Title

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The experimental observation[1,2] of the catalysis of nuclear reactions by μ mesons in liquid hydrogen[3] created interest at a number of laboratories and led to several independent theoretical investigations of the processes involved.[4] Although it soon became clear that this phenomenon could not lead to the production of useful power, some of the estimates of particular reaction rates were in wide disagreement, primarily because of the gross approximations made. Because of the intrinsic interest in the effect, and in order to obtain a more satisfactory understanding of these processes, we have made a detailed investigation of the molecular systems involved in these reactions.

It is assumed that nuclear catalysis proceeds through the following processes:

(1) The μ meson is slowed down by collisions in the liquid hydrogen and captured by a proton, forming a $(p\mu)$ atom.

(2) The $(p\mu)$ atom migrates and encounters a deuteron which captures the meson by exchange. Owing to the difference in reduced mass this process releases 135 ev to the system.

(3) The $(d\mu)$ atom slows down by collisions and forms a $(p\mu d)^+$ molecular ion by a process of electron ejection.

(4) The nuclear reaction $p + d \rightarrow He^3 + \gamma(5.5\ \text{Mev})$ occurs. The γ ray may then eject the meson.

In all these processes there is competition with the natural decay of the meson, while in Processes (2) and (3) there is also a competition with the formation of other molecular ions, such as $(p\mu p)^+$ and $(d\mu d)^+$.

In our investigations of the molecular ions we have used the Born-Oppenheimer approximation[5] as a starting point for a variational calculation of the bound-state and scattering-wave functions of the three-body system. In this calculation, corrections to first order in the ratio of mesic to nucleonic mass were included. In the unequal-mass case, $(p\mu d)^+$, this leads to a pair of coupled second-order differential equations, while in the equal-mass cases, $(p\mu p)^+$ and $(d\mu d)^+$, the two equations are not coupled. The solutions to these equations were carried out numerically by use of an IBM 701 computer. The wave functions and eigenvalues for all the bound molecular-ion states were obtained. These binding energies relative to the totally separated systems are given in Table I.

The free-state wave functions were also calculated, and the energy dependences of the scattering cross sections were investigated. The results of these calculations are shown in Fig. 1. Of particular interest is the anomalous behavior of the scattering cross section for $(d\mu)$ atoms on protons. For energies in the thermal range this cross section is extremely small, corresponding to a scattering length ~ 0.08 times the mesic Bohr radius. The unusually long gaps between the ending of the initial meson track and the beginning of the secondary track, which were observed experimentally,[1,3] can probably be explained by such a Ramsauer effect. In addition, the exchange cross sections were calculated, giving for Process (2) an exchange rate R_{ex} near zero energy of 11.5×10^9 sec^{-1} in pure liquid deuterium.

From the wave functions, estimates for rates of molecular-ion formation at low energies were also obtained. These are as follows:

$(p\mu) + H \rightarrow (p\mu p)^+ + e$, $\quad R_{2m} = 8 \times 10^6 \text{ sec}^{-1}$ (in liquid hydrogen);

$(d\mu) + H \rightarrow (d\mu p)^+ + e$, $\quad R_{3m} = 3 \times 10^6 \text{ sec}^{-1}$ (in liquid hydrogen).

By a phenomenological analysis of the experiments one can determine the ratio $R_{ex}/(R_{2m} + R_\mu)$, where R_μ is the natural meson-decay rate. Our calculated value for this ratio is 1.3×10^3, in good agreement with the experiments.

A full account of these calculations will be published.

This work was performed under the auspices of the U.S. Atomic Energy Commission.

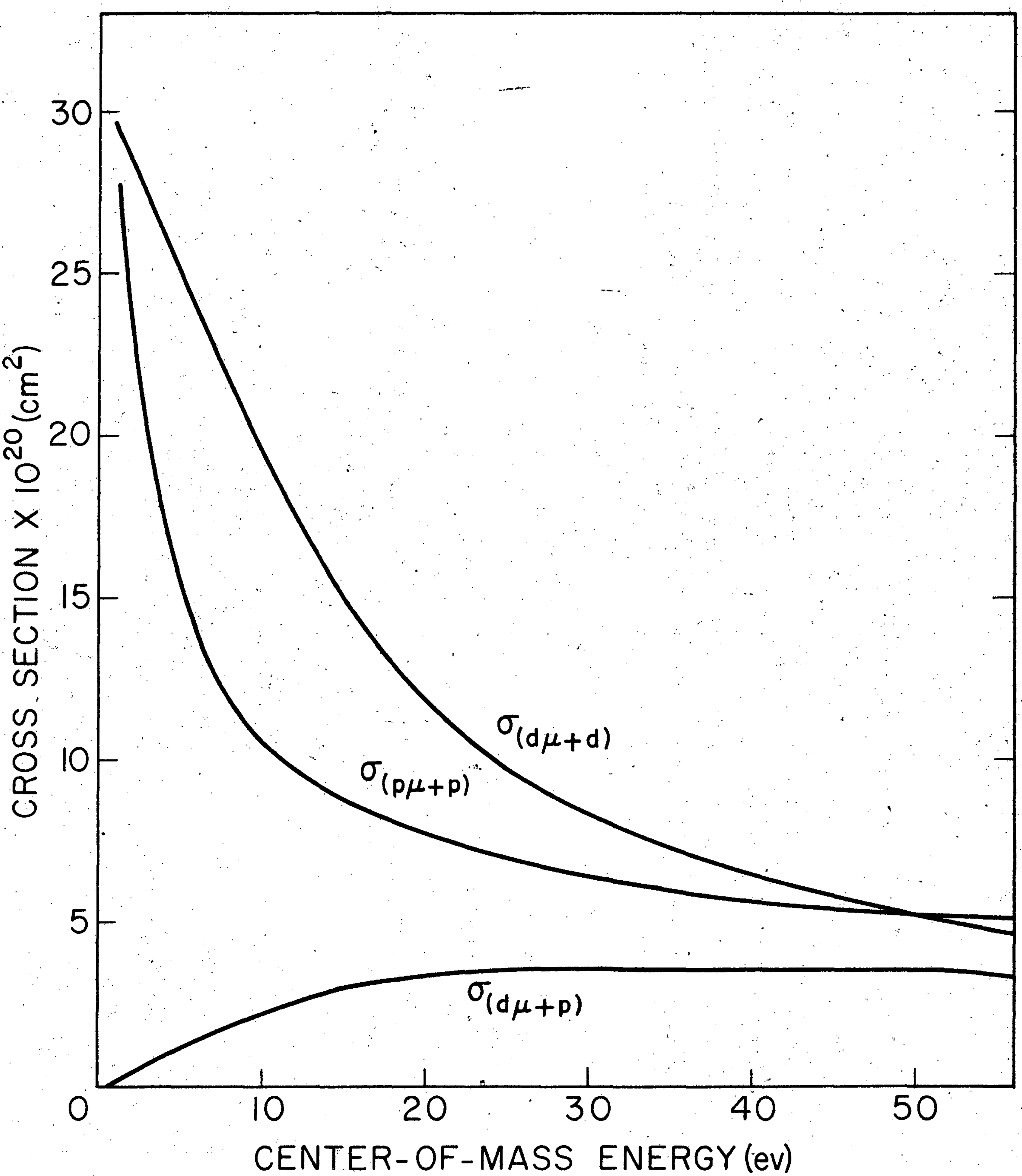
TABLE I

Calculated binding energies of bound states of μ-mesic molecular ions.

System	State	Binding energy (ev)
$(p\mu p)^+$	L = 0	2771
	L = 1	2624
$(p\mu d)^+$	L = 0	2878
	L = 1	2754
$(d\mu d)^+$	L = 0	2986, 2845
	L = 1	2887
	L = 2	2746

FIGURE CAPTIONS

Figure 1: The energy dependence of elastic-scattering cross sections for mu-mesic atoms from protons and deuterons.



30
25
20
15
10
5
0
10
20
30
40
50
CROSS SECTION X 10^{20} (cm^2)
CENTER-OF-MASS ENERGY (ev)
$\sigma_{(d\mu+d)}$
$\sigma_{(p\mu+p)}$
$\sigma_{(d\mu+p)}$

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