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Electro- and Photoinduced Spallation Reactions on ^{27}Al and ^{51}V at Intermediate Energies

I. Blomqvist, P. Janeček, G.G. Jonsson and R. Petersson
Department of Nuclear Physics, University of Lund, Lund, Sweden

H. Dinter and K. Tesch
Deutsches Elektronen-Synchrotron DESY, Hamburg, Federal Republic of Germany

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Cross sections for some electro- and photoinduced spallation reactions on ^{27}Al and ^{51}V have been measured in the energy region 130–580 MeV with the activation method. The cross sections per photon are compared to Monte-Carlo calculations based on a cascade-evaporation model. The electrodisintegration cross sections are compared to calculations based on the Dalitz formalism for virtual photon spectra.

1. Introduction

Electroinduced reactions are due to the interaction of the electromagnetic field of the scattered electron and the nucleus. A relation between the electrodisintegration cross section σ_e and the photodisintegration cross section σ_k has been given by Barber [1]:

$$\sigma_e(E_0)=\sum_L \int_0^{E_0} \sigma_k(k, L)\, N_e(E_0, k, L)\, dk. \qquad (1)$$

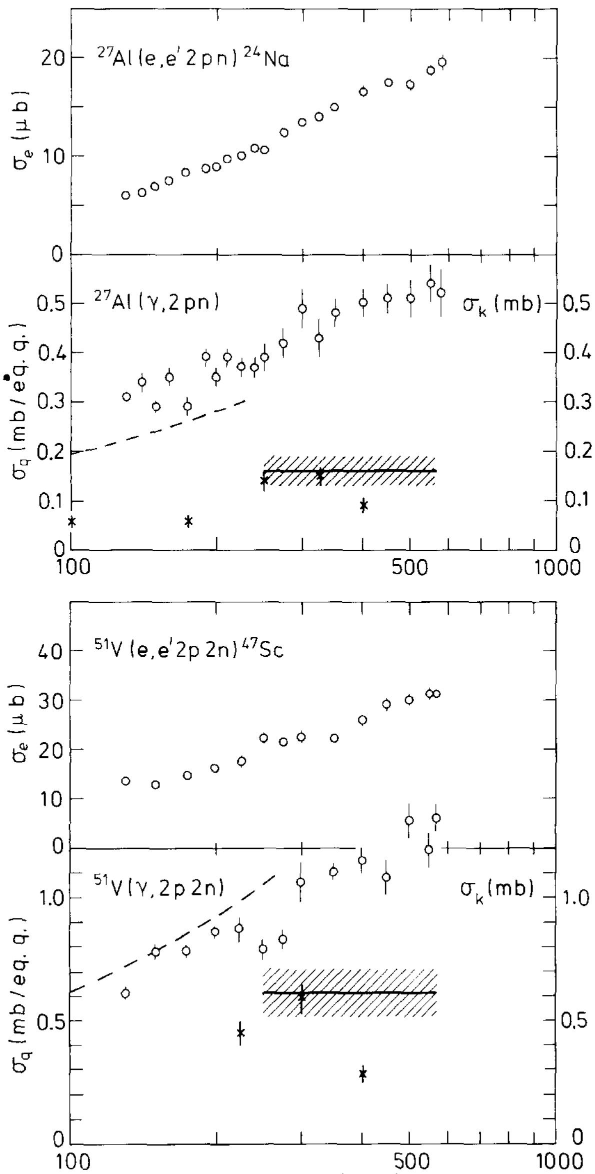
$N_e(E_0, k, L)$ is the virtual photon spectrum, depending on the electron energy E_0, transition energy k and multipolarity L of the interaction [2]. This formula is analog to the relation between the bremsstrahlung induced cross section per equivalent quantum σ_q and the photodisintegration cross section σ_k:

$$\sigma_q(E_0)=\int_0^{E_0} \sigma_k(k)\, S(E_0, k)\, dk, \qquad (2)$$

where $S(E_0, k)\, dk$ is the number of real gamma quanta with energy in the interval $k-k+dk$ per equivalent quantum (bremsstrahlung spectrum).
In formula (1) the photodisintegration cross section appear decomposed into the different multipoles.
Usually one has very little knowledge of the type and multipolarity of the interaction under study. Instead, formula (1) has often been used to obtain this information by fit to experimental data.
Experimental cross-section ratios, σ_q/σ_e, for various reactions have been collected in References 3, 4. In most cases only simple reactions, with few particles emitted, have been studied. These cross-section ratios are found to vary very little with target mass and with the number of nucleons emitted. The overall trend of these ratios versus energy agrees with theory on the assumption of $E1$ transitions [5]. Recently Noga et al. [6] found for 1.2 GeV electrons the ratio σ_q/σ_e to be somewhat smaller for reactions with emission of a proton than for reactions where a neutron has been emitted. This difference could be explained if one assumes that quasi-elastic scattering processes contribute to the cross section.
The aim of this work is to study some electro- and photoinduced spallation reactions of various complexity on ^{27}Al and ^{51}V at intermediate energies. The deduced photon cross sections σ_k are compared to Monte-Carlo calculations based on a cascade–evaporation model. The cross-section ratios, σ_q/σ_e, are compared to calculations based on the Dalitz formalism for the virtual photon spectrum [2].

2. Experimental Method and Results

The experiment was carried out at LINAC II at DESY in Hamburg. The experimental data were obtained as by-products of the experiment described in Reference 7. For ^{27}Al one and for ^{51}V eight different spallation products could be identified. The decay data were taken from Reference 8. The method of evaluation of the cross sections σ_q and σ_e was identical to that described in Reference 7. Figures 1–3 show σ_q and σ_e for the reactions studied versus energy of the incident electrons. The errors indicated are the random errors. The total systematic error is expected to be about 15% for all the reactions studied. The



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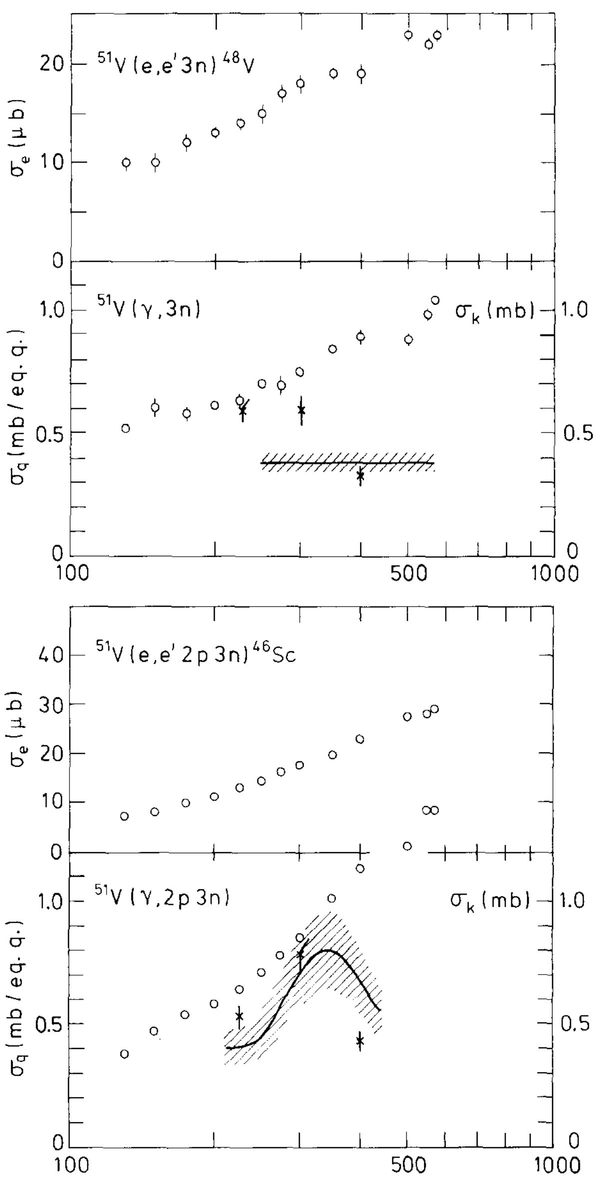
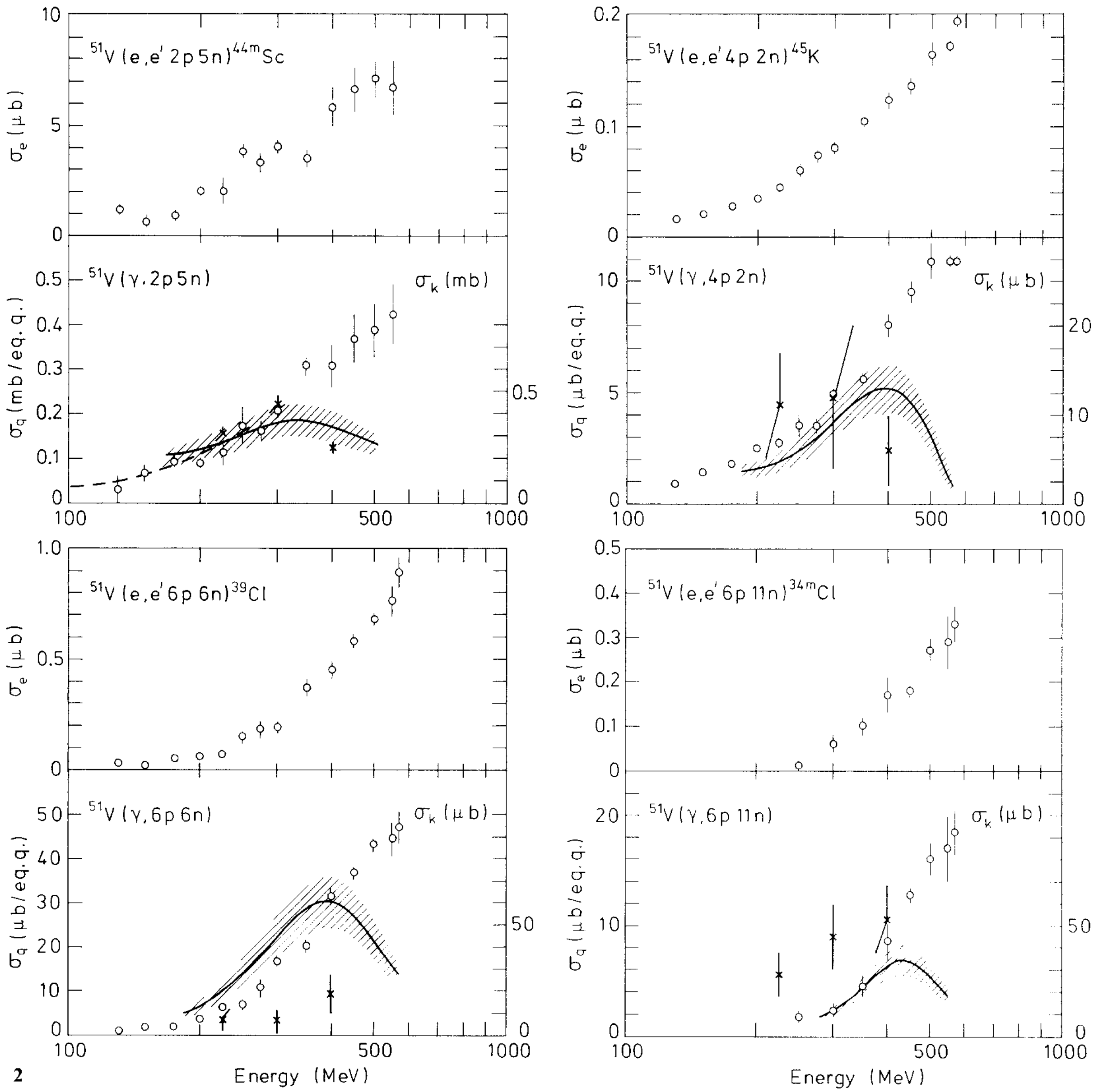


Figs. 1 and 2. Experimental cross sections σ_q and σ_e versus energy for different reactions on ^{27}Al and ^{51}V. The cross sections σ_k deduced from σ_q are given by the solid drawn curves, the hatched areas showing the uncertainty. Dashed curves show σ_q calculated from the low-energy data in Reference 11. Crosses give σ_k calculated with Monte-Carlo method

σ_q and σ_e curves show a similar energy dependence as expected from relations (1) and (2). From the σ_q curves the cross sections per photon, σ_k, were deduced with the unfolding method by Tesch [9] using a Schiff spectrum (integrated over angle) for the bremsstrahlung spectrum [10]. The obtained cross sections are shown in Figures 1–3. The hatched areas indicate the mean statistical error (about 20%). For the simple reactions ^{27}Al(γ, $2pn$), ^{51}V(γ, $3n$) and ^{51}V(γ, $2p\,2n$) the high-energy yields σ_q are dominated by the contribution from the giant resonance and it was not possible to unfold the data. In these cases mean cross sections over a broad energy region were calculated by use of the $1/E$-approximation for the bremsstrahlung spectrum.

The general feature of the spallation reactions is a broad resonance in the cross section at about 300 MeV clearly reflecting the influence of the (3,3)-resonance. The reactions ^{27}Al(γ, $2pn$), ^{51}V(γ, $2p\,2n$) and ^{51}V(γ, $2p\,5n$) have earlier been studied by Meyer et al. [11] for energies from threshold up to 250 MeV. The yields σ_q calculated from their cross-section data



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are shown by the dashed curves in Figures 1 and 2. The Al(γ, $2pn$) cross section at intermediate energies has been measured by many authors; see i.e. References 12–15. It is satisfactory to note that all these data, including the present ones, are in reasonable agreement with each others although they have been measured with quite different methods.

The reaction $^{51}\mathrm{V}(\gamma, \pi^- 2n)$ has been studied by Meyer and Hummel [16] and by Nydahl and Forkman [17]. These authors found a considerably higher cross section in the resonance region than obtained in the present work. However, the discrepances are almost removed if the old data are corrected to the new γ-ray branching ratios used in this work [8]. The corrected old data are shown in Figure 3.

Figure 4 shows the cross-section ratio σ_q/σ_e for the reaction $^{27}\mathrm{Al}\left(\begin{matrix}\gamma, & \\ e, & e'\end{matrix}\ 2pn\right)^{24}\mathrm{Na}$ as a function of electron energy. In the figure are also shown the results by Noga et al. [4, 6], Butement et al. [18] and Fulmer et al. [19]. Except for energies below 200 MeV the data are in fair agreement with each others. In Figure 5 σ_q/σ_e-ratios are given for spallation reactions of various complexity on ^{51}V (only some typical error bars are indicated). From this figure we can make the following conclusions:

a) the σ_q/σ_e-ratios depend very weakly on electron energy,

b) the σ_q/σ_e-ratios increase slightly with increasing complexity of the reaction.

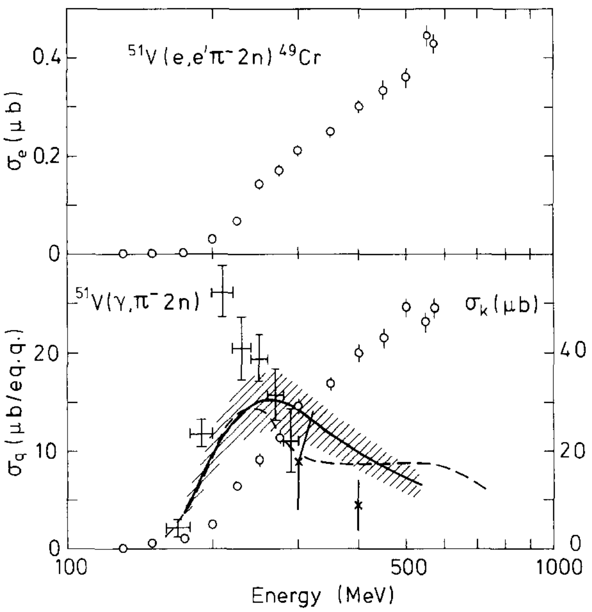

Fig. 3. Experimental and calculated cross sections for the reaction ^{51}V $\left(\begin{smallmatrix}\gamma \\ e', e'\end{smallmatrix}, \pi^- 2n\right)$ ^{49}Cr; se caption to Figures 1-2. ⨦ show the corrected σ_k by Meyer and Hummel [16], the dashed curve the corrected σ_k by Nydahl and Forkman [17]

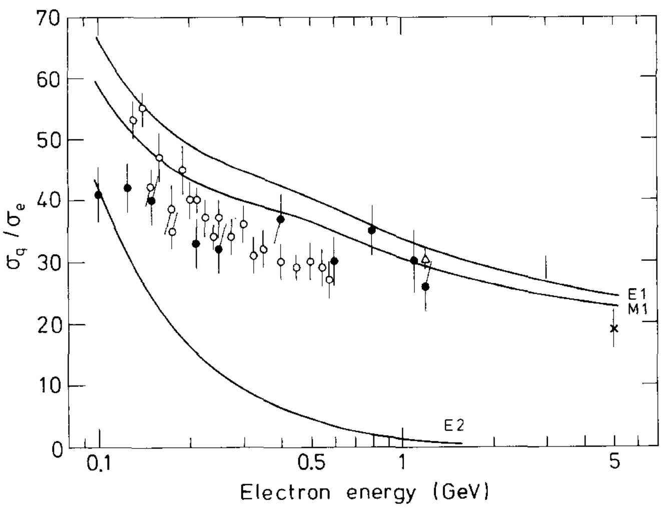

Fig. 4. The ratio σ_q/σ_e versus electron energy for the reaction ^{27}Al $\left(\begin{smallmatrix}\gamma \\ e', e'\end{smallmatrix}, 2pn\right)$ ^{24}Na. ○ present work, ● Reference 4, △ Reference 6, | Reference 18, ⁎ Reference 19. Solid curves give calculated cross-section ratios

3. Discussion

The cross sections per photon σ_k for the reactions studied were calculated at three photon energies with the Monte-Carlo method developed by Gabriel and Alsmiller [20]. The parameters were taken to be the same as those used in Reference 21. The calculated cross sections are shown in Figures 1-3 by the crosses with the error bars given by the statistical errors. For

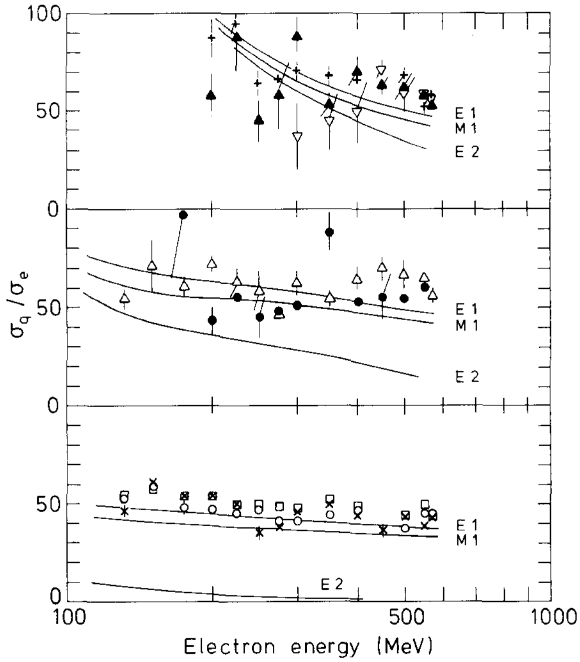

Fig. 5. The ratio σ_q/σ_e versus electron energy for different reactions on ^{51}V. ○ $3n$ emitted, × $2p\,2n$, □ $2p\,3n$, ● $2p\,5n$, △ $4p\,2n$, + π^-2n, ▲ $6p\,6n$, ▽ $6p\,11n$. The curves show calculated cross-section ratios for π^-2n (top), $2p\,5n$ (middle), $2p\,2n$ (bottom)

the reactions ^{51}V$(\gamma, 2p\,5n)^{44m}$Sc and $(\gamma, 6p\,11n)^{34m}$Cl were used isomeric ratios calculated as described by Eriksson and Jonsson [21]. These ratios were found to be 0.7 (Ref. 21) and $\simeq 5$ respectively in the energy region studied. As seen in the figures, good agreement with experimental data is obtained in most cases.

The cross-section ratio σ_q/σ_e was calculated for the reactions ^{27}Al$(\gamma, 2pn)$, ^{51}V$(\gamma, 2p\,2n)$, ^{51}V$(\gamma, 2p\,5n)$ and ^{51}V$(\gamma, \pi^- 2n)$. From Figures 1-3 it is seen that these selected reactions on vanadium are typical for the three reaction groups exposed in Figure 5. The real photon spectrum was taken to be a Schiff spectrum [10]. The virtual photon spectrum was taken from the calculations by Dalitz and Yennie for a point-like nucleus [2, 1]. The appropriate cross sections to be used in the calculations (see formulas (1) and (2)) were taken from Reference 11 and from this work. The results under the assumption of $E1$, $M1$ and $E2$ transitions are shown in Figures 4 and 5. For Al the calculated cross-section ratio under the assumption of $E1$ or transitions agrees with the experimental data at very high energies. However, at resonance energies the calculations exceed the experimental data. This could be an effect of the nuclear structure which has been neglected in these calculations. Some $E2$ admixture could also explain the low σ_q/σ_e-ratio.

For the reactions on V good agreement is obtained for the three reaction groups studied assuming $E1$ or $M1$ transitions.

The increasing cross-section ratios with complexity of reaction is evidently an effect of increasing thresholds as seen from Figures 1–3. This is especially apparent for the $E2$ curves. To be able to take into account nuclear size effects, appropriate nuclear form-factors must be used [22]. Analyses of reactions, whose cross sections are dominated by the giant resonance, show that nuclear size effects will somewhat increase the cross-section ratios for $E1$ and $E2$ transitions at high energies [1, 22].

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Ingvar Blomqvist
Petr Janeček
Göran G. Jonsson
Rolf Petersson
Department of Physics
University of Lund
Sölvegatan 14
S-22362 Lund
Sweden

Herbert Dinter
Klaus Tesch
Deutsches Elektronen-Synchrotron, DESY
Notkestieg 1
D-2000 Hamburg 52
Federal Republic of Germany