Sulfur Photoneutron Cross Section*

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Spicer's shell-model 1p-1h calculation for photoabsorption in S^{32} indicates that considerable dipole strength should be expected in the regions 3 and 10 MeV above the giant resonance peak. The $S^{32}(\gamma,n)S^{31}$ reaction cross section has been measured in 250-keV steps from 20 to 32 MeV, and qualitatively confirms these gross predictions. The present cross section has been normalized to that reported by Thompson, Taylor, and Webb. To account for the detailed structure that appears in the composite cross section, a calculation has been carried out including the coupling of the surface vibration phonons to the 1p-1h dipole states, as described by Drechsel, Seaborn, and Greiner. The calculation increases the number of states carrying appreciable absorption strength, as well as transferring strength to higher energies. The over-all agreement between the theoretical result and the (γ,n) cross section is remarkably good.

THE $S^{32}(\gamma,n)S^{31}$ reaction cross section has previously been reported by Thompson *et al.*[1] up to a photon energy of 22 MeV. A subsequent theoretical calculation based on the particle-hole model was carried out by Spicer,[2] and predicted considerable cross section at energies greater than 22 MeV. To determine the cross section above 22 MeV with greater accuracy and resolution than previously obtained, and to check the validity of the above-mentioned calculation, a further study of the $S^{32}(\gamma,n)S^{31}$ reaction was made, extending the earlier measurement up to 32 MeV.

A solid 0.4×3.1-cm-diam target of high-purity commercial sulfur was irradiated with bremsstrahlung from the Melbourne University betatron from 20 to 32 MeV in steps of 250 keV. The experimental arrangement used to collect and record the annihilation radiation from the 2.6-sec S^{31} β^+ activity was basically the same as has been reported for similar experiments in the Melbourne laboratory.[3,4]

The mean of five independent yield curves was used for analysis, the raw data having been corrected for dead-time losses and background. A running least-squares interpolation subroutine was incorporated into the analysis computer program to provide yield values at the correct analysis energies. The yield curve was then analyzed, using the matrix method of Penfold and Leiss[5] in 1-MeV intervals to give four independent cross sections which were interlaced to give information at 250-keV intervals.

The data of the previous experiment[1] have been reanalyzed, taking into account a shift in the betatron energy calibration which was discovered after that work was reported. The complete cross section from threshold to 32 MeV is shown in Fig. 1, in which arrows indicate the positions of peaks in the cross section. Also, the standard errors derived from the mean yield values are shown. The integrated cross section to 31.5 MeV is 138±9 MeV mb. This is approximately a quarter of the integrated cross section given by the classical dipole sum rule.

Comparison of this measurement with other results is difficult because there are very few data of sufficient resolution available for the region above 22 MeV. The (γ,n) data of Bolen and Whitehead[6] show only broad resonances at 22.8 and 24.3 MeV, while the total absorption cross section measured by Dular *et al.*[7] gives poorly resolved peaks at 22.2 and 25.5 MeV. On the other hand, the (γ,p) data of Ishkhanov *et al.*[8] give a distinct peak at 30.3 MeV. Within the resolution, these results are not inconsistent with the data reported here.

The calculation of Spicer[2] predicts the giant resonance maximum to be about 19 MeV, in good agreement with the experimental result. In addition to this, regions of strong absorption are predicted at approximately 22 and 29 MeV. This prediction is in good qualitative correspondence with the several peaks centered about 24 MeV and with the large resonance at 30.4 MeV. Although the simple particle-hole model appears to predict satisfactorily the gross shape of the cross section, it is clear that there is far more structure in the experimental cross sections than can be explained by this theory. The admixing of collective and single-particle aspects in the calculation of a photon absorption cross

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1 M. N. Thompson, J. M. Taylor, and D. V. Webb, Phys. Letters 14, 223 (1965).
2 B. M. Spicer, Australian J. Phys. 18, 1 (1965).
3 J. E. E. Baglin and B. M. Spicer, Nucl. Phys. 54, 549 (1964).
4 M. N. Thompson, J. M. Taylor, B. M. Spicer, and J. E. E. Baglin, Nucl. Phys. 64, 486 (1965).
5 A. S. Penfold and J. E. Leiss, *Analysis of Photo-Cross Sections* (University of Illinois Press, Urbana, Illinois, 1958).
6 L. N. Bolen and W. D. Whitehead, Phys. Rev. 132, 2251 (1963).
7 J. Dular, G. Kernel, M. Kregar, M. V. Mihailovic, G. Pregi, M. Rosina, and C. Zupančič, Nucl. Phys. 14, 131 (1959).
8 B. S. Ishkhanov, I. M. Kapitonov, V. G. Shevchenko, and B. A. Yur'ev, Phys. Letters 9, 162 (1964).

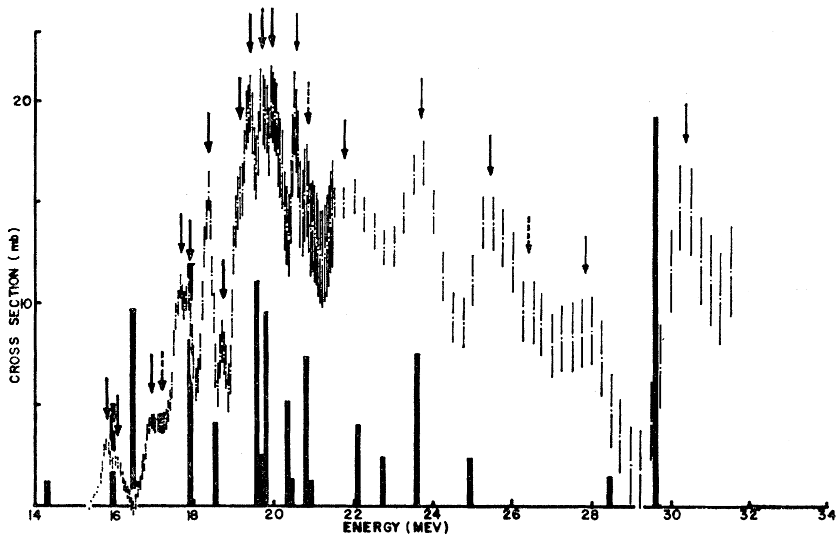

FIG. 1. The experimental cross section for the $S^{32}(\gamma,n)$ reaction, together with the predictions of the collective-correlations theory.

section has been shown to be a feasible mechanism which will fulfill the stated need.

One approach to the treatment of this admixing of complicated many-particle–many-hole states to the 1p-1h states of the giant resonance is to couple the collective surface phonons to the 1p-1h states.[9] This means that one simulates the collective many-particle–many-hole states which interact strongly with the 1p-1h states by vibrational states in the collective picture. Then we have the following Hamiltonian:

$$H=H_{\mathrm{ph}}^{(1)}+H_Q+H_{\mathrm{ph}\,Q}.$$

$H_{\mathrm{ph}}^{(1)}$ is the particle-hole Hamiltonian treated in the (1p-1h) subspace, and H_Q is the collective Hamiltonian of the surface vibrations. The interaction $H_{\mathrm{ph}\,Q}$ is obtained from the interaction H_{DQ} of the pure collective model[10] by translating the collective dipole oscillation variables $\alpha_\mu^{[1]}$ into particle-hole operators. This is achieved by the requirement that the dipole operators should be the same in both pictures, i.e.,

$$D_{\mathrm{ph}}^{[1]}=D_{\mathrm{coll}}^{[1]}=M_0\alpha^{[1]} \tag{1}$$

with $M_0=0.446R_0Z$. Here Z is the charge and R_0 is the radius of the nucleus. One obtains

$$H_{\mathrm{ph}\,Q}=\kappa_1[[D_{\mathrm{ph}}^{[1]}\times D_{\mathrm{ph}}^{[1]}]^{[2]}\times\alpha^{[2]}]^{[0]} + \sum_{j=0,2}\kappa_{2j}[[D_{\mathrm{ph}}^{[1]}\times D_{\mathrm{ph}}^{[1]}]^{[j]}\times[\alpha^{[2]}\times\alpha^{[2]}]^{[j]}]^{[0]}, \tag{2}$$

where the coupling constants are

$$\kappa_1=-64(\kappa/AR_0^2), \qquad \kappa_{20}=-28.5(\kappa/AR_0^2), \quad \kappa_{22}=-39(\kappa/AR_0^2). \tag{3}$$

Here κ is the symmetry energy constant of the Bethe-Weizsäcker mass formula and A is the nuclear mass number. The Hamiltonian is diagonalized in the space of 1p-1h states coupled with vibrational states up to four phonons. The unperturbed single-particle spectrum is taken from Spicer,[2] and for the surface vibrations we take $E_2=2.24$ MeV and $\beta=0.37$ from the low-energy data.[11] We utilized Gillet's residual force with a strength $V_0=-70$ MeV and $a_0=0$, $a_\sigma=-0.2$, $a_\tau=-0.3$, and $a_{\sigma\tau}=-0.1$.

The results of the calculation are given in Fig. 1 by the vertical bars, indicating the positions and the dipole strengths of the giant resonance states. The rather good over-all agreement is surprising. There seems to be too much strength in the region 16–18 MeV and at 30 MeV. However, one has to compare the results with the total γ absorption cross section, which is different from $\sigma(\gamma,n)$ because $\sigma(\gamma,p)$ is comparable in magnitude[12] at the cross-section peak. However, the (γ,p) threshold is lower than that for the (γ,n) reaction (8.86 MeV compared to 15.09 MeV), and the (γ,p) cross section has significant strength below the (γ,n) threshold. This will perhaps explain some of the discrepancies in the magnitude of the dipole strengths, particularly for the lower energies. In addition, ground-state correlations are expected to be of importance in the case of nonmagic nuclei. A calculation taking these correlations into account is in progress.

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[9] D. Drechsel, J. B. Seaborn, and W. Greiner, Phys. Letters **17**, 488 (1966); J. B. Seaborn, D. Drechsel, H. Arenhövel, and W. Greiner, *ibid.* **23**, 576 (1966); D. Drechsel, J. B. Seaborn, and W. Greiner, Phys. Rev. **162**, [redacted] (1967).

[10] M. G. Huber, H. J. Weber, M. Danos, and W. Greiner, Phys. Rev. Letters **15**, 529 (1965); H. J. Weber, M. G. Huber, and W. Greiner, Z. Physik **192**, 223 (1966); M. G. Huber, M. Danos, H. J. Weber, and W. Greiner, Phys. Rev. **155**, 1073 (1967). We use their notation here.

[11] P. H. Stelson, and L. Grodzins, Nucl. Data **1**, 21 (1965).

[12] K. Shoda, K. Abe, T. Ishizuka, N. Kawamura, and M. Kimura, J. Phys. Soc. Japan **17**, 735 (1962).