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MEASUREMENTS OF CROSS SECTIONS RELEVANT TO γ-RAY LINE ASTRONOMY

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Measurements of cross sections relevant to γ-ray line astronomy

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Abstract: Gamma-ray production cross sections have been measured for the γ-ray lines which are most strongly excited in the proton bombardment of C, O, Mg, Si, and Fe targets of natural isotopic composition. High resolution germanium detectors were used to collect γ-ray spectra at proton bombarding energies of 20, 30, 33, 40 and 50 MeV.

Introduction

Observations of discrete γ-ray lines can provide unique signatures of nuclear reactions occurring in astronomical environments. Because of their highly penetrating nature, γ-rays may provide specific information on astrophysical sites that are opaque to longer wavelength radiation. γ-ray lines have been observed within the solar system, in solar flare events, and in extra-solar system sites such as the galactic center, Centaurus A, SS-433, and perhaps the Crab Nebula. In principle, discrete line γ-ray spectra can be used to obtain the relative abundances and energy spectra of the particles responsible for the γ-ray production. However, in order to make use of such spectra, cross sections for the production of nuclear γ-rays must be known.

There are several mechanisms which result in γ-ray emission: charged particle induced reactions such as inelastic scattering and spallation reactions, radioactive decay to excited states of nuclei, e^+e^- annihilation, and neutron capture. Within the first category, the high cosmic abundances of hydrogen and helium imply that only proton and α-particle induced reactions need be considered.

We present in this paper preliminary results of measurements of γ-ray production cross sections using a proton beam on a variety of targets. In a second paper to be published later we will present results for α-particle bombardments. This work is an extension of the earlier measurements of Dyer et al.[1,2] and Seamster et al,[3] who determined the γ-ray production cross sections for both proton and α-particle bombardments of a large number of targets from threshold to 23 MeV for proton and from threshold to 27 MeV for α-particle bombardments.

Experimental Method

Beams of protons were provided by Lawrence Berkeley Laboratory's 88-Inch Cyclotron over the energy range of 20 to 50 MeV. The beam impinged on targets of natural isotopic composition of C, O, Mg, Si, Fe, and a thick meteoritic sample. The oxygen target was constructed of a thin mylar foil ($C_{10}H_8O_4$). The target thicknesses varied from 200 μg/cm^2 to 8.16 mg/cm^2 for the various targets, with the exception of the meteoritic target which was a cut and polished slice of the Allende meteorite.

γ-rays produced by various reactions were observed by two high purity Ge detectors of 110 cm^3 volume. For all but the oxygen target, the detector angles were chosen to be the zeroes of $P_4(\cos\theta)$ to aid in the reduction of the angular distribution data into total cross sections. For the oxygen target, complete angular distributions were determined at each energy. In addition, at one bombarding energy, angular distributions over a wider range of angles were taken for all targets to confirm the multipolarity of the γ-rays.

The energy of the beam was varied in 10-MeV steps from 20 to 50 MeV. Data were also collected at 33 MeV, chosen to coincide with the proposed energy per nucleon of matter in the jet of SS-433. Single parameter energy histograms were collected at each energy and angle combination for all targets with the two detectors. These histograms were stored on magnetic tape for later analysis. In order to determine the system dead-time, the output of the current integrator was used to trigger a pulser that was fed into both detectors preamplifiers and into a scaler.

Results

In order to provide a graphic illustration of what the spectra obtained from future γ-ray observatories may look like, we bombarded a thick sample of the Allende meteorite with 33 MeV protons. Allende is a carbonaceous chondrite and contains all but the most volatile elements in roughly their cosmic abundances. Thus, except for the reduction of lines from C, N, O, and Ne, this spectrum is representative of what might be observed form proton interactions with the interstellar medium. As can be seen in Figure 1, γ-ray lines from proton-induced reactions on ^{12}C, ^{16}O, ^{24}Mg, ^{28}Si, and ^{56}Fe are very prominent.

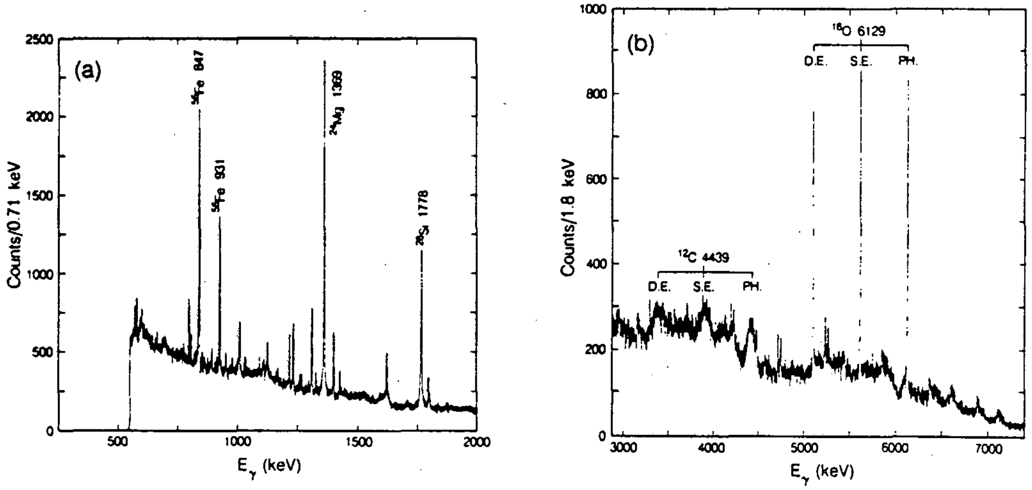
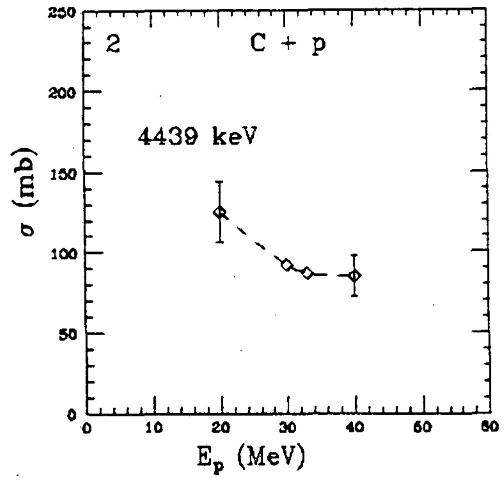
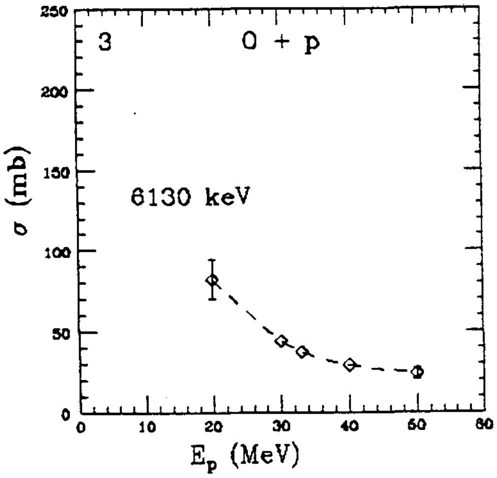
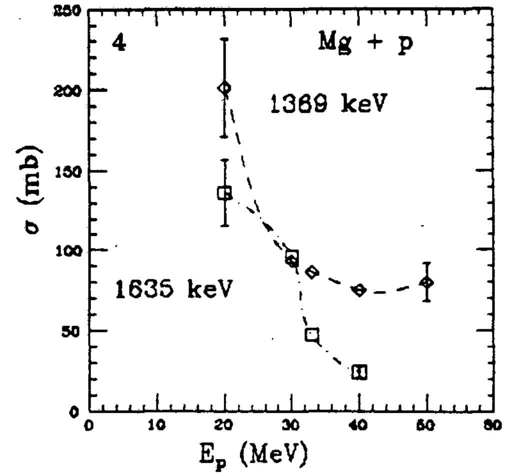


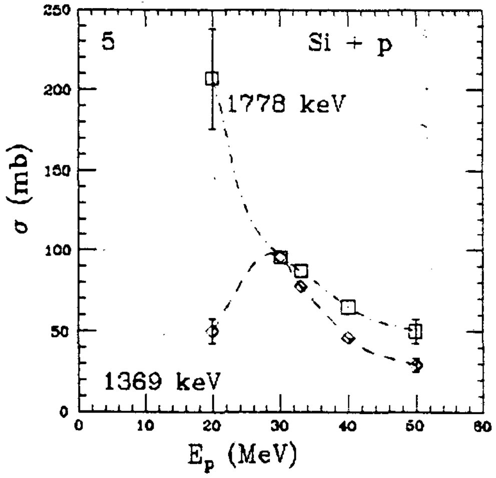
Figure 1. γ-ray spectrum observed during the bombardment of a thick sample of the Allende meteorite with 33 MeV protons. The prominent γ-rays are identified by target isotope. PH, SE, DE stand for, respectively, photo-peak, single escape-peak, and double escape-peak.

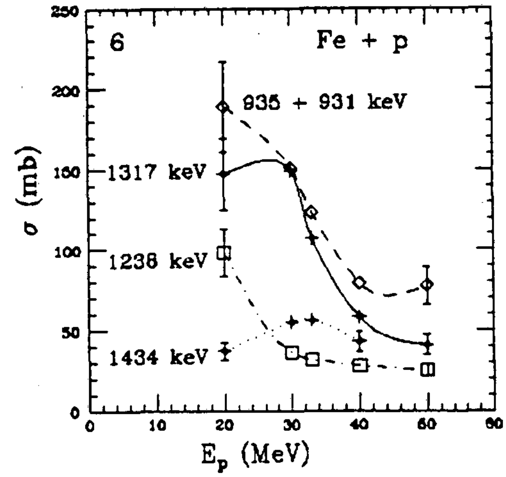
To obtain cross sections from the measurements on the elemental targets, background and deadtime corrected γ-ray yields were determined for the most prominent peaks in each spectrum. These differential cross sections were then used to obtain angle-integrated total cross sections using the technique of Dyer et al.[1]. In order to convert our results into absolute cross sections, we normalized our data obtained at E_p = 20 MeV to those reported by Dyer et al.[1]. The results of this work are summarized in Figures 2-6.











Figures 2.- 6. γ-ray production cross sections for proton bombardments of C, O, Mg, Si and Fe targets. Typical errors are indicated. Lines drawn through the data points are to guide the eye.

In an earlier work, Ramaty et al.[4] used the differential cross sections of Foley et al.[5] and Zobel et al.[6] to deduce total, angle integrated γ-ray production cross sections. This procedure is risky because the measurements were made at a single angle and it is difficult to deduce the accurate total cross sections without angular distribution data. When comparisons between our data and those summarized by Ramaty et al. can be made, we find that the two data sets agree at the 20-50% level. However, for many of the systems we find a much smaller energy dependence of the production cross sections, such that our cross sections at higher energies differ signficantly from those of Ref. 4.

It is interesting to compare our measured spectrum from the bombardment of a meteoritic sample to Ramaty et al.'s Monte Carlo simulated γ-ray spectra. In the simulated spectra energetic cosmic ray particles interact with matter in the interstellar medium that contains both small grains and gases with solar-system elemental abundances. With the exception of highly volatile elements, the meteoritic composition is a good approximation to solar-system abundances. While we used a mono-energetic beam of protons and the simulation used a power law distribution for the cosmic ray spectrum, we note striking similarities between the two spectra. The prominent peaks due to Fe, Mg, Si, C and O are all present in both spectra in roughly similar proportions. The γ-ray lines from ^{16}O observed in our spectrum are narrow due to our thick target which assures that most of the excited nuclei will stop before they emit their γ-rays. In the simulation, interactions with the gaseous target components result in substantial Doppler broadening for the ^{16}O nuclei which recoil into vacuum.

While the actual number of extra-terrestrial γ-ray sources remains limited to a few, and while the number of γ-ray lines which have been unambigiously identified is even fewer, it is hoped that with additional observations of γ-ray sources in the coming years the γ-ray production cross sections we present here will be of value in determining quantities such as the modes and sites of nucleosynthesis, particle fluxes and nuclear abundances in the interstellar medium, and even the properties of exotic astrophysical environments such as neutron star surfaces.

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