Bremsstrahlung in α-α Scattering at 9.35 MeV

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A measurement of the α-α bremsstrahlung cross section at 9.35 MeV has established the upper limit 5.1 μb/sr^2 with 90% probability. We give a comparison with predictions, including only single-scattering terms.

A considerable amount of experimental and theoretical effort has been devoted so far to the *p-p* system, where a satisfactory agreement seems to exist at present between theory and experiment.[1] The phenomenon of emission of electromagnetic radiation during times comparable to transit times in the nuclear interaction volume is a general one of two-body processes. This phenomenon is important also in other respects[2] than those well known for the *p-p* system. Recent experiments have directed attention to the α-α,[3] and to the *p*-α and *p-d* systems.[4] We present here a report of the consolidation of results on the α-α bremsstrahlung at 9.35 MeV.

Below the threshold for reactions the α particle may be looked upon as a structureless boson. There are indeed no bound excited states of the α particle. The elastic scattering amplitude of the α-α system is well known from experiment, and it is consistent with broad α-particle states of ^{8}Be, i.e., states of the rotational band 0^+, 2^+ 4^+, $\cdots$, up to 16.6 MeV excitation. The formal problem of calculating bremsstrahlung for the α-α interaction seems to be considerably simpler, in this context, than in the nucleon-nucleon case.

The experiment reported here was performed at the Van de Graaff laboratory with 9.35-MeV α particles striking helium gas at low pressures in a 50-cm-diam scattering chamber. Havar-alloy[5] foils 2.5 μm thick were employed to isolate the gas from the vacuum. A triple-parameter system, implemented for use on line with a PDP-9 computer and associated software,[6] served to measure energies of the α particles at symmetrical angles with respect to the beam, as well as time spectra from an ORTEC 437A time-to-amplitude converter (TAC). Three 400-channel Victoreen analog-to-digital converters were interfaced to the on-line system. The main difficulties of the experiment reside in the short range of the α particles (of energy about 3 MeV at the center of the target), in limiting the gas pressure, and in the usual noise and walk of fast circuits, which had to be overcome. The details of the system employed are published elsewhere.[7] In brief, it consists of ORTEC time pickoff units placed after the preamplifiers, and of two TAC units, one of them operated in a "fast" manner from the pickoff units, and the other operated in

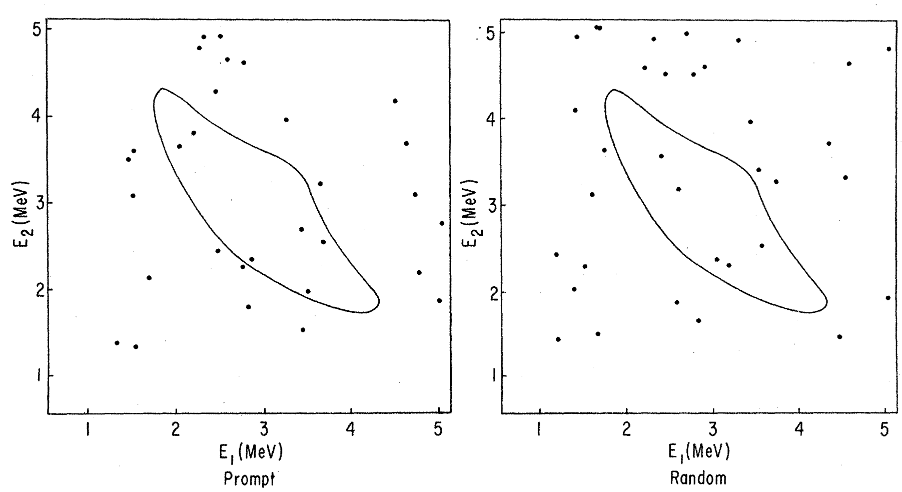

FIG. 1. Two-dimensional plot of bremsstrahlung events at 27.5° and −27.5° in the lab system. The energy scales are reduced to the center of the target. The boundary of the kinematically allowed region is shown with a solid line. The prompt and random regions are obtained as described in the text. The choice for the random region is the best possible one to eliminate any systematic trends in the background structure.

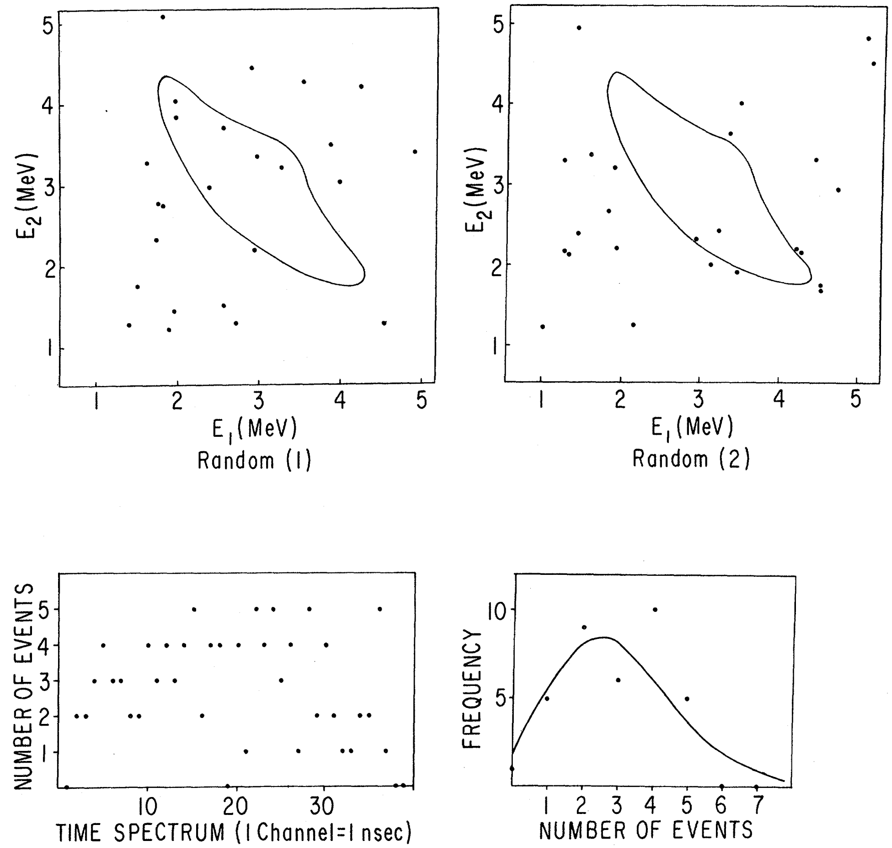

FIG. 2. Typical two-dimensional displays of results [Random (1) and Random (2)] corresponding to events in an 8-nsec time interval delayed by 120 and 130 nsec, respectively. The time spectrum corresponds to those events for which the particle energies lie between 2.5 and 3.5 MeV, approximating by a square the region of the kinematic locus. Each point in the diagram represents the addition of the contents of ten kicksorter channels. The true coincidence region is mostly included in channel 20. The frequency distribution of the number of events per channel in the time spectrum is well fitted by a Poisson distribution drawn with a solid line in the lower right diagram. The time spectrum seems to exhibit a larger than average population over about 100 nsec around the prompt region. However, all calibrations seem to exclude such a large time region for α-α bremsstrahlung events. A much larger cross section would follow from it, which explains the preliminary results of Ref. 3 obtained with much lower time resolution.

a "slow" manner from the bipolar pulses of the linear amplifiers. In this way noise events are eliminated by the slow system, but the time resolution is given by the fast system. Walk was corrected for on the digital output with experimentally determined functions giving an effective time resolution of 4 nsec with very low background level. The system is sensitive to cross sections in the $\mu b/sr^2$ range for energies as low as 700 keV. The very low counting rate of the experiment did not permit an exclusively automatic operation of the on-line system. Hence each event was also printed on paper as a safeguard against computer failures. The reduction of data was performed with the aid of an IBM 360-50 computer, and the necessary software was developed for this purpose.

Figures 1 and 2 show two-dimensional displays of results at 27.5° and $-27.5°$ in the lab system, together with a boundary of the kinematically allowed region. At variance with the p-p case, because of the increased mass of the α-α system and the low energies, the boundary is essentially the envelope of small loci corresponding to angles accepted by the finite detection geometry. A 400-nsec time interval was recorded with the prompt region centered. The results shown have been obtained by the addition of three runs. The experimental system was checked before and after each run with the peaks and the tails corresponding to the α-α elastic correlation as described by Birchall *et al.*[7] and by Slobodrian.[8]

Events corresponding to the "prompt" region include an 8-nsec time interval. The "random" region in Fig. 1 includes 4 nsec ahead of and 4 nsec behind the prompt region. The limits for the cross section are 2.96 μb/sr^2 with 67% probability and 5.07 μb/sr^2 with 90% probability.[9] These values include the corrections for noncoplanar scattering. Table I summarizes results with and without corrections. Figure 2 shows two displays of 8-nsec time intervals at different delays with respect to the center of the prompt region and a statistical analysis of the time spectrum corresponding to the kinematic region of bremsstrahlung events; the fluctuations of events show an excellent consistency with statistical expectations.

The coplanar bremsstrahlung cross section was calculated from the yield Y of events through the relation

$$d^2\sigma/d\Omega_1\,d\Omega_2 = Y/nNG,$$

where n is the number of target nuclei per unit volume, N is the number of α particles in the beam, and G is a factor containing details of the geometry of the detectors and collimators. The finite size of the detectors and collimators allows detection of noncoplanar as well as coplanar bremsstrahlung events. Account of this is taken in the computation of G.[10] It is assumed that the noncoplanar bremsstrahlung cross section is related to the coplanar cross section by

$$d^2\sigma(\Phi)/d\Omega_1\,d\Omega_2 = f(\Phi)d^2\sigma(\Phi=0)/d\Omega_1\,d\,\Omega_2,$$

where Φ is the angle of noncoplanarity as defined by Drechsel and Maximon.[11] G is given by

$$G = \int\int\int f(\Phi)\,d\Omega_1\,d\Omega_2\,dx,$$

where $d\Omega_1$ and $d\Omega_2$ are solid-angle elements on detectors 1 and 2, subtended by a point at a distance x along the beam path. Various functions $f(\Phi)$ have been used: (a) a square distribution, $f(\Phi)=1$, $\Phi \le \Phi_m$; (b) a parabolic distribution, $f(\Phi) = 1-(\Phi/\Phi_m)^2$, $\Phi \le \Phi_m$; and, in all cases, $f(\Phi)=0$ for $\Phi > \Phi_m$, where Φ_m is the maximum noncoplanarity angle kinematically allowed. Results are compared in Table I.

The theoretical cross section has been estimated with a model-independent formula given by Signell,[1] taking into account only single scattering terms. The average elastic-scattering amplitude at 90° was taken for the values at the initial and final energies. The value obtained for $E_{lab} = 9.35$ MeV is 0.35 μb/sr^2, not inconsistent with experiment.[12]

TABLE I. Limits of the α-α bremsstrahlung cross section at 9.35 MeV for 27.5° and −27.5°.

	Measured limits of the cross section (μb/sr^2)	
Distribution	67% limit	90% limit
Uncorrected	1.15	1.97
Parabolic	2.96	5.07
Square	1.94	3.33

A preliminary study has also been made of the bremsstrahlung cross section in the ^{3}He-α system at 9.6 MeV. This system is interesting since the $E1$ transition, forbidden in the α-α case, is allowed and should increase the ^{3}He-α cross section with respect to that for α-α. However, experimental difficulties arise in studying the ^{3}He-α system. For example, for ^{3}He particles of 9.6 MeV, one is above the threshold for the reaction ^{4}He(^{3}He,p)^{6}Li, and the random coincidence rate in the bremsstrahlung kinematic region due to particles from this reaction is very high. In addition, particle identification at low energies is difficult. The experiment has been repeated at 7.4 MeV where the (^{3}He,p) cross section is much smaller and where such events lie out of the bremsstrahlung kinematic region. Further work is still necessary in order to reach definite conclusions about the ^{3}He-α bremsstrahlung.

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[5]Hamilton Watch Co., Lancaster, Pa.

[6]This system was developed by Dr. C. St-Pierre.

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[8]R. J. Slobodrian, Nucl. Instrum. Methods 79, 141 (1969).

[9]The probability of observing N true plus random events when the expected numbers of true and random

events are x and $\bar{r}$, respectively, is

$$P(x)=\sum_{n=0}^{N} p(n,x)p(N-n,\bar{r}).$$

$p(k,a)$ is the Poisson probability distribution for k events when the expected number is a. The confidence limit for the expected number x_0 of true events is obtained by integrating $P(x)$ over x from $x=0$ to x_0. The results quoted are for $N=6$ and $\bar{r}=5$.

[10]J. Birchall, to be published.

[11]D. Drechsel and L. C. Maximon, Ann. Phys. (New York) 49, 403 (1968).

[12]The results are quoted as upper limits for obvious reasons. However, the value obtained from Fig. 1 is 0.85 μb/sr^2, using the parabolic correction for noncoplanarity.

Acceleration of Cosmic Rays in Supernova Remnants

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If the electromagnetic wave theory of pulsars is correct, then particle acceleration occurs within the nebulous debris of the supernova explosion. Model calculations show that each event produces about 10^{49} erg in ionic cosmic rays. Particle energies range from 10^9 to 10^{16} eV (with spectral index ~2 before corrections for losses), and the chemical composition is mostly that of matter processed through several stages of nuclear burning. Both the electronic and the ionic components of the galactic cosmic rays can be maintained by particles accelerated in supernova remnants.

We know cosmic rays are produced in supernova remnants. The relativistic electrons are seen directly, emitting their characteristic synchrotron radiation. The better observed nebulae typically contain about 10^{48} erg in electrons having energies of 10^7 to 10^{14} eV. The pool of galactic cosmic-ray electrons can be maintained by the electronic content of dissolving supernova remnants (see below). Furthermore, one can show[1] that both the very high- and the relatively low-energy electrons must have been created somewhere within the nebulae; they cannot be survivors of the original explosion.

There is no direct evidence for relativistic ions in supernova remnants, but the indirect arguments are strong. First, whatever process accelerates electrons is likely to accelerate the associated ions. Second, supernova explosions can provide the requisite energy (see below). Finally, and most significantly, both the chemical abundances found in galactic cosmic rays, and the abundances inferred at the source, are considerably different from that seen elsewhere. Relative to the solar system, cosmic rays are progressively richer with larger atomic number; the C-N-O group of primaries at the source is overabundant by 10^1 and the iron group by 10^2 relative to hydrogen and helium.[2] It is not easy to see how material originally on ordinary stars or in interstellar space could be simultaneously accelerated and sorted into the observed cosmic-ray abundance distribution. Supernova remnants, however, are thought to contain much gas which has been processed in the stellar interior to higher A, Z; the filaments in the Crab nebula are known, for example, to have a ratio of helium to hydrogen higher than that found in galactic nebulae.[3]

The idea that supernovea contribute significantly to the cosmic-ray backgound is, of course, not new.[4,5] However, a new element was added with the discovery of pulsars, and the initial steps taken towards understanding them. It now appears that many supernovae leave, as stellar remnants, rotating magnetic neutron stars capable of emitting electromagnetic energy[6,7] and very high-energy particles.[7-10] Two of the outstanding problems in this subject—the origin of the electromagnetic field and that of the very high-energy short-lived particles in the Crab nebula—have been plausibly solved by electromagnetic theories.[6-10] According to these theories, between 10^{50} and $10^{52.5}$ erg is available per supernova event in the form of rotational