right parameters (mass between 4 and 10 GeV/$c^2$, cross sections around $10^{-36}$ $cm^2$ on protons and low enough rate of annihilation ), this is sufficient to explain the solar deficit. Conventional particles (e.g,photinos) do not appear to work[7], but it is possible to construct consistent particle physics models which have the right properties [8,9]. In addition to explaining the neutrino deficit, this model may also solve the discrepancy between observations of solar

oscillations and the standard model [6].

It is possible to test experimentally the hypothesis that dark matter is made out of non-baryonic particles for masses above a few GeV/$c^2$, a range quite natural in these theories. Arguments which are rather model independent [10], give a lower limit on the elastic interaction rate of dark matter from the halo of our galaxy with a suitable target in the laboratory: a few events per kg and per day for particle masses near 10 GeV/$c^2$, which is small but compares favorably with the level of radioactive background obtained at low energy by double $\beta$ decay experiments (0.5 events/kg/keV/day).These particles, however, have typically the virial velocity of 300km/s and the energy deposition is rather small ( a few hundred electron volts in the lower part of the mass range) and requires the development of detectors of extreme sensitivity.

Existing double $\beta$ experiments, which use large germanium detectors, have begun to explore the problem. Only relatively massive dark matter candidates with particularly large cross section (e.g. because of large asymmetry between particle or antiparticle, or special coherence effects) can be detected, and some limits exist already [11] in extremely favorable cases (the $Z^o$model that we describe below). Currently at least two groups (PNL-USC and LBL-UCSB) are decreasing their thresholds to 1.5 keV equivalent electron energy, but it is unlikely that they will be sensitive to masses below 8 to 10 GeV/$c^2$.

Cryogenic detectors [12] are being developed to tackle fully the questions [13]. But it will take several years before they will be operational.

In this paper, we point out that conventional silicon ionization detectors can detect dark matter particles with masses between 4 and 10 GeV/$c^2$, if the elastic cross section is large enough for the WIMP mechanism to be operative in the sun. The technology is well known, and it may be possible therefore **to prove or rule out this explanation,** within two years.

## 2. Advantages of ionization silicon detectors for Dark Matter searches.

For dark matter searches, silicon diodes may present significant advantages with respect to the germanium detectors presently used in double $\beta$ experiments: they may be designed to have lower thresholds; the efficiency of transfer of the energy of a recoiling nucleus to ionization is significantly higher; and the nucleus mass is better matched to the possibly low mass of the projectile. We review these three aspects in turn.

2.1 Lower thresholds. Because of lower leakage current, silicon detectors have intrinsically higher resolution and lower equivalent electron energy thresholds. They cannot be built in dimensions as large as that of germanium detectors ; this experimental drawback can be turned into an advantage, since it limits the capacitance of the detectors, leading to still lower thresholds. It is possible to get equivalent electron energy thresholds of 600eV with silicon detectors of the order of 10 grams[14].

2.2 Efficiency of energy transfer to electrons. Dark matter particles, if they exist, interact elastically with the nucleus, and the energy is deposited in the crystal by the recoiling nucleus. It is

well known that a slowly moving nucleus transfers very little of its energy to the electrons in the material, and the resulting pulse height in an ionization detector of a slow nucleus is much smaller than that of an electron of the same kinetic energy. This is shown in Fig. 1(a) and 1 (b) respectively, for germanium and silicon. The vertical axis gives the ratio of pulse height between an electron and a nucleus. The experimental points are those of Sattler [15] (open squares) and Chasman and coworkers [15] (closed circles). The curves are the prediction of Lindhard's model [16] with the parametriation of Robinson [17]. The silicon measurements of de Cosnac et al [18] above 100 keV are compatible both with those of Sattler and with Lindhard's theory. Two conclusions can be drawn from these data. Stattler's points are systematically lower than those of Chasman, a fact that the latter attributes to systematic effects in Sattler's method [16]. But overall the agreement with Lindhard's theory is remarkable, even at low energy as shown in germanium.

It has been argued in a picture where atoms interact with individual electrons that an ionization threshold may appear at very low energy . However, a recent experiment of Ahlen et al . (performed with scintillators where the same effect would be expected to exist) [19] shows that this picture is to a large extent incorrect and that very little deviation from Lindhardt's model appears down to $\beta$ of $10^{-3}$.

We can therefore conclude that Lindhard's theory represents a very reliable first approximation of the energy deposited by a nucleus. Furthermore, to come back to the main point of our paper, **the energy transfer to ionization in silicon is about a factor 1.5 better than in germanium.**

2.3 Better match between projectile and target masses. A third advantage of silicon is that for dark matter masses below 50 GeV, the nucleus mass M is better matched to the mass $m_\delta$ of the incident particle. It is easy to show that the average energy deposition at low energy is

$$E_d = \frac{m_\delta^2 M}{(m_\delta + M)^2} \langle v \rangle^2,$$

where $\langle v \rangle$ is the average velocity of the projectile.The energy is maximum when the target has the same mass as the incident particle. The minimum detectable mass for a particle of velocity $\beta c$ with a detector of threshold $E_{min}$ is

$$m_{\delta\,min} = \frac{\sqrt{(E_{min} M)/2}}{\beta}$$

For $\beta = 2\ 10^{-3}$, and taking into account the results of Fig 1., this leads to a mass sensitivity down to 3 GeV/$c^2$ for a silicon detector with an equivalent electron energy threshold of 0.6keV and 8 GeV/$c^2$ for a germanium with an equivalent electron energy threshold of 1.5keV.

### 3. Scientific importance of silicon diodes in dark matter searches.

The interest of this improvement in mass sensitivity obtained with silicon detectors can be

illustrated in three archetypes of dark matter.

3.1 Heavy Dirac Neutrinos.

As an example, we took the case where the dark matter is a heavy Dirac neutrino, coupling through $Z^0$ exchange with a hypercharge 1/2 [20]. We took a halo density of 7. $10^{-25}$ g/cm$^3$ and a Maxwellian velocity distribution with a root mean square average of 300km/s (without any truncation). Fig. 2 shows the expected distribution of the equivalent electron energy deposited by the recoiling silicon nuclei for 3 incident masses: 4,7 and 10 GeV/c$^2$ Other masses are given in Table I. It can be seen that, if the radioactive background in silicon can be brought to as low a level as in germanium (0.5 events/kg/keV/day) and if it does not rise at low energy (e.g. if it is dominated by gamma Compton scattering [10]), it should be relatively easy to detect this kind of dark matter down to 4 GeV/c$^2$ with a detector set of a few tens of grams. Table II gives the corresponding germanium event rates with a threshold of 1.5 keV equivalent electron energy.

3.2 WIMPs responsible for cooling the sun core.

As remarked above, this region of mass is particularly interesting in view of the proposal that WIMPs could cool the center of the sun. Below 4 Gev/c$^2$ they will evaporate, and above 10 Gev/c$^2$, which is about the limit for germanium detection, they will not travel far enough from the core to cool it efficiently. It is known [7] that the ordinary weak interaction cross section of a heavy neutrino such as that used in the model above, is marginal for the mechanism to work (e.g. at 5 Gev/c$^2$, $\sigma_{el}$=0.6 .$10^{-38}$ cm$^2$ on protons – using the axial couplings of Kane and Kani [21]– and $\sigma_{el}$= 3. $10^{-38}$ cm$^2$ on helium). So within this framework, even bigger cross sections than those considered in 3.1 would be expected, and detection should be easier .

As a naive example,we took the cross of $10^{-36}$cm$^2$ preferred by Gilliland et al [6] for the cooling of the sun core. In order to take into account the expected coherence effects, we arbitrarily chose to multiply these cross sections by the square of the number of protons for silicon and germanium targets, which leads to 2 $10^{-34}$ cm$^2$ and 1. $10^{-33}$ cm$^2$ respectively. The results shown in Tables I and II show that it should be quite easy to confirm or rule-out such a scenario.

As a more sophisticated case, we studied the model proposed recently by Raby and West[9a]. They postulated that the 4th generation neutrino is heavy and has in addition a large magnetic moment. In that case in addition to $Z^0$ exchange, there is a significant contribution from $\gamma$ exchange . Taking into account the interference term, and assuming a spin zero target, the cross section becomes [9b]

$$\sigma=\frac{\pi\,\alpha^2 Z^2 \mu^2}{m^2_\delta}\left\{1+\left(\frac{M}{m_\delta+M}\right)^2\left(1+\frac{\rho^2}{\mu^2}+\frac{G_F\, m^2_\delta\ \bar{N}}{2\sqrt{2}\,\pi\,\alpha\, Z\,\mu}\right)^2\right\}$$

where $\mu$ is the heavy neutrino magnetic moment and $\rho$= 2 $m_\delta$ r, where r is its charge radius. $\bar{N}$= N-Z(1-4sin$^2\theta_W$). Using the value suggested by the authors, $\mu$=1/(8$\pi^2$) and $\rho^2/\mu^2$=0.5, we obtain the rather large rates shown in Figure 3 and Table I.

We should note, for completeness, that spin 1/2 WIMPs with pure axial coupling to the

quarks would escape detection in silicon. Such particles would have the advantage from an Astrophysics point of view of not having the potential difficulty of the ordinary WIMP model with the horizontal branch [22].Let us remark, however, that such a model is not very attractive from a particle physics point of view, because it requires "fine tuning". The only natural way to impose pure axial coupling at the hadron vertex at low energy is to assume that the dark matter particle is of the Majorana type. In that case it has to have an axial coupling at its vertex, and mixed couplings such as A-V or V-A vanish in the elastic scattering at low energy (see e.g.[10]), resulting in a pure axial coupling at the hadron vertex. However, unless very specific mechanisms are invoked [8,9], a high elastic cross section necessary for an efficient heat transfer leads to a high annihilation cross section , which in turn through the Lee-Weinberg mechanism [23],would lead to too small a current density in the universe for those Majorana particles to account for dark matter. Moreover, they will annihilate in the sun, and not reach a large enough concentration for the proposed mechanism to work. In other words, they will have in the context of the cooling of the sun core problems similar to that of supersymmetric particles[7]. Therefore some vectorial coupling should exist and should be seen by a detector of a few tens of grams.

3.3 Dark matter particles without cosmic asymmetry

Finally, let us note that even if the WIMP explanation of the solar neutrino puzzle is incorrect, low threshold silicon diodes would also be interesting to search for dark matter with coherent interactions even if they do not have any initial asymmetry. Table I shows an example where we have rescaled the $Z^0$ exchange cross section used for Figure 2, to be compatible with the Lee-Weinberg value [10] (with $\Omega h^2=1/4$). Rates are still detectable at low masses.

## 4. Signatures and backgrounds.

4.1 Signatures

As shown in Fig. 2 and 3, interactions appear as a roughly exponential peak at the low end of the spectrum. What are the signatures that would permit distinguishing them from the background?

The most convincing signature would be the observation of the expected yearly modulation [24,10] of 10% in rate and mean energy deposition. This modulation of known phase is due to the fact that depending on the time of the year, the earth is adding or subtracting part of its velocity to that of the sun. However a $5\sigma$ effect would require 5000 events : this would be obtained in 2 years with a realistic detection of 100g, if the event rate was greater than 70 events/kg/day.

Even with poorer statistics, some experimental checks can be made to exclude instrumental effects. Observation of the line shape of X-ray lines present in the detector permits estimating precisely the tail of the electronics noise. Compatibility of the rates in the various elements of the detector would eliminate as a source short-range radiation ( $\alpha,\beta$ ) coming from the surroundings. The level of $\gamma$ ray Compton constitution can be estimated from the higher energy

region and comparison with rates observed in germanium in the same shield would provide an additional handle on understanding the background.

4.2 Radioactive background

It remains to be seen, however, what is the absolute rate of background in the silicon detector. The best germanium detectors [11] have backgrounds of 0.5-1 event 1 kg/day/keV between 15-20keV and 150 keV. The flatness of the background and its magnitude suggest that it is dominated by Compton scattering (which should be about the same in silicon and germanium). If these levels could be obtained in silicon, cross sections at least 2 orders smaller than those preferred for the cooling of the sun core could be excluded easily, as shown by number in parentheses in Table I and II.

It has often been stated [24], however, that silicon is a poor material for low-level, low-energy counting because of $^{32}Si$ contamination. In particular, a rate of $3.10^4$ disintegrations/kg/day has been reported for a sea sponge [25]. This radioisotope has a lifetime of 100 years and is produced by cosmic rays interacting in the atmosphere, particularly with argon. Thus this activity is important only for living organisms which are in equilibrium with the atmospheric isotope distribution. If the silicon is obtained from silicate rock or sands that have been deep underground for many lifetimes, this activity will become negligible. Although $^{32}Si$ has a $\beta^-$ decay with an endpoint energy of only 0.22MeV, and would be missed in high threshold detectors, it goes completely to $^{32}P$, which also has a 100% $\beta^-$ decay with an endpoint of 1.71 MeV and a 14.3-day lifetime, so that the latter decay should be observed. In detector grade silicon this activity has not been reported, but existing measurements[26] set limits only two orders of magnitude below the activity of the sponge. Nevertheless, if some care is taken with the source of the silicon, $^{32}Si$ should not be a problem, since after chemical purification, subsequent cosmogenic $^{32}Si$ production is not possible, because the stable isotopes of Si are lighter than $^{31}Si$.
We conclude therefore that there is no solid evidence yet that the background level cannot be as low in silicon as in germanium.

## 5. Conclusion

The above discussion shows that silicon diode detectors may be quite an interesting intermediate step in the search for dark matter particles. They would complement nicely the germanium detectors from double $\beta$ experiments, extending the sensitivity down to 4 GeV/$c^2$ for particles with coherent scattering.This is particularly interesting in view of the intense discussion of role of the WIMPs in transporting energy from the central to outer regions of the sun. While a positive result would be of course quite interesting, **a negative result would be sufficient to rule out one of the few serious contending explanations** of the solar neutrino puzzle.

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**Table I**

Rates in silicon in events/kg/day above 0.6 keV equivalent electron energy
(Numbers in brackets are the differential rates in events/kg/keV/day at 0.6 keV)

| Mass(GeV/$c^2$) | 4 | 7 | 10 | 15 | 20 | 30 |
|---|---|---|---|---|---|---|
| Model | | | | | | |
| $Z^o$exchange | 1.5<br>(6.5) | 12.<br>(19.) | 23.<br>(21.) | 35.<br>(18.) | 41.<br>(15.) | 45.<br>(11.) |
| $\sigma$=2. $10^{-34}cm^2$ | 72.<br>(320.) | 239.<br>(377.) | 262.<br>(234.) | 226.<br>(115.) | 188.<br>(67.) | 136.<br>(32.) |
| Raby-West | 155.<br>(664.) | 194.<br>(305.) | 138.<br>(122.) | 91.<br>(46.) | 73.<br>(26.) | 60.<br>(14.) |
| Heavy neutrino normalized to Lee-Weinberg | 2.4<br>(10.5) | 4.2<br>(6.6) | 3.<br>(2.8) | 2.3<br>(1.2) | 1.5<br>(0.6) | 0.8<br>(0.2) |

**Table II**

Rates in germanium in events/kg/day above 1.5 keV equivalent electron energy
(Numbers in brackets are the differential rates in events/kg/keV/day at 1.5 keV)

| Mass(GeV/$c^2$) | 7 | 8 | 10 | 15 | 20 | 30 |
|---|---|---|---|---|---|---|
| Model | | | | | | |
| $Z^o$exchange | 0.4<br>(1.4) | 1.6<br>(4.7) | 9.4<br>(18.) | 61.<br>(56.) | 127.<br>(72.) | 237.<br>(72.) |
| $\sigma$=1. $10^{-33}cm^2$ | 3.2<br>(12.) | 11.<br>(32.) | 44.<br>(84.) | 142.<br>(130.) | 188.<br>(107.) | 193.<br>(58.6) |
| Raby-West | 3.6<br>(14.) | 11.<br>(33.) | 39.<br>(75.) | 127.<br>(116.) | 199.<br>(112.) | 292.<br>(89.) |
| Heavy neutrino normalized to Lee-Weinberg | 0.1<br>(0.5) | 0.4<br>(1.2) | 1.5<br>(3.) | 4.<br>(3.7) | 5.<br>(2.7) | 4.<br>(1.1) |

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## Figure captions

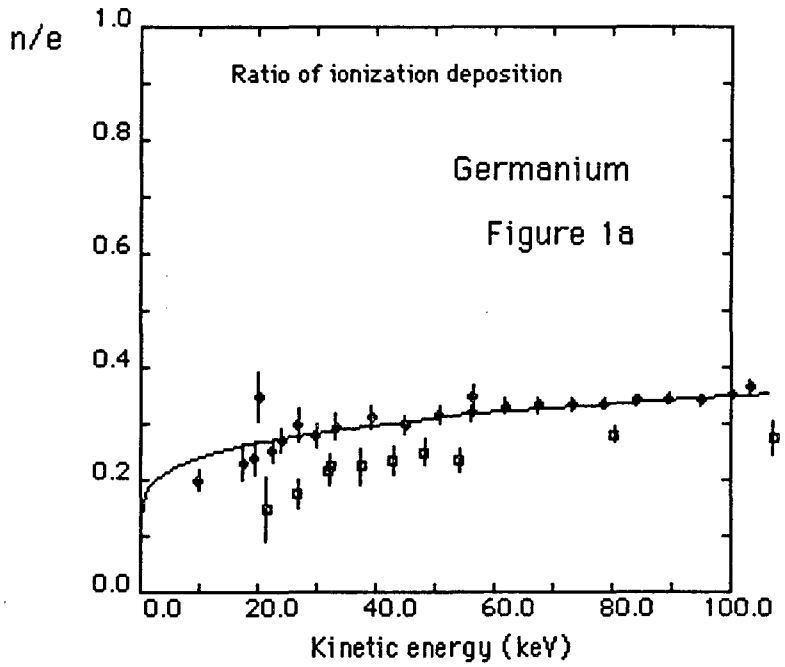
Figure 1. Ratio of the ionization deposition of a recoiling nucleus to that of an electron of the same kinetic energy, as a function of the kinetic energy. The curves are Lindhard's model [16] in the parametrization of Robinson[17].

1a) In germanium. The data points are from Chasman et al. [15b] (full circles) and from Sattler [15a] (open squares).

1b) In silicon. The data points are from Sattler [15a] (open squares).

Figure 2. Predicted event rate as a function of the equivalent electron energy for a heavy neutrino coupling through $Z^o$ exchange with hypercharge 1/2 [10,20].

Figure 3. Predicted event rate as a function of the equivalent electron energy for a heavy neutrino coupling through $Z^o$ exchange with hypercharge 1/2 , a magnetic moment $\mu=1/(8\pi^2)$ and $\rho^2/\mu^2=0.5$ [9].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1.0
0.8
0.6
0.4
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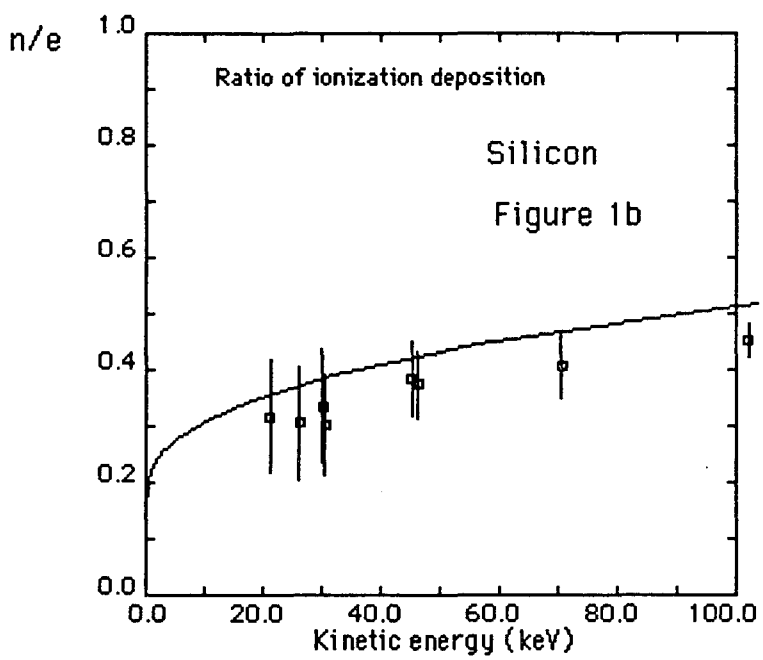
Ratio of ionization deposition
Germanium
Figure 1a
0.0
20.0
40.0
60.0
80.0
100.0
Kinetic energy (keV)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Ratio of ionization deposition
Silicon
Figure 1b
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Kinetic energy (keV)

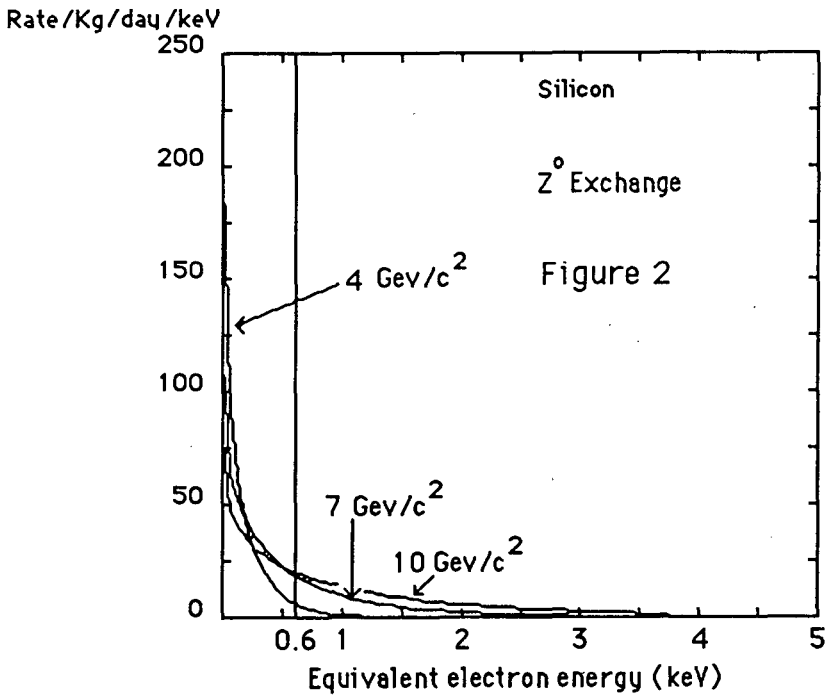


Figure 2

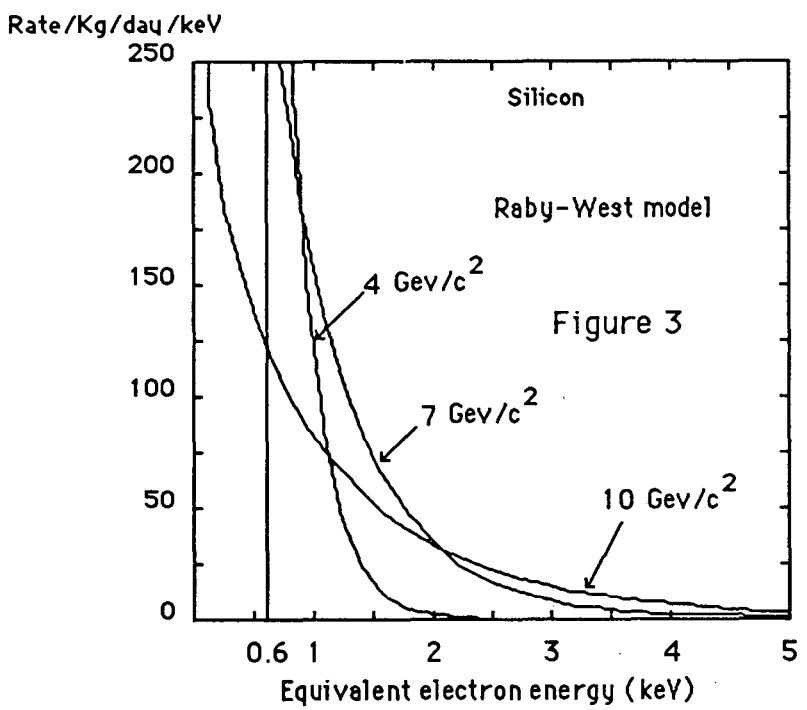


Figure 3

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