POSITRON–MOLECULE SCATTERING / DISPERSION POSITRON–MOLÉCULE

Positron annihilation in a simulated interstellar medium

K. Iwata, R.G. Greaves, and C.M. Surko

Abstract: The annihilation of positrons in a simulated interstellar medium consisting of molecular hydrogen and a small admixture of the polycyclic aromatic hydrocarbon, naphthalene, was studied in a Penning trap containing cold positrons. The experiments demonstrate the ability to distinguish two distinct components in the annihilation γ-ray spectra. The significance of the experiment for the analysis of γ-ray spectra of astrophysical origin is discussed.

Résumé : Dans un piège Penning contenant des positrons froids, nous avons étudié l'annihilation de positrons dans un milieu interstellaire simulé contenant de l'hydrogène moléculaire et des traces d'un hydrocarbone aromatique polycyclique, la naphthalène. Cette expérience démontre la possibilité de distinguer nettement deux composantes dans ce spectre γ d'annihilation. Nous étudions la possibilité d'utiliser ces résultats dans l'analyse des spectres γ en astrophysique.

[Traduit par la rédaction]

1. Introduction

The 511 keV positron annihilation line is the strongest γ-ray line of astrophysical origin [1], and it has been studied extensively, both observationally and theoretically [2–4]. Recently, the Gamma Ray Observatory increased our knowledge of astrophysical positron annihilation dramatically [5]. These studies reveal that there are at least two components of the annihilation radiation: a steady, diffuse component from the interstellar medium (ISM) [6], and a possibly variable component from discrete, compact sources such as the strong source located near the galactic center [7].

The narrow energy spread of the observed annihilation line is interpreted as coming from positrons that have been slowed down to a few electronvolts before annihilating on either free electrons or on electrons in molecules of the ISM. The physics of positron slowing and annihilation in the ISM has been the subject of many analytical models and numerical simulations [8, 9]. One scenario postulates that the positrons thermalize with the ISM and then annihilate on neutral gas atoms and molecules [3]. In this case, the lineshape of the γ-ray spectrum would be determined entirely by the temperature and chemical composition of the ISM.

Another scenario for the fate of astrophysical positrons involves annihilation following in-flight positronium-atom formation by interaction with neutral gas atoms and molecules. In this scenario, the γ-ray lineshape would be qualitatively different from that of annihilation on neutral atoms and molecules, and would depend on the dynamics of the slowing-down process. The effects of temperature of annihilating media have also been studied theoretically [8]. Other scenarios include the effects of interstellar dust and molecular clusters [10].

We developed a technique for accumulating and storing cold positrons in a vacuum of less than 10^{-9} Torr (1 Torr = 133.3 Pa). This provides a tool for studying low-energy positron–molecule interactions in a controlled environment. We previously measured annihilation rates [11–15] and annihilation γ-ray spectra [16], and discovered that large organic molecules have anomalously high annihilation rates (attributed to resonance binding of the positron to the molecule) [11] with measurably different γ-ray spectra from that of hydrogen [16].

There exist extensive sets of infrared spectral measurements indicating that hydrocarbons are present in the ISM [17–20]. The molecules have been identified as polycyclic aromatic hydrocarbons (PAH), and their molecular concentration is $\sim 10^{-7}$ of that of hydrogen. Stability analyses of these molecules indicate that PAHs with four to nine aromatic rings (examples of which are shown in Fig. 1) dominate the interstellar PAH population [19]. At present, we are only able to study the two- and three-ring PAHs, naphthalene and anthracene, because the larger PAHs have very low vapor pressure. However, we believe that these two PAHs are representative of the family, in that all hydrocarbons studied previously, including the single-ring benzene and the two-ring naphthalene have larger γ-ray linewidths than that of hydro-

Invited paper/Article sollicité.

Received November 28, 1995. Accepted March 7, 1996.

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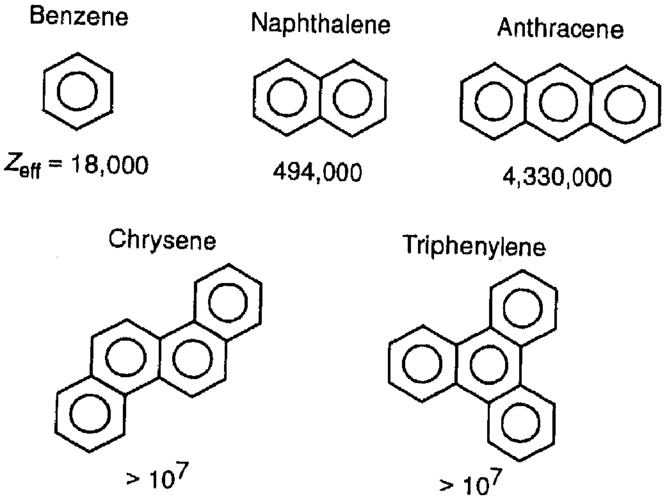
Fig. 1. Chemical structures of a selection of PAHs. Benzene, naphthalene, and anthracene were studied previously in the positron trap, and values of their normalized annihilation rates, Z_{eff}, are listed. Chrysene and triphenylene are the smallest PAHs believed to exist in the IMS. Their Z_{eff} values are extrapolated to be greater than 10^7. In comparison, atomic hydrogen has a Z_{eff} of 7.



gen and we expect this to extrapolate to the larger PAHs. Moreover, we noted a systematic increase in the annihilation rates for the PAHs as one adds more rings. This trend should continue up to some saturation level, where the resonance binding time becomes comparable to the annihilation time scale. The saturated value could be 10^6 times as great as or greater than that of atomic hydrogen so that the interstellar PAH molecules may contribute significantly to interstellar positron annihilation even though the PAH molecules are present in only small concentrations as pointed out earlier [21, 22]. These measurements have led us to simulate positron annihilation in a cold medium similar to the cold cloud phase of the ISM.

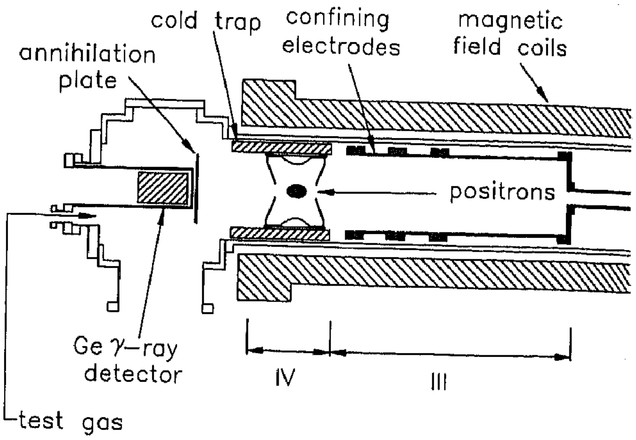
In this paper, we describe an experiment to measure the annihilation γ-ray spectrum from a simulated ISM consisting of molecular hydrogen and a PAH, namely naphthalene, at room temperature. To our knowledge, this is the first experimental simulation of astrophysical positron annihilation in a mixed-gas medium. Section 2 describes the experiment in more detail. In Sect. 3, we present the annihilation data and describe the analysis, while Sect. 4 summarizes the paper, and discusses the implications of the experiment for the analysis of astrophysical data.

2. Description of the experiment

This experiment was performed using a technique similar to our previous γ-ray study [16], but with improvements in the experimental geometry and in the gas-handling systems. These improvements, in addition to ongoing refinements in our trapping techniques [23, 24], increased our γ-ray count rates by about two orders of magnitude, so that we are now able to resolve detailed features of the spectral lineshape.

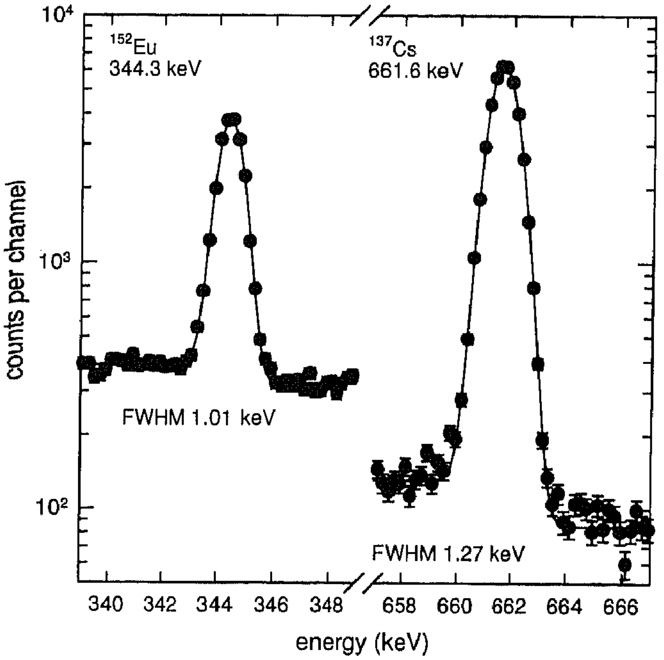
The layout of the experiment is shown in Fig. 2. Positrons from a ^{22}Na source are slowed to a few electronvolts by a solid neon moderator [24, 25]. They are then accelerated to about 30 eV and guided by a magnetic field into a Penning trap. The trap has three stages of progressively lower potential and lower pressure of the nitrogen buffer gas, which is introduced into the first stage. The positrons are trapped in the third stage by a series of electronic, vibrational, and rotational excitation collisions with the nitrogen gas, and cool to the temperature of the gas in the order of 1 s. After the positrons are trapped in the third stage, they are transferred to a fourth stage close to the γ-ray detector, as shown in Fig. 2. Further details of the trapping mechanism and the operation of the trap are presented in refs. 23 and 26. An annular cold trap surrounding the final positron accumulation area was filled with a −7.2°C water–ethanol mixture to reduce condensable impurities in the vacuum system. For this experiment, the positron lifetime in the fourth stage is 17 s at an operating pressure of $\sim 5 \times 10^{-7}$ Torr, and increases to 33 s if the buffer-gas feed is switched off after the positrons have been loaded. This relatively short lifetime is caused by the impurities in the vacuum system. The lifetime can be extended greatly (up to a half hour with the buffer gas turned off) if the cold trap is filled with liquid nitrogen. This is not possible for this experiment because the naphthalene condenses on surfaces at liquid-nitrogen temperature. With positrons loaded and cooled, and the buffer gas pumped out, various sample gases can be introduced for controlled annihilation studies.

Fig. 2. Schematic diagram of the experiment, showing the proximity of the positron cloud in the final stage of the trap with the high-resolution γ-ray detector.



The γ-ray lineshape was measured using an intrinsic germanium detector with a design optimized for high-resolution measurement of 511 keV γ-rays. The spectra were accumulated over repeated cycles of positron filling and annihilation. At the start of each cycle, the nitrogen buffer-gas feed was switched on and positrons were accumulated in stage four for 18 s. The positron beam was switched off, and the stored positrons were allowed to cool for 1 s. The buffer-gas feed was then switched off, followed by an 8 s delay to allow the buffer-gas pressure to fall by an order of magnitude, which reduces annihilation of positrons on N_2 to negligible levels. The sample gases were then introduced, and a multichannel analyzer was gated on to allow accumulation of the spectrum for 4 s. By repeating this cycle for 12 h we were able to build up a spectrum containing 5.7×10^5 integrated counts.

Fig. 3. γ-ray lines from calibration sources; ^{152}Eu and ^{137}Cs. The continuous line is a fit with a combination of a Gaussian, a step function convolved with the same Gaussian, and a baseline.



Calibration of the detector was performed before and after the measurement using ^{152}Eu and ^{137}Cs test sources, with γ-ray lines at 344.3 and 661.6 keV, respectively. The calibration lines, shown in Fig. 3, were fit with a combination of a Gaussian function, a step function convolved with the same Gaussian, and a baseline. The step function models the Compton scattering of the γ-ray line in the crystal, while the baseline accounts for the Compton scattering from higher energy γ-ray lines. The fit has five free parameters, and it produces the fitting parameter, $\chi_n^2 \sim 1$, where $\chi_n^2 \equiv \chi^2/(n-j)$; n is the number of datum points to fit, and j is the number of free parameters. The small χ_n^2 indicates that the model provides a good fit to the data. The detector resolution of 1.14 keV (FWHM) at 511 keV was calculated by linearly interpolating the widths of the calibration lines from the Gaussian fits.

The pressures of molecular hydrogen and naphthalene were adjusted so that approximately equal number of γ-rays originate from annihilation on each of the sample gases. The numerical values are listed in Table 1. Note that, although the naphthalene has four orders of magnitude lower pressure than that of hydrogen, it nonetheless contributes significantly to the annihilation, owing to its anomalously large annihilation cross section [13].

3. Experimental results

The observed spectrum from positrons annihilating on the mixture of molecular hydrogen and naphthalene molecules is shown in Fig. 4. A single Gaussian with a step function and a baseline was fit to the data, as for the calibration lines, producing a linewidth of 2.01 keV. However, the fit parameter χ_n^2 was 13.4, which indicates that a single Gaussian does not model the data adequately.

Fig. 4. γ-ray line for positrons annihilating on mixture of hydrogen and naphthalene molecules. (- - - -), annihilation spectrum from molecular hydrogen; (— - — -), annihilation spectrum from naphthalene; (——), combined fit to annihilation spectrum from the mixed medium.

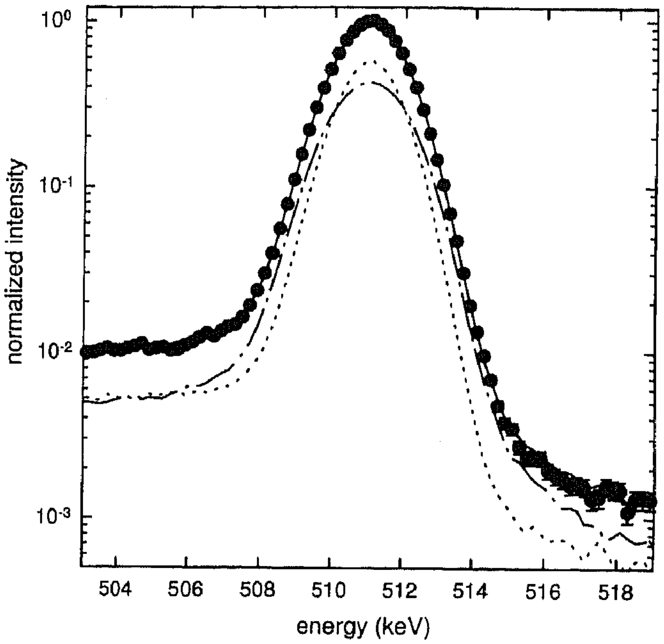


Table 1. The fraction of annihilations on each component: ΔF, calculated from fit to data; ΔF_p, calculated from pressure and Z_{eff}.

Molecule	Pressure (Torr)	Z_{eff}	Width (keV)	$\Delta_p F$ (%)	ΔF (%)
Hydrogen	3.0×10^{-5}	14.7[a]	1.71	21	51
Naphthalene	3.5×10^{-9}	494 000[b]	2.29	79	49

Note:
[a] Ref. 29.
[b] Ref. 13.

To find a better fitting function, the spectra from annihilation on H_2 and naphthalene were measured separately. Then, a superposition of these two spectra was fit to the mixed-gas data by adjusting the relative weights of the two components. The fit has only two free parameters, namely, the weights of the H_2 and naphthalene spectra. The resulting fit and the separate components from H_2 and naphthalene are plotted on Fig. 4. The fit produced $\chi_n^2 = 0.98$, indicating that the choice of the individually measured component spectra as fitting functions is a very good model. By integrating the area under each component, the fractions of positrons annihilating on H_2 and on naphthalene can be calculated (see Table 1).

Annihilation fractions were also calculated using the pressures and annihilation rates listed in Table 1. The annihilation rates are expressed in terms of the normalized rate Z_{eff} [15]. A total annihilation rate on one component is proportional to its Z_{eff} and pressure. The annihilation fractions are calculated comparing the data for H_2 and naphthalene. These fractions differ by a factor of 4 from the fractions calculated with the two-spectrum fitting procedure. Uncertainties in measuring the low naphthalene pressure ($\sim 10^{-9}$ Torr) using an ionization vacuum gauge could be in error by as much as 50%, which would account for a large part of the discrepancy.

4. Summary

We have demonstrated a method for analyzing γ-ray spectra from positrons annihilating on gas mixtures. These data introduce the possibility of identifying the minority constituents of the ISM from the γ-ray spectra, assuming a scenario under which positrons thermalize and then annihilate on neutral atoms and molecules of the ISM. In practice, such an analysis would involve building up a library of annihilation lineshapes for candidate molecules in the ISM, and using them to fit the astrophysical measurements. At present, the signal-to-noise ratio of astrophysical data is too low to attempt such fits, but these kinds of analyses may be possible in the future using high-resolution data from orbital missions [27].

For this experiment, molecular hydrogen was used for convenience, but, in principle, experiments with atomic hydrogen are also possible [28]. At present, annihilation studies of PAHs larger than naphthalene are difficult because of the low vapor pressures of these molecules. To eliminate this restriction, we plan to construct a "hot cell" to perform studies of these molecules. In the future, we plan to carry out experiments to test other scenarios for positron annihilation in the ISM, such as interaction with dust and clusters, as well as the annihilation by in-flight positronium formation. Currently, the pressure measurement, as discussed in the previous section, is the main source of uncertainty of annihilation rates, and we plan to improve this aspect of the experiment.

Acknowledgments

The authors are grateful for expert technical assistance by Mr. E.A. Jerzewski and useful discussion with Dr. R.E. Lingenfelter. This work was supported by the National Science Foundation under grant No. PHY 9221283 and by the Office of Naval Research.

References

1. R. Ramaty and R.E. Lingenfelter. *In* High energy astrophysics. *Edited by* J. Matthews. World Scientific, New York. 1994. p. 32.
2. R.W. Bussard, R. Ramaty, and R.J. Drachman. Astrophys. J. **228**, 928 (1979).
3. P. Wallyn, P. Durouchoux, C. Chapuis, and M. Leventhal. Astrophys. J. **422**, 610 (1994).
4. D.M. Smith, M. Levanthal, N. Gehrels et al. Astrophys. J. **443**, 117 (1995).
5. W.R. Purcell, D.A. Grabelsky, M.P. Ulmer, W.N. Johnson, R.L. Kinzer, J.D. Kurfess, M.S. Strickman, and G.V. Jung. Astrophys. J. Lett. **413**, L85 (1993).
6. R. Ramaty, J. Skibo, and R.E. Lingenfelter. Astrophys. J. Suppl. Ser. **92**, 393 (1994).
7. R. Ramaty, M. Leventhal, K.W. Chan, and R.E. Lingenfelter. Astrophys. J. Lett. **392**, L63 (1992).
8. N. Guessoum, R. Ramaty, and R.E. Lingenfelter. Astrophys. J. **378**, 170 (1991).
9. R.J. Gould. Astrophys. J. **344**, 232 (1989).
10. W.H. Zurek. Astrophys. J. **289**, 603 (1985).
11. C.M. Surko, A. Passner, M. Leventhal, and F.J. Wysocki. Phys. Rev. Lett. **61**, 1831 (1988).
12. T.J. Murphy and C.M. Surko. J. Phys. B: At. Mol. Opt. Phys. **23**, 727 (1990).
13. T.J. Murphy and C.M. Surko. Phys. Rev. Lett. **67**, 2954 (1991).
14. K. Iwata, R.G. Greaves, and C.M. Surko. Hyperfine Interact. **89**, 271 (1994).
15. K. Iwata, R.G. Greaves, T.J. Murphy, M.D. Tinkle, and C.M. Surko. Phys. Rev. A: At. Mol. Opt. Phys. **51**, 473 (1995).
16. S. Tang, M.D. Tinkle, R.G. Greaves, and C.M. Surko. Phys. Rev. Lett. **68**, 3793 (1992).
17. A. Leger and J.L. Puget. Astron. Astrophys. **137**, L5 (1984).
18. L.J. Allamandola, A.G.G.M. Tielens, and J.R. Barker. Astrophys. J. Lett. **290**, L25 (1985).
19. L.J. Allamandola, A.G.G.M. Tielens, and J.R. Barker. Astrophys. J. Suppl. Ser. **71**, 733 (1989).
20. J. Szczepanski and M. Vala. Nature (London), **363**, 699 (1993).
21. C.M. Surko, R.G. Greaves, and M. Leventhal. Hyperfine Interact. **81**, 239 (1993).
22. C.M. Surko, M. Leventhal, and A. Passner. Phys. Rev. Lett. **62**, 901 (1989).
23. R.G. Greaves, M.D. Tinkle, and C.M. Surko. Phys. Plasmas, **1**, 1439 (1994).
24. R.G. Greaves and C.M. Surko. Can. J. Phys. **74**, (1995). This issue.
25. A.P. Mills, Jr. and E.M. Gullikson. Appl. Phys. Lett. **49**, 1121 (1986).
26. T.J. Murphy and C.M. Surko. Phys. Rev. A, **46**, 5696 (1992).
27. C. Winkler, O. Pace, and S. Volonte. ESA J. **17**, 207 (1993).
28. S. Zhou, W.E. Kauppila, C.K. Kwan, and T.S. Stein. Phys. Rev. Lett. **72**, 1443 (1994).
29. G.R. Heyland, M. Charlton, T.C. Griffith, and G.L. Wright. Can. J. Phys. **60**, 503 (1982).

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Invited paper/Arti
Received July 21, 19

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