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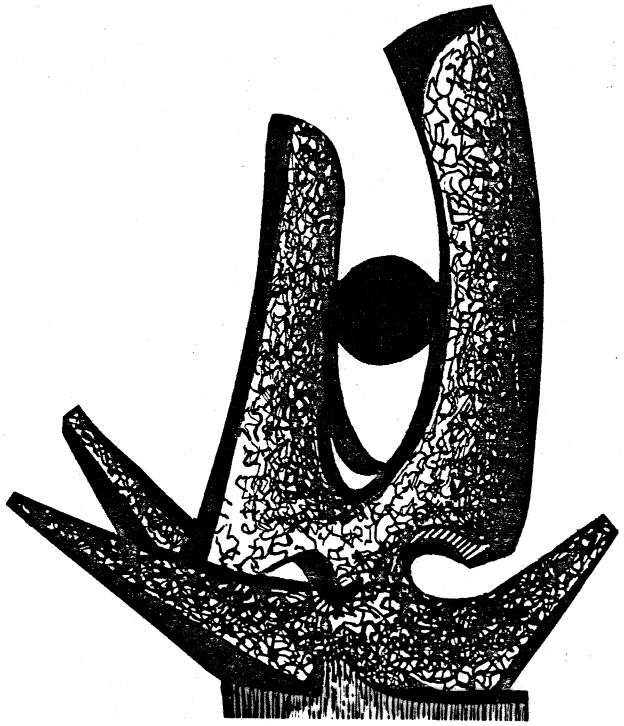
J. NARAYANASWAMY, P. DYER, S.R. FABER, and SAM M. AUSTIN



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Production of 6.13-MeV gamma rays from the $^{16}O(p,p'\gamma)^{16}O$ reaction at 23.7 and 44.6 MeV

J. Narayanaswamy, P. Dyer, S.R. Faber,[+] and Sam M. Austin

Cyclotron Laboratory and Physics Department
Michigan State University, East Lansing, MI 48824

We have measured the cross sections for production of the astrophysically prominent 6.13-MeV gamma ray from the $^{16}O(p,p'\gamma)^{16}O$ reaction at E^{p}_{lab} = 23.7 and 44.6 MeV to be 58.9 and 40.4 mb, respectively. Our results are compared to earlier measurements.

NUCLEAR REACTIONS: $^{16}O(p,p'\gamma)^{16}O$. E = 23.7 and 44.6 MeV. Measured gamma-ray angular distributions and production cross sections. Implications for gamma-ray astronomy.

The interpretation of astrophysical gamma-ray line spectra requires the gamma-ray production cross sections and Doppler broadened line shapes for proton and alpha induced reactions over a broad range of projectile energies.[1-4] One can, in principle, calculate the gamma production cross section from inelastic proton and alpha scattering data and gamma-ray branching ratios. However, because of the uncertainties in the contribution of cascade processes to gamma-ray production and the uncertainties in calculating the broadening effects, it is desirable to measure the gamma-ray yields directly. Unfortunately, only a few direct measurements are available for astrophysically abundant nuclei such as ^{12}C, ^{16}O, and ^{56}Fe, and the results are sometimes inconsistent.[1-5] This paper reports a direct measurement for 6.13-MeV gamma rays from the reaction $^{16}O(p,p'\gamma)^{16}O$ at incident lab proton energies of 23.7 and 44.6 MeV. This 6.13-MeV line is one of the most prominent lines in astrophysical gamma-ray line spectra. Our results agree at the lower energy with the cross sections of Dyer et al.,[1] but disagree with those of Zobel et al.[5]

Protons from the Michigan State University sector-focused cyclotron bombarded a gas target of oxygen, and the resulting gamma rays were detected with two Ge(Li) spectrometers. The natural O_2 target at one atmosphere of pressure was contained in a 3.8 cm diameter aluminum cell with 25μ thick Kapton windows. The increase in the cell diameter when it was filled with gas was found to be 4%, and was taken into account. Beam current, typically 5 nA, was integrated downstream of the gas cell. The beam energy was determined to ±0.1% by magnetic analysis. Average beam energies within the target were 23.66 and 44.61 MeV, for the two cases.

The smaller detector (nominal efficiency 9%) was kept fixed in position to monitor gamma rays from the target. The larger detector (nominal efficiency 16%) was mounted on a goniometer arm about 32 cm from the target. A lead absorber 1 mm thick was placed in front of the larger detector to reduce the counting rate from x rays and low-energy gamma rays. At 6.13-MeV, the detector resolution was about 15 keV, but most peaks were much wider due to Doppler broadening. Count rates were typically 5000 counts/sec. For determining dead times (about 15%), signals from the monitor detector were used to trigger a pulser which fed the preamplifier of the larger detector and a scaler.

The 6.13-MeV line arises from an E3 transition, and determination of total cross section, therefore, requires measurements at at least 3 angles. Measurements were made at several angles between 45° and 157° relative to the incident beam direction. At each angle, data were acquired with the cell filled with gas and with the cell empty, typical counting times being 90 and 45 minutes, respectively. Energy spectra were recorded with a Sigma 7 computer. Detector efficiency was measured with a calibrated source[6,7] of 6.13-MeV gamma rays (^{238}Pu + ^{13}C) in the same source-detector geometry as that of the experimental runs.

Typical spectra (after subtracting the cell contribution) are shown in Fig. 1. The analysis was complicated by the overlap of the broad 6.13-MeV full energy peak (FEP) with the double escape peak (DEP) of the 7.12-MeV line from ^{16}O, at 6.10 MeV. The latter peak (about 10% of the total area) had to be subtracted before extracting the area under the full energy peak. This was done based on FEP to DEP ratios and spectrum shapes from the ^{238}Pu + ^{13}C source; the subtraction contributes negligible error.

For extraction of areas under the broad 6.13-MeV peaks, a reference peak shape was created by adding four offset spectra from the ^{238}Pu + ^{13}C source (to create a broader line). Five to nine such reference peaks were then used to fit the data, using a modified version of Bevington's routine 'CURFIT'.[8] Peak positions and amplitudes were varied to minimize χ^2. This procedure permitted a consistent treatment of the Compton edges for these broad lines; otherwise, a detailed fit of the complex peak structure is unnecessary to obtain the gamma-ray production cross sections.

The angular distribution of gamma rays relative to the beam direction is

$$\frac{d\sigma}{d\Omega}(\theta) = \sum_{\ell=0}^{L} a_\ell P_\ell(\cos\theta) \qquad \text{even } \ell$$

The quantity L is the smaller of the two values - (a) twice the spin of the decaying state and (b) twice the multipolarity of the gamma ray.[9] For 6.13-MeV gamma rays, L = 6. The total cross section depends on a_o only and is given by

$\sigma_{tot} = 4\pi a_o$. We fit the observed differential cross section with a sum of P_o, P_2, P_4 and P_6, varying the a_ℓ's to minimize χ^2. Table I lists the resulting coefficients (with statistical errors).

Statistical errors in the total cross sections (from extraction of peak areas) are 2.5% at 23.7 MeV and 6.5% at 44.6 MeV. Systematic errors resulted from (a) charge integration uncertainty estimated to be 4%, (b) uncertainty in target thickness, resulting primarily from determination of the diameter of the pressurized cell, estimated to be 4%, (c) uncertainty in $^{13}C + {}^{238}Pu$ source strength, quoted by the manufacturer as 8%, and (d) peak extraction uncertainty in the measurement of detector efficiency of 3%. These uncertainties give rise to an overall systematic error of about 10%. The lab to C.M. frame transformation of angles and cross section was not carried out, as the required correction was less than 1%.

Table II shows total cross sections derived from the present experiment and from previous work based on γ-ray or (p,p') measurements at or near the proton energies of this work. Our cross section at 23.7 MeV compares favorably with the value measured by Dyer et al.[1] at 23 MeV. Austin et al.[10] have measured cross sections for inelastic proton scattering to the unresolved states at 6.05 and 6.13 MeV. As discussed in their paper, for proton energies above about 18 MeV, most of the cross section comes from the 6.13-MeV state. However, such cross sections only represent a lower limit to the production of 6.13-MeV gamma rays, since gamma-

ray decay of higher states, particularly those at 8.87 and 11.08 MeV, also populate the 6.13 MeV state. Comparison of our results with those of Austin et al. indicates that such cascade contributions are significant for E^p_{lab}>25 MeV. The (p,p') cross sections of Bayer[11] for the 6.13 MeV state are also somewhat lower than our values, again showing the significance of cascade effects.

Zobel et al.[5] measured gamma-ray production cross sections at proton energies of 16, 33, 56 and 160 MeV. They assumed the yield to be isotropic and measured at one angle only, namely 135°, relative to beam direction, with the exception of 16 MeV, where they measured the yield at 90° to check for anisotropy. Zobel's 135° differential cross sections are higher than ours by almost a factor of two. They claim to have measured gamma rays in the range 6.1 - 6.3 MeV and attribute part of the measured cross section to a line at 6.328 MeV, presumably from the $^{16}O(p,2p)^{15}N$ reaction. We do not observe a strong line at 6.328 MeV; such a line, then, cannot explain the discrepancy between our results and those of Zobel et al. Our angular distribution coefficients indicate that the assumption of isotropy, although reasonable at energies above 40 MeV, is not valid at the lower energies. Our total cross sections are compared with previous values in Fig. 2.

We have measured the cross sections for the production of the astrophysically prominent 6.13-MeV gamma ray from $p + {}^{16}O$ at incident proton energies of 23.7 and 44.6 MeV.

Our cross sections are consistent with those of Dyer et al.[1], but smaller than those measured earlier by Zobel et al.[5] We are, of course, far from having all the relevant data for unambiguous interpretation of celestial gamma-ray line spectra. Extension of this type of work to include higher proton and alpha energies and more targets is useful not only for gamma-ray astrophysics but also, as discussed by Zobel et al.[5], for computing the contribution of secondary gamma rays to radiation dose rates produced by charged particles in space.

Acknowledgments

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+ Present address: Bell Laboratories, 6H 338, Warrenville and Naperville Roads, Naperville, IL 60566

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Table I. Legendre polynomial coefficients for gamma-ray angular distribution from $^{16}O(p,p'\gamma)^{16}O$.

E^{p}_{lab}(MeV)	$a_o\left(\frac{mb}{sr}\right)$	$a_2\left(\frac{mb}{sr}\right)$	$a_4\left(\frac{mb}{sr}\right)$	$a_6\left(\frac{mb}{sr}\right)$
23.7	4.68±0.12	1.74±0.29	-0.03±0.52	-0.94±0.60
44.6	3.21±0.20	-0.32±0.74	-0.28±1.06	-1.18±1.02

Table II. Comparison of $p+^{16}O$ cross sections.

Reference	σ_{tot}(mb)[f]	
	E^{p}_{lab} ~ 25 MeV	E^{p}_{lab} ~ 44 MeV
Dyer et al.[a]	58 ± 9	
Ramaty et al.[b]	79	35
Zobel et al.[c]	124 ± 10	86 ± 6
Austin et al.[d]	60 ± 2	26 ± 1
Bayer[e]	54 ± 5	30 ± 6
Present work	58.9 ± 6.2	40.4 ± 4.9

a: Reference 1: $(p,p'\gamma)$; 6.13 MeV γ-rays; $E^{p}_{lab} = 23$ MeV.

b: Reference 2: Estimated from (p,p') data, γ-ray cross sections, and branching ratios; 6.13 MeV γ-rays; $E^{p}_{lab} = 23.8$ and 44.7 MeV.

c: Reference 5: $(p,p'\gamma)$; 6.1-6.3 MeV γ-rays; $E^{p}_{lab} = 28.2$ and 48.3 MeV; measured at $\theta=135^{o}$, assumed isotropic yield

d: Reference 10: (p,p') to 6.05 plus 6.13 MeV states; $E^{p}_{lab} = 23.4$ and 43.1 MeV.

e: Reference 11: (p,p') to 6.13 MeV state; $E^{p}_{lab} = 24.6$ and 40.1 MeV

f: Errors quoted here are combination of statistical and systematic errors added in quadrature.

FIG. 1. Spectra of gamma rays with empty cell background and the 7.12-MeV DEP subtracted. The remaining background is assumed to be flat and with the (fitted) magnitude shown in the highest channels. The curve is the result of the fit using unsmoothed reference peaks derived from the $^{238}U+^{13}C$ source.

FIG. 2. Total cross section σ_{tot} vs. lab proton energy.
Heavy solid line: estimate by Ramaty et al. (Reference 2).
Filled circles: cross sections measured by Dyer et al. (Reference 1), averaged over 1-MeV-wide energy bins; solid line connects the points.
Filled squares: Measurements by Zobel et al. (Reference 5), dashed line drawn to guide the eye; gamma rays in the range 6.1-6.3 MeV are included.
Filled triangles: Present work.

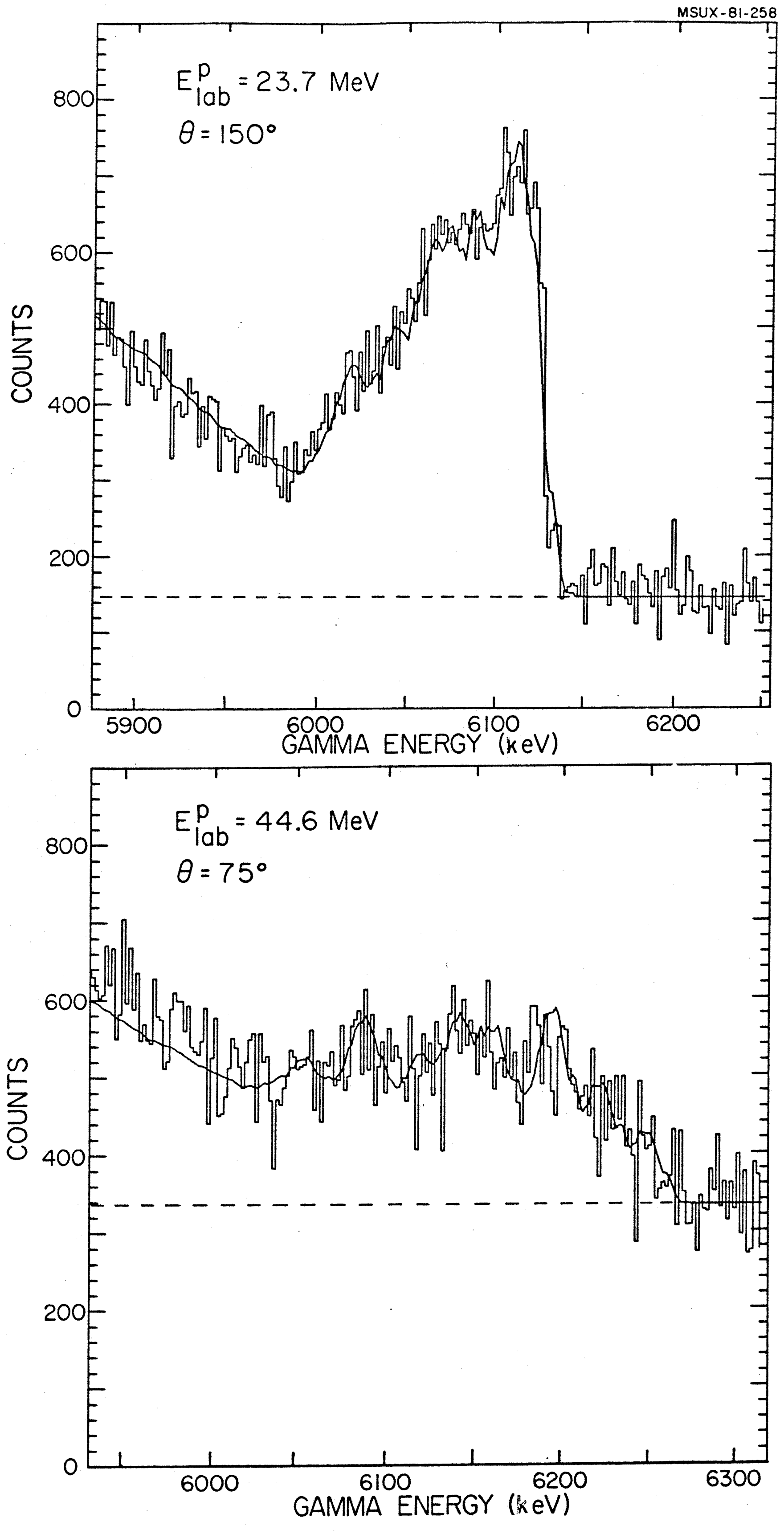
MSUX-81-258
E^p_{lab} = 23.7 MeV
θ = 150°
COUNTS
0
200
400
600
800
5900
6000
6100
6200
GAMMA ENERGY (keV)
E^p_{lab} = 44.6 MeV
θ = 75°
COUNTS
0
200
400
600
800
6000
6100
6200
6300
GAMMA ENERGY (keV)

Fig. 1

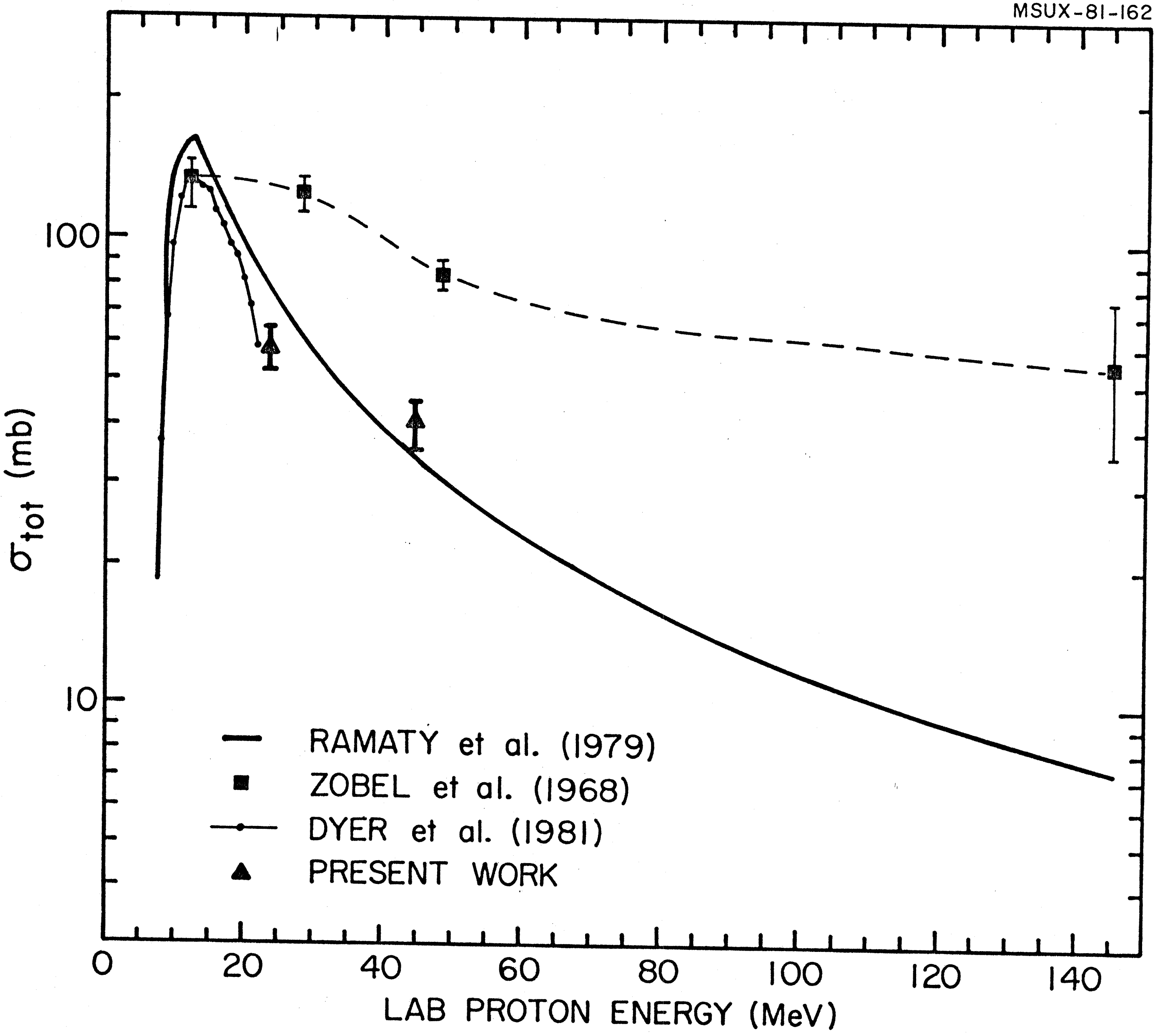
MSUX-81-162
σ_{tot} (mb)
100
10
0
20
40
60
80
100
120
140
LAB PROTON ENERGY (MeV)
RAMATY et al. (1979)
ZOBEL et al. (1968)
DYER et al. (1981)
PRESENT WORK

Fig. 2