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MUON CAPTURE AT LARGE y – ENERGETIC NUCLEON EMISSION

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Capture of a negative muon by a nucleus leads in some fraction of cases to emission of a nucleon carrying a substantial fraction of the entire available energy $Q = \Delta m + m_\mu - B_\mu$. Here Δm is the difference of initial and final (excited) nuclear masses, m_μ is the muon mass, and B_μ is the atomic binding energy of the muon before capture. This corresponds to emission of nucleons with 350-420 MeV/c of momentum, while the momentum transfer at the leptonic vertex is small and generally timelike ($| Q^2 | < 100 MeV/c$).

Such high momentum emitted particles have very poor wave function overlap with bound nucleons in conventional nuclear models, making the observed rates much too large to account for in such models [1,2].

In this report I will examine energetic nucleon data from muon capture in ^{40}Ca, to see how this reaction can be understood. I will show that in addition to the usual IA mechanism [3], the data requires an additional capture interaction between the muon and a pair of nucleons. The resulting nucleon and neutrino energy/momentum distribution in the rest system of the (pair + muon) is essentially given by phase space. The strength of the pair capture relative to the IA is several per cent.

We [4] have measured protons with kinetic energy greater than 28 MeV emitted following muon capture in carbon, calcium, and yttrium. The experimental setup used a 73 mm thick plastic scintillator telescope to stop protons originating in thin (0.3 g/cm^2) targets. Muons of 45 $\pm$ 3.5 MeV/c from the MuE4 channel at PSI were degraded in the targets and stopped after being registered by a beam telescope of 1 mm thick scintillators. The high intensity (0.2×10^6 stops per second in the indicated conditions), low pion contamination (measured to be $< 0.5 \times 10^{-4}$), and small spot size ($4 \times 6\,\text{cm}^2$) available from this beam permitted very sensitive measurements of the rather small branching ratios encountered.

Protons were redundantly identified against the background of Michel

electrons by time of flight, $\Delta E/E$, and time correlations with a muon stop signal. After cuts were applied to select protons,the remaining background was about 10^{-8} particle per muon stop. The detection solid angle was 4.5% of 4π. Energy calibration was obtained from sampling Michel electrons and from stopping pion runs.

Our proton spectrum from muon capture in Ca is shown in Figure 1 as the open triangles. Except at the highest energies, the statistical errors are smaller than the plotted symbols. There is an additional 10% overall normalization uncertainty. Also shown in Figure 1 is the neutron spectrum from muon capture in Ca measured by Van der Pluym et al [5].

Other data exist on energetic nucleons [6] following muon capture, but the dataset for Ca shown in Figure 1 is the only complete and high quality one available for a given nuclide, with measurements extending to the kinematic limits.

Neutrons can be produced in muon capture by a one-nucleon IA mechanism [3]. However, IA calculations fall far below the data above 40 MeV. This failure of the IA has been known, and its significance debated, for a long time [2,1]. The present measurements permit persuasive argument that the effect is due to an intrinsic two-nucleon capture mechanism, rather than from e.g. enhanced high momentum components in the nuclear wave function [7].

Protons cannot be directly produced in the IA through the elementary interaction $\mu^- + p \rightarrow n + \nu$. It is natural to ask first whether the observed protons are of secondary origin [8], resulting from intranuclear cascades initiated by primary IA neutrons. To study this question, I have performed hybrid-model intranuclear cascade calculations with the Livermore code Alice-LLL [9].

First I fit the observed neutron spectrum of Van der Pluym et al [5]with an energy distribution of cascades initiated by a one-neutron-particle, one-proton-hole (two exciton) configuration. The fit is shown as the full line in Figure 2. This energy distribution of two exciton cascades produces secondary protons with the spectrum shown as the dashed line in Figure 2. This calculated proton spectrum falls far short of our proton data. The observed protons cannot be accounted for by cascading of primary neutrons produced in the IA.

Capture by nucleon pairs can be modelled with the code by initiating cascades from initial configurations with two excited nucleons instead of one. When this is done, I find that 10 - 20 % of the cascades must be initiated by a configuration with an excited proton, in order to fit the proton and neutron spectra simultaneously. This corresponds to 10 - 20 % of capture via $\mu^- + (pp) \rightarrow n + p + \nu$ in addition to $\mu^- + (np) \rightarrow n + n + \nu$ and/or $\mu^- + p \rightarrow n + \nu$. The energy distribution of (pp) capture cascades needed for a fit turns out to be somewhat different than that of (np) capture cascades.

A microscopic method of calculation for the pair capture was presented by Van der Pluym et al [5]. Assuming that capture occurs on pairs of nucleons and that the resulting nucleon spectrum in the (pair + muon) rest frame is given by NNν phase space, one can use a Fermi gas model to obtain the momentum and internal energy distribution of the capturing pairs. This permits the nucleon spectrum in the lab to be calculated. I have introduced the Bodek-Ritchie [10] prescription for overall energy/momentum conservation into this calculation. The resulting proton spectrum is shown as the full curve in Figure 3, arbitrarily normalized to fit the data. This plane-wave estimate fits the shape of the energetic proton spectrum reasonably well. Van der Pluym et al [5] also obtained a good fit to their neutron spectrum from their calculation, which included an optical-model treatment of nucleon FSI in addition.

Lifshitz and Singer [11] have further extended this type of calculation by weighting the phase space with dynamical factors from the Feynman diagrams for meson exchange corrections (MEC) to the capture process. They simulated FSI using an exciton-model cascade calculation similar to that discussed above. Their results hardly differ from the pure phase space distribution shown.

In the low energy region, other processes involving giant resonances, etc. come to dominate the spectrum. Extrapolating the nucleon spectra into this region using the pair curves for the shape, one obtains energy-integrated branching ratios of 2.0% of the total capture rate for the process $\mu^- + (np) \rightarrow n + n + \nu$, and 0.18% for $\mu^- + (pp) \rightarrow n + p + \nu$. Space does not permit a full discussion of the reason for the large capture preference for pseudodeuteron (np) pairs over diprotons. This preference in muon capture is not statistical or kinematical in nature [12]. A similar selectivity seen in pion absorption is understood as an effect of the dynamics of virtual πNN and ΔN intermediate states [13,14,15,16]. Observation of this selectivity in muon capture as well is a further strong indication that the energetic nucleon emission results from an elementary interaction involving pairs of nucleons.

The surprising nature of the present results is indicated by a comparison with quasielastic electron scattering, widely regarded as a prototypical one-nucleon reaction.The Rosenbluth-separated one-nucleon scaling function

$F_L(y)$ for Ca has been obtained[17] up to y=500 MeV/c from (e,e') at q=500 MeV/c. This function is closely related to the one-nucleon momentum distribution function $n(p)$ given by

$$n(p) = \frac{1}{y}\frac{dF(y)}{dy}|_{\mathrm{p}}$$

.

The momentum transfers from the leptons in this (e,e') scattering and in muon capture are of course completely different. Nevertheless in an IA model they both depend on the momentum distribution $n(p)$ for $\mathrm{p} \tilde{>} \mathrm{p}_F$, in the regions of $\mathrm{y} < -\mathrm{p}_F$ and $\mathrm{T}_n > 35$ MeV respectively . Furthermore the kinematics are such that the energies of outgoing nucleons are similar in the two reactions. Using $n(p)$ from the electron scattering data, I have computed the phase space distribution expected in PWIA for neutrons from muon capture;

$$\frac{d\Gamma}{dT_n} \propto \int n(p_R)\, d^3\vec{p_n}\, d^3\vec{p_R}\, d^3\vec{p_\nu}\; \delta(\vec{p_n} + \vec{p_R} + \vec{p_\nu})\; \delta(Q - T_n - T_R - E_\nu)$$

.

Here subscripts n refer to the outgoing neutron, R to the recoil ^{39}K (always assumed to be in its ground state) , and ν to the neutrino.

The resulting arbitrarily normalized curve is shown as the dashed curve in Figure 3. The shape of the data is well reproduced. However, we have seen above that the muon capture neutrons are actually produced by capture on pairs, not on single high-momentum nucleons. Furthermore, when the normalization is calculated correctly, the electron scattering data predicts nearly a factor of 100 too many high momentum nucleons. The total capture rate is interestingly only high by a factor of 3.3, not unexpectedly since nuclear excitation will reduce the final neutrino phase space considerably.

The universal shape of the nuclear response far from quasielastic kinematics has been seen in many reactions [18,19], including backward proton scattering at GeV energies. The present work indicates that this universal response cannot result from a primary interaction of the probe with single high momentum nucleons in the sense of the IA. The response shape is often parametrized by k_{min}, the minimum one-nucleon initial momentum required to give the observed final state [18,19]. In a calculation based on interactions with nucleon pairs, k_{min} comes from transforming the internal momentum of a moving pair into the lab frame. This model permits k_{min} values up to $\sim 2p_F \sim 500$ MeV/c. Although such large momenta cannot be probed in muon capture due to the limited available energy, it is known from high energy scattering data [18,20] that there is no limit or change of slope in observed k_{min} (or scaling variable y) distributions near $2p_F$. This suggests that the actual mechanism may involve nucleon substructure in a more direct way [21].

1 Figure Captions

Figure 1: Experimental data for energetic nucleon spectra from muon capture in Ca. Crosses: neutron data from ref.[5]. Triangles: proton data from present work. Statistical errors are shown when they exceed the size of the plotted symbols.

Figure 2: Data as in Figure 1. Full curve: Alice-LLL fit to expermiental neutron spectrum using cascades initiated by a neutron particle, proton hole configuration. Dash-dotted curve: secondary proton spectrum calculated for the cascades giving full curve for neutron spectrum. Short-dashed curve: pair capture proton spectrum. This was generated by re-fitting the neutron data with cascades starting from two neutron particle, correlated two hole hole configurations ((pn) capture). To this was added a distribution of cascades starting from one neutron particle, one proton particle, correlated two hole configurations ((pp) capture), as required to fit the proton data. This mixture gives a neutron spectrum indistinguishable from the full curve.

Figure 3: Data as in Figure 1. Full curve: proton spectrum estimated in plane-wave, Fermi gas model for (pp) pair capture, as described in the text. Dot-dashed curve: PWIA neutron spectrum calculated from (e,e') y-scaling data of ref.[17].

References

[1] R.A. Eramzhyan, Y.A. Salganic, Nuc. Phys. A207, (1973), 609.

[2] N.C. Mukhopadhyay, Phys. Rep.30C, (1977),1.

[3] H. Primakoff, Rev. Mod. Phys. 31, (1959), 802.

[4] The collaborators on SIN/PSI experiment R86.08 are: C.J. Martoff, W.J. Cummings, D. Pocanic, S.S. Hanna (Stanford University), H. Ullrich (Kernforschungszentrum Karlsruhe), M. Furic, T. Petkovic (University of Zagreb), T. Kozlowski (Institute for Nuclear Study, Swierk,

Poland and PSI, Villigen, Switzerland), J. P. Perroud (Institut de Physique Nucleaire, Lausanne)

[5] J. Van der Pluym et al, Phys. Lett. B 177,(1986),21.

[6] References to earlier work can be found in reviews: ref.[2]; P. Singer, Springer Tracts in Modern Physics 71, (1977), 39, G. Höler ed.; Y.A. Batusov, R.A. Eramzhyan, Sov. J. Part. Nuc. Phys. 8, (1977), 229. Additional proton data is given in K. S. Krane et al, Phys. Rev. C20, (1979), 1873.

[7] M. Lifshitz, P. Singer, Phys. Rev. C22, (1980), 2135.

[8] A. Wyttenbach et al, Nuc. Phys. A294, (1978), 278.

[9] M. Blann, Ann. Rev. Nuc. Sci. 25, (1975), 123; Phys. Rev. C28, (1983), 1648; and LLNL report UCID 19614 (1982).

[10] A. Bodek, J.L. Ritchie, Phys. Rev. D23, (1981), 1070.

[11] M. Lifshitz, P. Singer, Nuc. Phys. A476, (1988), 684.

[12] P. Singer, Phys. Rev. 124,(1961), 1602.

[13] D.S. Koltun, A. Reitan, Phys. Rev. 141, (1966), 1413; and ibid., 155, (1967), 1139.

[14] B. Gotta et al, Phys. Lett. 112B, (1981), 129.

[15] K. Ohta, M. Thies, T.S.H. Lee, Ann. Phys. 163, (1985), 420 .

[16] D. Ashery et al, Phys. Rev. Lett. 47, (1981), 895.

[17] Z.E. Meziani et al Phys. Rev. Lett. 52, (1984), 2130 and priv. comm.

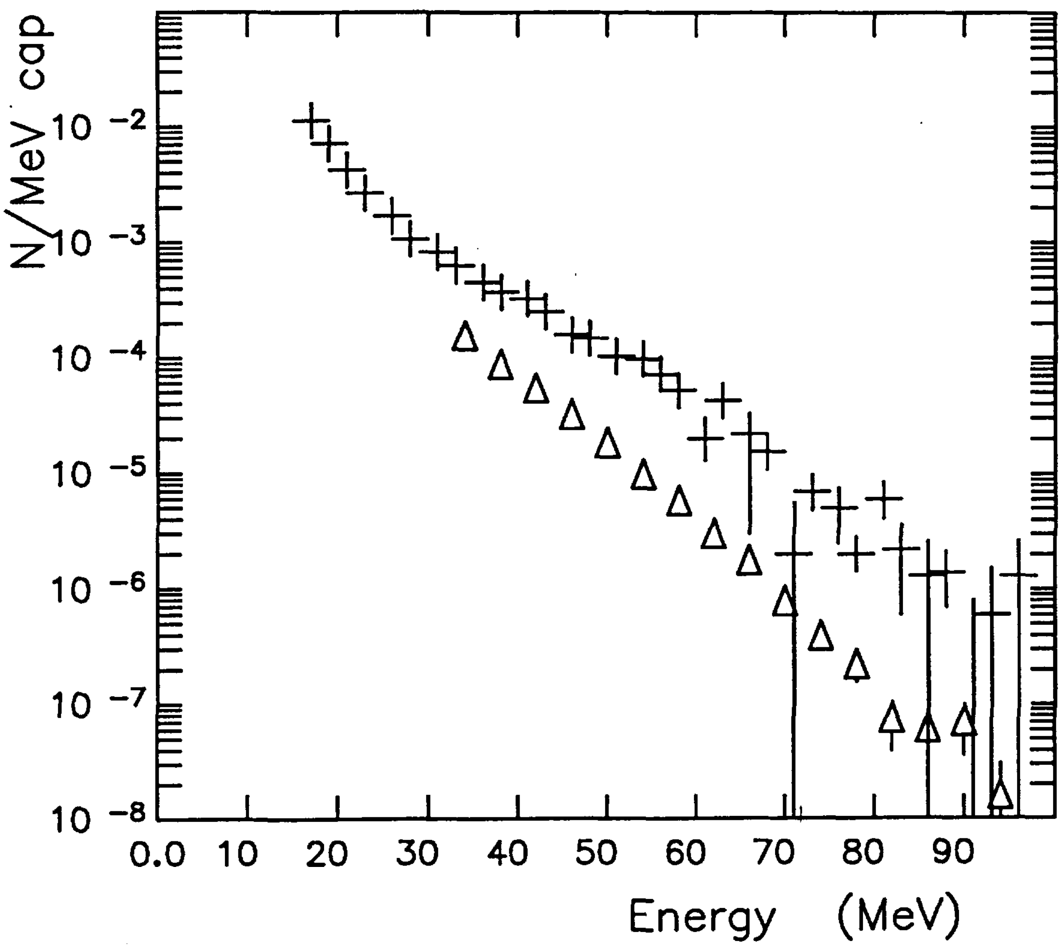
[18] S. Frankel, Phys. Rev. Lett. 38, (1977), 1338.

[19] P. Singer, N.C. Mukhopakhyay, R.D. Amado, Phys. Rev. Lett. 42, (1974), 162.

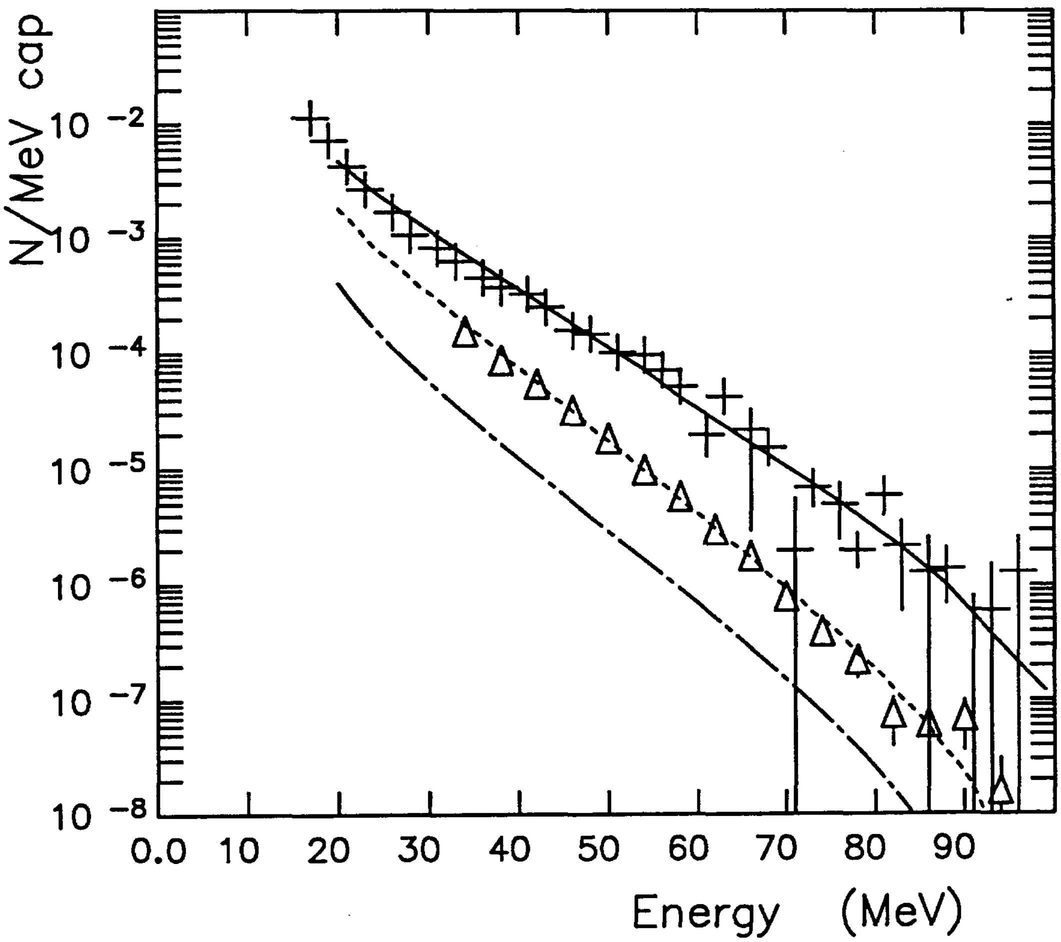
[20] P. Bosted et al, Phys. Rev. Lett. 49, (1982),1380.

[21] G.A. Miller, A. Gal, Phys. Rev.C.36, (1987) , 2450.

Mu capture data



Mu capture calculations with program ALICE/LLL



Mu capture data and y-scaling curve