CSIRO Publishing

Publications of the Astronomical Society of Australia

VOLUME 19, 2002

© ASTRONOMICAL SOCIETY OF AUSTRALIA 2002

An international journal of astronomy and astrophysics

For editorial enquiries and manuscripts, please contact:
The Editor, PASA,
ATNF, CSIRO,
PO Box 76,
Epping, NSW 1710, Australia
Telephone: +61 2 9372 4590
Fax: +61 2 9372 4310
Email: Michelle.Storey@atnf.csiro.au

For general enquiries and subscriptions, please contact:
CSIRO Publishing
PO Box 1139 (150 Oxford St)
Collingwood, Vic. 3066, Australia
Telephone: +61 3 9662 7666
Fax: +61 3 9662 7555
Email: publishing.pasa@csiro.au

CSIRO PUBLISHING

Published by CSIRO Publishing
for the Astronomical Society of Australia

www.publish.csiro.au/journals/pasa

Publ. Astron. Soc. Aust., 2002, 19, 228–232

The Source Energy Spectrum of Cosmic Rays

R. W. Clay

Department of Physics and Mathematical Physics, University of Adelaide, South Australia 5005
rclay@physics.adelaide.edu.au

Received 2001 September 6, accepted 2002 January 8

Abstract: An examination is made of the relationship between the observed energy spectrum of cosmic rays and the averaged spectrum of the cosmic rays at their sources. These spectra differ greatly, due to propagation effects. A form of the source spectrum is deduced which is a rather featureless power law over the full range of observations from 10^{10} eV to 10^{20} eV. We suggest that this lack of features is indicative of a common source for all cosmic rays over the full energy range, as opposed to lower energy Galactic and higher energy intergalactic components such as is often suggested.

Keywords: cosmic ray spectrum — cosmic ray propagation — cosmic ray origins

1 Introduction

The cosmic ray energy spectrum measured at Earth has structure which will depend both on the nature of the cosmic ray sources and on the properties of the propagation from those sources to the observer. The propagation effects must be understood before a realistic source spectrum can be determined and then interpreted. Cosmic rays propagate to us through magnetic fields which are known to have a significant random, turbulent, component. Their propagation will thus have a diffusive nature. By estimating typical characteristics of the diffusion from Galactic escape time considerations, or from our knowledge of the Galactic magnetic field, estimates may be made of the characteristics of the cosmic ray source spectrum. Those source spectrum characteristics may then be interpreted in terms of the properties of the sources themselves. Derivations of cosmic ray source spectra in terms of detailed measured spectra are often made at energies below 10^{15} eV; we wish here to consider the broad features of the averaged source spectrum over the full range of measured cosmic ray energies.

2 The Observed Cosmic Ray Energy Spectrum

The measured cosmic ray energy spectrum extends roughly as a power law from 10^9 eV to above 10^{20} eV (e.g. Bhattacharjee & Sigl 2000). Close to the lower energy limit, the spectrum turns over due to the effect of the heliosphere on inward propagation to the Earth, which inhibits the arrival of lower energy particles. The true form of the spectrum outside the heliosphere is not well known below 10^{10} eV but could well be an extension (for at least a decade in energy) of the power law which extends from there up to an energy between 10^{15} eV and 10^{16} eV. At the latter energy, there is a 'knee', or the onset of steepening. Above the knee, the steepened spectrum extends to between 10^{18} eV and 10^{19} eV where it flattens somewhat (this is known as the ankle, see Takeda et al. 1998). At higher energies still, the statistical confidence we have in the form of the spectrum diminishes due to a lack of sufficient numbers of events but, at this time, there is no evidence for a steepening at 6×10^{19} eV which is expected due to interactions with the cosmic microwave background (e.g. Lampard, Clay, & Dawson 1997a,b). Such steepening should occur if the propagation distances of the higher energy cosmic rays extended above a few tens of megaparsecs.

2.1 The Cosmic Ray Anisotropy

The cosmic ray flux is extremely isotropic when observed from the Earth. The amplitude of the first harmonic in right ascension of the anisotropy rarely extends above the value to be expected on the basis of statistical fluctuations which are determined by the limited sizes of the available datasets (Clay 1987). There is evidence that some real anisotropies have been measured through coherence in the phases derived from datasets over certain limited energy ranges (Smith & Clay 1997). Two such regions are immediately below the knee (Clay et al. 1998) and, possibly, above 10^{18} eV. The limited magnitudes of the observed broad-scale anisotropies are not compatible with there being widely distributed Galactic cosmic ray sources at energies above 10^{18} eV (Lee & Clay 1995). This deduction follows from detailed modelling of cosmic ray propagation to determine whether a 'Milky Way' band should be visible across the cosmic ray sky. Such a band is predicted on the assumption that there is a distribution of high energy cosmic ray sources through the volume of the Galaxy, but that band is not observed. It is a common view that the lack of a Galactic anisotropy at the highest energies, plus the spectral flattening at the ankle, imply a source of the highest energy cosmic rays which is extragalactic. The modelling result assumes a light (proton dominated) composition and the anisotropy argument would not be so compelling for a heavy composition, with smaller radii of curvature in the Galactic magnetic field.

3 The Cosmic Ray Beam at the Highest Energies

Cosmic rays have been observed with energies above 10^{20} eV in sufficient numbers, and with a sufficiently large

© Astronomical Society of Australia 2002
10.1071/AS01064 1323-3580/02/02228$05.00

spread in observational technique, that one must conclude *prima facie* that, for some reason, the GZK cut off (e.g. Lampard et al. 1997a,b) is not a major factor affecting cosmic ray propagation. The most straightforward interpretation of this observation is that the cosmic rays at 10^{20} eV have not travelled for a distance greater than a few tens of megaparsecs. This appears to be in contradiction to our previous comment that cosmic ray anisotropy measurements are not compatible with a Galactic source, since there are few suitable extragalactic candidate objects within the required distance limit, apart from galaxies rather like our own. It is possible that a broad spatial distribution of exotic particles could be the source of these particles (Bhattacharjee & Sigl 2000). The distance limit for sources of conventional particles is further tightened if the possibility of intergalactic fields is considered since the total path length is considerably increased for a given linear source distance (Lampard et al. 1997a,b).

4 Propagation at Medium Energies and the Galactic Magnetic Field

At energies below 10^{18} eV, the propagation of cosmic rays to us must be greatly influenced by the Galactic magnetic field. Details of that field are not well known, but it is known to have a large-scale component which appears to follow structure related to the spiral arms. The magnitude of that field is of the order of a few microgauss (Beck et al. 1996). There is also a turbulent component which probably has a magnitude somewhat larger than that of the regular field.

A cosmic ray proton with an energy of 10^{15} eV would have a radius of gyration of 1 pc in a 1 μG field. Since the Galaxy has structure with dimensions of at least hundreds of parsecs, one would expect the propagation to be dominated by those fields up to about 10^{18} eV where the radii of gyration would significantly exceed any scales of Galactic turbulence which contain significant field components (Lee & Clay 1995; Clay 2001). Honda (1987) has discussed the form of the propagation, and diffusion coefficients which are likely to apply, at energies a little below 10^{18} eV.

Because of the diffusive cosmic ray propagation through Galactic magnetic fields, it will take time for the cosmic rays to leave the Galaxy. That containment time may be considerably greater than the time which would have been taken to leave without the influence of the magnetic field. For instance, at the lower cosmic ray energies, where the lifetimes of radioactive cosmic ray nuclei can be studied, containment times of tens of millions of years are directly found. At energies above 10^{17} eV, where propagation can be modelled and possible cosmic ray paths followed, significant containment times are also found although the limits of the influence of the Galactic field are being approached (Clay & Smith 1996; Berezinsky et al. 1991). The magnetic containment (perhaps better described as a slowing of the loss process) has two important consequences. Firstly it reduces the anisotropy (to the order of the direct loss time without the magnetic field divided by the containment time). This assumes that the anisotropy is not determined purely by propagation along a simple, but twisted, line (Allan 1972). The cosmic rays slowly diffuse past us at a rate determined by the diffusion coefficient. The flux is then spread rather uniformly over the whole sky by the diffusion process. Secondly, the slowed propagation results in an increased energy density (or flux). This increase is of the order of the inverse of the reduction factor of the anisotropy. For instance, protons at 10^{17} eV will have their escape time increased by about 50 times (Smith & Clay 1990). This will increase their overall measured flux by that factor and similarly reduce the anisotropy from a distant source to the order of 2%.

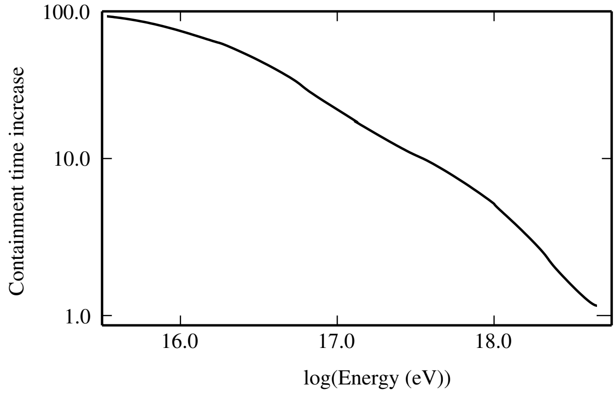

Figure 1 The result of a simulation of cosmic ray proton propagation from a hypothetical source close to the Galactic centre. The Galactic magnetic field is as described in Clay (2000) except that the random component has a rather constant mean strength and extends to 1 kpc above and below the Galactic plane. The random and regular fields have similar characteristic strengths of about 2 μG. The containment time is the extra factor of time required for the particles to leave the Galactic field, over that which results purely from their source directional distribution without any magnetic effects.

Figure 1 shows the result of a propagation calculation using the technique described in Clay (2000). A source is assumed to reside close to the Galactic centre and protons are followed from there through a model of the Galactic magnetic field which includes both regular and random components. The regular field follows the spiral arms and the random field has a Kolmogorov turbulence spectrum with a maximum scale size of 100 pc. Particles diffuse out of the Galaxy with a containment time indicated in Figure 1, which decreases with energy. This time acts as an integration time constant for those particles, and there is a resulting build up of particle flux within the Galaxy. The structure of Figure 1 is characteristic of all such calculations with the exact energies of its features being dependent on the strengths of the magnetic field components, their characteristic scale sizes, and the dimensions of any Galactic magnetic halo. However, Figure 1 represents a rather conservative selection of parameters. The overall shape is rather independent of the regular field except for a slight bump at about 10^{18} eV which results from the characteristic dimensions of the spiral arms being close to the gyroradius of the particles under consideration (see Honda 1987) — of the order of 1 kpc. These issues will be discussed in detail in a later paper.

If we wish to know the cosmic ray source spectrum, we must attempt to make allowance for the increase in flux due to containment. We can estimate the increase by using the various estimates of the containment time together with estimates of the escape time without magnetic containment. This correction is large at the lower cosmic ray energies but decreases until it becomes unity at about $10^{18.5}$ eV. Containment times rise with decreasing energy from about 3×10^4 yr at 10^{18} eV to about 2×10^6 yr at 10^{16} eV (e.g. Clay & Smith 1996). Ptuskin (1995) indicates an energy dependence of the diffusion coefficient no stronger than $E^{0.3}$ in the region below the knee where gyroradii are much smaller than the large-scale Galactic dimensions. This is consistent with the calculations of Honda (1987) for propagation in turbulent magnetic fields. As a result, we can use the dependence of the containment time at energies below 10^{16} eV, together with an estimate of the containment time for that energy (Clay & Smith 1996), to estimate containment times at energies down to those at which more direct observations are made using cosmic ray spallation data and observations of radioactive nuclei. Those data are broadly consistent with our simple approach. We emphasise that the containment time calculations substantially above the knee are straightforward, and have been repeated by a number of workers with consistent results (see Clay & Smith 1996). The better calculations require extrapolation down to the knee from about 10^{17} eV but there is little room for uncertainty in joining those results with propagation work below the knee (e.g. Ptuskin 1995).

If an allowance is made to compensate the measured energy spectrum for the increase in flux due to containment, and thus estimate an averaged source spectrum, the form of the spectrum changes. The knee, which is dominated by propagation processes, is not now a strong source spectral feature (see Figure 2), a result consistent with rigidity arguments made four decades ago by Peters (1961). This is an inevitable consequence of the knee being close to the energy at which Galactic propagation must begin to change in character given the known strength of the internal Galactic magnetic fields, and the well known structural dimensions of the Galaxy.

The detailed nature of the knee may not be completely explicable by this broad Galactic mechanism but it must occur and be the major factor contributing to the knee. Experiments are inconsistent on the details of the knee and on any compositional features associated with it. In our picture, it marks the onset of a change in the nature of Galactic propagation. Its detailed structure then depends on details of the physical structure and strength of the local field on a 1–10 pc scale (the gyroradius of protons at that energy). It is possible that local supernova sources might add a second component at the knee, giving it structure over a small energy range. This would be an unlikely coincidence in energy, unless it is the supernova field alone which dominates the local magnetic field structure.

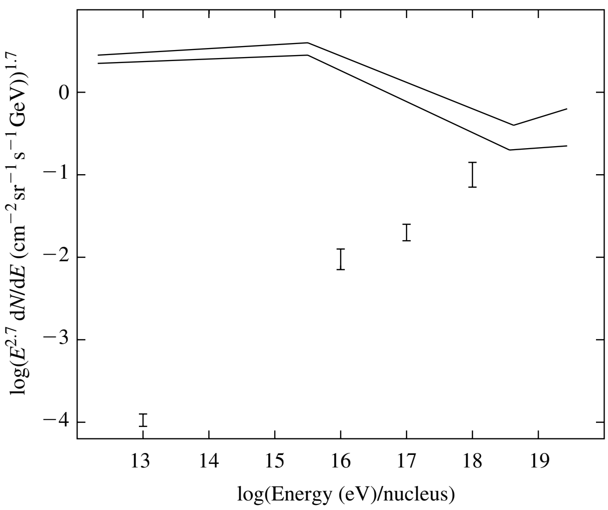

Figure 2 The cosmic ray energy spectrum (band of data — from Particle Data Group 1996) together with an unnormalised source spectrum (data with error bars) derived from the above spectrum using estimates of the Galactic containment time as a function of energy. The error bars are based on the spread in the energy spectrum alone, not including uncertainties in the containment time estimates. Shibata (1995) indicates that a power law with a differential index of approximately −2.3 applies to the source spectrum below 10^{15} eV.

Otherwise, the overall Galactic propagation and the local effect would tend to smear the knee beyond its known energy limits.

Remarkably, there is now little or no evidence for an ankle either. The differential energy spectrum extends as a simple power law through both the knee and ankle with a constant index of the order of −2.3 (with an uncertainty of about 0.1). An examination of the AGASA spectrum (Takeda et al. 1998), with its statistical uncertainties, indicates that the flattening above $10^{18.5}$ eV is indeed compatible with such a spectral index.

5 A Spectrum without Features

The source spectrum which was just described was derived from a complex measured spectrum. That measured spectrum has been interpreted as a composite of Galactic and extragalactic components. Such an interpretation took into account possible compositional changes above the knee which could have been interpreted as propagation effects. The present interpretation would still have compositional changes, similar to these, as the nature of the containment changes. The Galactic magnetic field still dominates the nature of compositional changes within the all-particle spectrum.

The remarkable feature of the spectrum is that there is now no clear change from a Galactic to an extragalactic component. The rather close agreement between the 'extragalactic flux' and the extrapolated lower energy Galactic flux below the knee has been remarked upon before (Clay & Smith 1996). We now not only match the level of the flux between an extrapolation from lower energies and the higher energy spectrum, but we also match the spectral slope. If there is no clear reason to assume a change in source, the difficulty now is to decide whether all the cosmic rays above (say) 10^{14} eV are extragalactic or, in contrast, whether all cosmic rays to the limits of present measurements are Galactic.

In principle, one can imagine an extragalactic flux filling the whole universe including our Galaxy. However, this would be barely compatible with gamma-ray observations of, for instance, the Magellanic Clouds (Sreekumar et al. 1993). Liouville's theorem precludes us from building up flux from extragalactic particles by Galactic containment unless there is an energy exchange process. Clay & Smith (1996) investigated this possibility. A process of energy exchange has also been considered in understanding heliospheric cosmic rays (Axford 1965). However, the likely build up of flux above intergalactic levels is still small compared to what is required to avoid the gamma-ray problem unless very unlikely energy exchanges occur.

Galactic particles have not usually been considered as candidates for the highest energy cosmic rays. The lack of a Galactic acceleration process and the low levels of observed anisotropies seem to be against the possibility. However, even in the conventional Galactic plus intergalactic scenario, it is required that some Galactic cosmic rays reach the ankle at $10^{18.5}$ eV. Even there, there is not a sharp cut-off and, in the model, it is possible (or likely) that Galactic acceleration to higher energies would occur. Further, recent data from AGASA strongly suggest at least one galactic source of cosmic rays which currently operates to at least $10^{18.5}$ eV (Hayashida et al. 1999; Bellido et al. 2001). So, our Galaxy does indeed have some sources capable of accelerating particles to within two decades of the highest known energies.

As we noted before, a more serious problem in a Galactic source scenario is the lack of an anisotropy which reflects the Milky Way in the cosmic ray sky. This may not be so serious as previously thought when we consider the recent AGASA result at 10^{18} eV (Hayashida et al. 1999). We have to consider the possibility that a source such as the AGASA one has a limited lifetime and that the Galactic cosmic rays result from infrequent energetic bursts in variable sources. At any one time, there may only be a single source in an active state. We might then think that the AGASA source, which is indeed in the plane of the Milky Way, happens to be the only one visible at the present time. Over a long period of time, a succession of such sources would integrate to a cosmic ray 'Milky Way' but, at a given instant, only one might be detectable. In this picture, the issue of the lack of a directional distribution which shows a Milky Way anisotropy is not what is really important. The key issue is to know where the particles from non-Milky Way directions originate. Smith & Clay (1995) have shown that a source, or containment, volume with dimensions of the order of 100 kpc can produce anisotropies compatible with observation at 10^{19} eV. The existence of a rather larger volume containing a substantial magnetic field might satisfy observational constraints at higher energies even with a Galactic source.

In order to understand the broad directional distribution at the highest energies, we thus need to have information on the conditions in the intergalactic medium around us. Our Galaxy lies within a local group of galaxies with an extent up to several hundred kiloparsecs (Hartwick 2000). Further, Clarke et al. (2000) have shown that X-ray bright clusters of galaxies contain microgauss level magnetic fields and that those fields typically extend at least to hundreds of kiloparsecs. Mulchaey (2000) indicates that non-X-ray luminous, poor, clusters are unlikely to be much different from X-ray bright clusters in their other physical properties. One can conclude that, even in the case of our 'poor' Local Group, there is probably an intra-group magnetic field at the microgauss level out to large distances. Beck (2001) has shown that M31, in some ways not dissimilar to the Milky Way, has a large-scale outer magnetic field at the microgauss level. Clay (2001) has also shown that the Milky Way has a surrounding microgauss field at least to distances of several kiloparsecs. We should consider the implications of such a field for cosmic ray propagation with the expectation that the anisotropy can be low for such a large containment volume.

We noted earlier that 10^{18} eV cosmic ray protons have gyroradii of the order of a kiloparsec in a microgauss field. With an estimate of the magnitude of the intergalactic magnetic field at that level, we can estimate the time taken for such particles to diffuse in intergalactic space. In particular, if they were to come through such fields from another galaxy more energetic than our own (together with the higher energy particles), a time longer than the age of the universe would be required. This applies for source distances down to as low as the level of about a megaparsec. The result of a dominant extragalactic flux above about 10^{18} eV would thus be a cosmic ray deficit in the region of 10^{18} eV–10^{19} eV. That is not observed, and this lack is a further argument against the highest energy particles coming from distant energetic galaxies.

A possible scenario, then, is that our Galaxy accelerates particles, from time to time, to the highest known energies. At the present time, only the AGASA source is directly detectable. Source variability is required. That is exactly what is found in most energetic objects, AGN, active solar regions, etc. Once the high energy cosmic rays have left the Galaxy, they diffuse within a containment region with dimensions at least as large as the Local Group (a few hundred kiloparsecs) and containing microgauss magnetic fields, as do other galactic clusters. The cosmic rays diffuse in the turbulent extragalactic magnetic fields with containment times up to limits set by at least the GZK cut-off. At $10^{20.5}$ eV, the highest cosmic ray energy so far recorded, a containment volume with a radius of the order of 1 Mpc would give a containment time of 20 Myr, probably just low enough for there to be no significant spectral effect due to the GZK mechanism.

The Local Group structure around us is anisotropic and, at some energy, one would expect that structural anisotropy to be reflected in the cosmic ray anisotropy. In a galactic source scenario, that anisotropy would become recognisable at an energy which would indicate the magnitude of the Local Group magnetic field strength/dimension combination. Hartwick (2000) has shown that the supergalactic plane is related in orientation to a number of rather local structures. The shortest axis of the Local Group spatial distribution lies close to the supergalactic pole, as does the short axis of the next structure out from us (with a centre of gravity 2.8 Mpc distant), the Coma-Sculptor Cloud. If the highest energy cosmic rays are at all related to local sources, one must expect this to eventually show some supergalactic plane effect in their directional distribution. There may also be a further anisotropy effect in the Galactic plane, depending on the time distribution of any variable sources.

6 The Nature of the Sources

There is no agreed upon source for the highest energy Galactic cosmic rays. This is true even if we have the standard scenario of a change from Galactic to extragalactic particles at $10^{18.5}$ eV. We have no real source models for reaching above about 10^{14} eV where supernovae shocks probably cease to be effective. However, a source is known to exist. We do see evidence for a source at 10^{18} eV, roughly towards the Galactic centre, although not well aligned in direction. It could be much closer. Still, a single strong source direction, such as is observed, does not seem to be the result one would expect to find from a large-scale distribution of exotic particles. They would have to have accumulated in some sort of way in a small volume to be consistent with the observation.

The only Galactic source type which has historically been suggested to be capable of accelerating particles to these energies is the neutron star binary system. A number of such systems were associated with possible observations of UHE gamma rays (e.g. Cassiday et al. 1989). Perhaps there are such systems which have a limited lifetime in a high energy or flaring state such that $10^{20.5}$ eV can be reached.

7 Conclusions

If an allowance is made for the containment of cosmic rays in known regions with known magnetic fields, the cosmic ray energy spectrum to the highest energies reduces to a featureless power law with a differential index of about -2.3. This spectrum is most simply interpreted if all the cosmic ray particles originate in our Galaxy. The highest energy particles must then be 'contained' within an extended volume comparable in dimension with our Local Group of galaxies.

Acknowledgement

Paul Sommers is thanked for very illuminating discussions on models for the origin and anisotropy of the highest energy cosmic rays.

References

Allan, H. R. 1972, ApJ, 12, L237
Axford, W. I. 1965, P&SS, 13, 115
Beck, R., et al. 1996, ARA&A, 34, 155
Beck, R. 2001, SSRv, 99, 243
Bellido, J. A., et al. 2001, APh, 15, 167
Berezinsky, V. S., et al. 1991, in Astrophysical Aspects of the Most Energetic Cosmic Rays, eds M. Nagano, & F. Takahara (Singapore: World Scientific), 134
Bhattacharjee, P., & Sigl, G. 2000, PhR, 327, 109
Cassiday, G. L., et al. 1989, PhRvL, 62, 383
Clarke, T. E., et al. 2000, astro-ph/0011281
Clay, R. W. 1987, AuJPh, 40, 423
Clay, R. W. 2000, PASA, 17, 212
Clay, R. W. 2001, PASA, 18, 148
Clay, R. W., & Smith, A. G. K. 1996, PASA, 13, 121
Clay, R. W., et al. 1998, PASA, 15, 208
Hartwick, F. D. A. 2000, AJ, 119, 2248
Hayashida, N., et al. 1999, APh, 10, 303
Honda, M. 1987, ApJ, 319, 836
Lampard, R., Clay, R. W., & Dawson, B. R. 1997a, APh, 7, 213
Lampard, R., Clay, R. W., & Dawson, B. R. 1997b, PASA, 14, 258
Lee, A. A., & Clay, R. W. 1995, JPhG, 21, 1743
Mulchaey, J. S. 2000, ARA&A, 38, 289
Particle Data Group 1996, PhRvD, 54, 1
Peters, B. 1961, Nuovo Cimento, 22, 800
Ptuskin, V. S. 1995, Il Nuovo Cimento C, 19, 755
Shibata, T. 1995, Il Nuovo Cimento C, 19, 713
Smith, A. G. K., & Clay, R. W. 1990, AuJPh, 43, 373
Smith, A. G. K., & Clay, R. W. 1995, Proc. 24th Int. Cosmic Ray Conf. (Rome), eds N. Iucci, & E. Lamanna (Bologna: Societa Italiana di Fisica), 2, 784
Smith, A. G. K., & Clay, R. W. 1997, AuJPh, 50, 827
Sreekumar, P., et al. 1993, PhRvL, 70, 127
Takeda, M., et al. 1998, PhRvL, 81, 1163