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TRANSFER AND EXCITATION PROCESSES STUDIED IN H-LIKE S AND LI-LIKE AND H-LIKE F COLLIDING WITH H_2

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ABSTRACT

We have studied transfer and simultaneous excitation by three different experimental techniques. Coincidences between two K X rays were measured for S^{15+}, coincidences between one K X ray and the charge exchanged projectile for Li-like F and projectile Auger electrons for H-like F in each case colliding with H_2. For all three collision systems, the measured cross sections are dominated by Resonant Transfer and Excitation (RTE). Also, for the F projectiles, strong contributions from Two Electron Transfer and Excitation (2eTE) were found.

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1. Introduction

Transfer and excitation (TE) processes have been studied intensively in the past few years [1-6]. The main interest has been focussed on Resonant Transfer and Excitation (RTE). In this process, a weakly bound target electron is captured by the projectile and, simultaneously, a projectile electron is excited by an interaction with the captured electron, leaving the projectile in a doubly excited state. In most of the experiments done so far, RTE was studied for Li-like ions by measuring coincidences between an X ray and the charge-exchanged projectile [1]. For Li-like O, RTE could also be identified by measuring projectile Auger electrons in high resolution [2]. RTE is also called RTEX for the radiative or RTEA for the Auger decay channel, respectively. However, RTEX was never observed for ions with $Z < 10$. In this work, we studied RTEX for Li-like F colliding with H_2 by measuring F X rays in coincidence with the charge-exchanged projectiles.

The study of RTE for H-like ions is especially interesting since, in this case, no spectator electrons are present which make the process much more complex. For example, the interaction of the active electrons with the spectator electrons in Li-like ions leads to a much higher multiplicity of doubly excited states. Also, the presence of spectator electrons opens additional and irrelevant decay channels.

However, with the X-ray particle coincidence technique employed in most experimental studies on RTE performed so far, RTE cannot be separated from simple capture to an outer shell with subsequent radiative stabilization. We employed the X-ray-X-ray coincidence technique to study RTE in S^{15+} colliding with H_2 and measured projectile Auger electrons to study RTE in $F^{8+} + H_2$ collisions.

2. X-ray-X-ray coincidence studies for $S^{15+} \rightarrow H_2$

At the MP Tandem of the Max Planck Institut für Kernphysik in Heidelberg, we used H-like S beams at energies between 70 and 156 MeV. The beam passed through a three times differentially pumped H_2 gas target. The X rays produced here were measured with two Si(Li) detectors. With the advent of an RTE process, the two electrons of the S ion occupy an outer shell, and there are two vacancies in the K shell. Therefore, the doubly excited state can decay by the emission of two correlated K X rays. These correlated X rays were selected by setting up a timing coincidence requirement between the two Si(Li) detectors. The beam was collected in a Faraday cup for normalization.

In fig. 1, the cross sections for correlated emission of two S K X rays (in the following, we call these correlated K X rays $K_{\alpha\alpha}$ etc.) are plotted versus projectile energy. In the $K_{\alpha\alpha}$ cross sections ($\sigma_{\alpha\alpha}$), there are two pronounced and well separated maxima. Also in $\sigma_{\alpha\beta}$ and $\sigma_{\alpha\gamma}$ (gamma refers to K_γ and higher K X rays) clear maxima can be seen.

The curves in fig. 1 show calculated cross sections for RTE followed by the emission of two K X rays (RTEXX) from McLaughlin and Hahn [6]. For each type of correlated transitions resolved in the experiment, a separate calculation with a detailed analysis of cascade transitions was performed.

The positions of the first maximum in $\sigma_{\alpha\alpha}$ agrees very well with the calculation and with the resonance energy for KLL RTEXX resonances (the resonance energies for some KLn states are indicated by arrows in fig. 1). Also, the second maximum in $\sigma_{\alpha\alpha}$ and the maxima in $\sigma_{\alpha\beta}$ and $\sigma_{\alpha\gamma}$ are very well reproduced by the calculation, and fall in a region where KLn(n > 2) RTEXX resonances are expected. The shape of the maxima and the absolute magnitude are in reasonably good agreement. Only the second maximum in $\sigma_{\alpha\alpha}$ and the maximum in $\sigma_{\alpha\gamma}$ are slightly underestimated by theory. However, considering the complexity of the problem, the overall agreement is remarkable.

Both experiment and theory agree that high n state KLn RTEXX resonances with cascade transitions to lower n states play an important role. These contributions manifest themselves particularly in the second maximum of $\sigma_{\alpha\alpha}$. But also in $\sigma_{\alpha\beta}$ and $\sigma_{\alpha\gamma}$, the influence of cascade transitions can be seen. If cascade transitions would not occur, $K_{\alpha\beta}$ ($K_{\alpha\gamma}$) transitions could only occur after a KLM (KLN) state was populated which resonates at 130 (141) MeV. The fact that the maximum is at almost 140 (150) MeV shows that higher n state KLn resonances followed by a cascade transition must be contributing.

3. X-ray-particle coincidence studies for Li-like F colliding with H_2.

At the EN tandem of the Oak Ridge National Laboratory, we obtained Li-like F beams at energies between 15 and 33 MeV. The beam passed through a differentially pumped H_2 gas target. The X rays produced here were detected by two gas proportional counters. The beam was then charge-state analyzed by an electrostatic analyzer. The projectiles that have captured one electron were counted by a ceratron, the beam fraction that did not undergo charge exchange was collected in a Faraday Cup for normalization. Here, capture with coincident emission of an X ray is a signature of a TE process.

In fig. 2, the cross sections for capture with simultaneous X-ray emission (σ^X_{q-1}) are plotted versus the projectile energy. The data show pronounced structures. There is a maximum at about 24 MeV and a shoulder at about 28 MeV. The arrows in fig. 2 show the RTE resonance energies for some Knn' states. The maximum in the data falls in an energy region where KLn RTE resonances are expected. The shoulder is above the KLn series limit in a region where the population of Knn'(n,n' > 2) states is in resonance.

An interesting result is that apparently the KLL RTEX resonances seem to play only a minor role. At the KLL resonance energy, the data just barely start rising and the cross section is here at most 30% of the one in the maximum. The position of the maximum is slightly above the KLM resonance energy and even very close to the KLn series limit (KL∞). Thus, it is clear that the high n state KLn resonances play an even more important role than observed in the case of $S^{15+} \rightarrow H_2$.

A surprising result is the shoulder in σ^{x}_{q-1}, which is above the KLn RTE series limit. Higher resonances, such as KMM, were never observed before and are also expected to be negligible compared to the KLn series [7]. Hahn and McLaughlin have proposed a new transfer and excitation process [8], which is called "Two Electron Transfer and Excitation" (2eTE) [9]. In this process one target electron is captured by the projectile and, at the same time but uncorrelated with the capture process, a second target electron excites a projectile electron.

In the approximation that the target electrons are free, the electron-electron excitation process has a threshold energy for K to L excitation at a projectile energy equal to the KLn RTE series limit. Therefore, both 2eTE and Knn'(n,n' > 2) RTE resonances could occur in a projectile energy region where the shoulder in the data is observed. Since this region is still well below the K to M excitation threshold, mainly KLn states should be populated by 2eTE, whereas, RTE can only populate Knn'(n,n' > 2) states at these energies. Therefore, one possibility to distinguish these processes would be to measure KLn and Knn'(n,n' > 2) Auger electrons.

4. Projectile Auger spectroscopy of H-like F colliding with H_2

H-like F beams obtained from the EN Tandem at the Oak Ridge National Laboratory were passed through a differentially pumped H_2 gas target. The electrons emitted at an angle of 9.6° were energy analyzed by a two-stage 30° parallel-plate electron spectrometer and detected by a position-sensitive microchannel plate detector. Before entering the spectrometer, the electrons were decelerated by a factor of two by a high voltage applied between the two inner pumping stages of the gas cell. The beam was collected in a Faraday cup for normalization.

In fig. 3, the F Auger electron-emission cross sections σ_{KLn}(n = L,M,N,O) are plotted versus the projectile energy for KLL, KLM ,KLN and KLO transitions. In σ_{KLL}, a pronounced maximum can be seen at 21 MeV and a second, even though rather weak, maximum at 29 MeV. The cross sections for all the other transitions show a maximum at 29 MeV. The arrows in fig. 3 show the RTE resonance energies for populating the doubly excited state that corresponds to the observed Auger transition. Also, the KLn series limit (KL∞) is shown. Only the position of the first maximum in σ_{KLL} agrees with the corresponding resonance energy. The second maximum in σ_{KLL} and the maxima in all the other transitions are at 29 MeV, which is at the KLn RTE series limit or even slightly above it. This shows that at least the KLn RTE resonances followed by a direct Auger transition to the ground state are not the main contributor to σ_{KLM}, σ_{KLN}, and σ_{KLO}. In principle, RTE resonances near the series limit followed by a radiative transition to a lower lying doubly excited state followed by an Auger transition to the ground state could contribute. However, the lifetime of radiative cascade transition is very long compared to the Auger lifetime so that these contributions should be negligible.

As mentioned above, 2eTE can lead to KLn Auger transitions and should contribute above the KLn RTE series limit to the cross sections. The curves in fig. 3 show an estimate of the projectile-energy dependence of the cross section expected for this process. The projectile-energy dependence is a combination of the decrease of the capture probabilities with increasing energy and the threshold behavior of the excitation process by a free electron folded with the Compton profile of the target electron. The relative n- distribution is obtained using the OBK approximation for n = 2, 3, 4, and 5. The absolute magnitude was obtained by fitting the estimated 2eTE cross section to the data point of σ_{KLN} at 29 MeV.

The agreement of the estimated projectile-energy dependence of 2eTE with σ_{KLN} and σ_{KLO} is very good. In σ_{KLM}, the estimated 2eTE cross section approaches the measured cross sections only at high energies. In σ_{KLL}, the agreement is reasonable above energies where the KLL RTE resonance has strong contributions. Also the calculated n- distribution is consistent with our data. If the estimated 2eTE cross sections are subtracted from σ_{KLM}, the resulting cross sections (open circles in fig. 3) show a shape that looks like what is expected for an RTE resonance. The position of the maximum in these points also agrees with the KLM resonance energy (25.5 MeV). The height of this maximum is about one order-of-magnitude smaller than the first maximum in σ_{KLL}.

5. Conclusions

We have studied Transfer and Excitation processes by three different experimental techniques. For H-like S colliding with H_2, three groups of RTE resonances could be separated by measuring X-ray-X-ray coincidences. Calculated RTE cross sections [6] predicting strong contributions from high n states are in good agreement with our data.

For Li-like F colliding with H_2, TE processes were studied by X-ray-particle coincidence technique. Here, the high n- state RTE resonances play an even more important role than for H-like S and are clearly dominating the KLL resonances. Furthermore, a shoulder above the KLn RTE series limit was observed in the measured cross sections.

An Auger electron spectroscopy study was performed for H-like F colliding with H_2. The Auger emission cross sections clearly reveal a dominance of KLL RTE resonances over the high n- state resonances. We conclude that the n distribution of the observed RTE resonances depends very sensitively on the decay channel, i.e., RTEA favors low n states and RTEX higher n states. Finally, maxima above the KLn series limit were observed in the cross sections for all measured Auger transitions which are due to 2eTE.

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Figure Captions

Fig. 1. Cross sections for emission of two correlated X rays in collisions of H-like S with H_2. The curves show calculated RTEXX cross sections from ref. [6].

Fig. 2. Cross sections for capture and simultaneous X-ray emission for L-like F colliding with H_2.

Fig. 3. Auger emission cross sections for H-like F colliding with H_2. The curves show an estimate of the projectile-energy dependence of 2eTE cross sections and of the n- distribution of the populated states.

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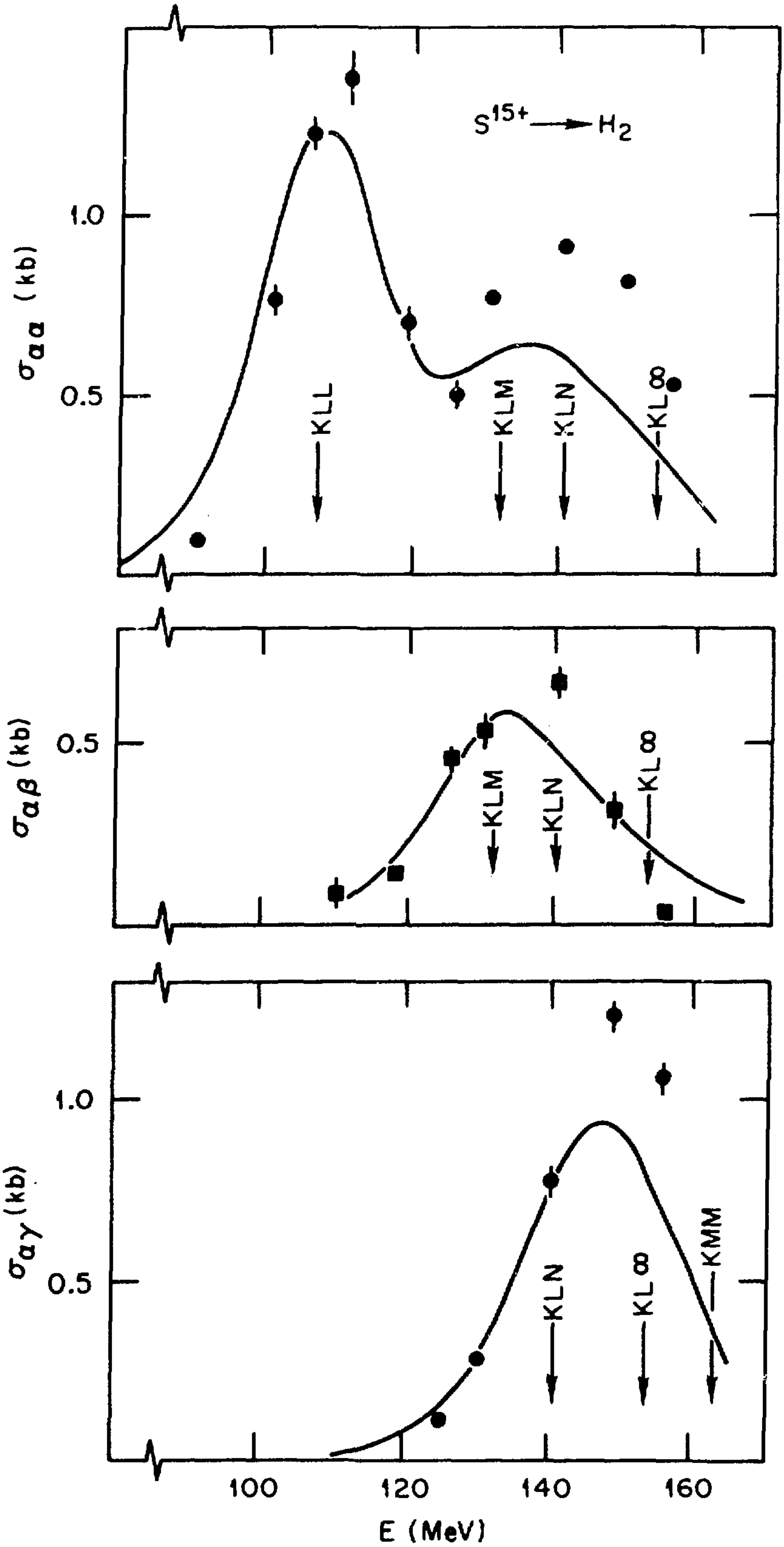

Fig. 1

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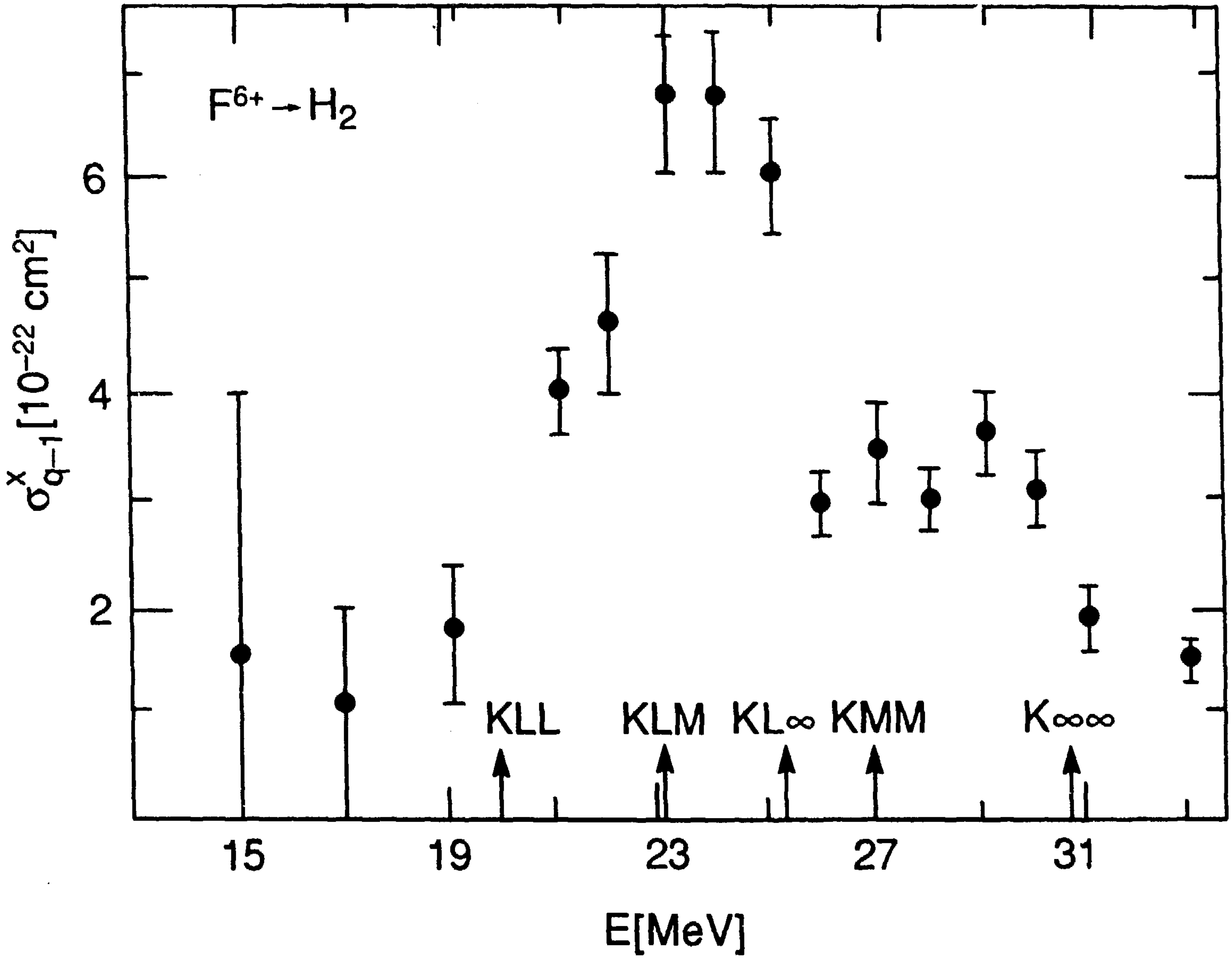

Fig. 2

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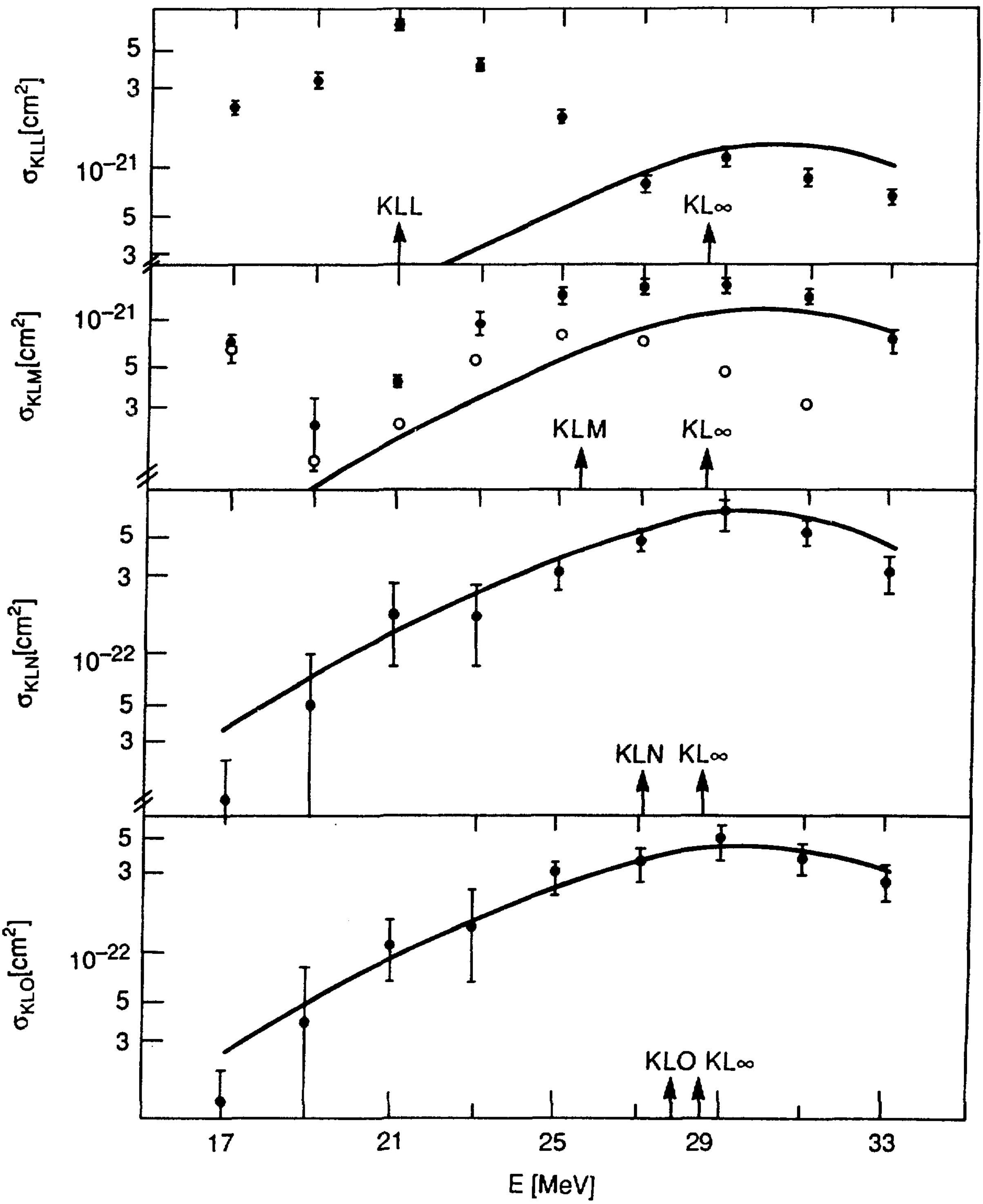

Fig. 3