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DEEPLY BOUND PIONIC STATES WITH THE (Σ^-, Λ) REACTION.

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ABSTRACT

We study the reaction $\Sigma^- + A \longrightarrow \Lambda + (A\,\pi^-)$ with the π^- bound in the nucleus, as a means of producing deeply bound pionic states in nuclei, so far unobserved. The reaction is similar to the (n, p) reaction but, because of the Σ^-, Λ mass difference, it allows the reaction to occur with smaller momentum transfer, thus increasing the transition probability and reducing the effects of distortion. The ratios of signal to background are one to two orders of magnitude better than in the (n, p) reaction.

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The search for deeply bound states of pionic atoms not observable with the traditional X ray technique offers a real challenge to experimentalists but is has also awakened us to the fact that we are still very far away from a consensus on the optical potential of pionic atoms at the empiral level, not to say a the theoretical level. Indeed two recent optical potentials, one empirical[1], the other one theoretical[2], both giving reasonable results for the so called anomalous atoms, provide very different results for these deeply bound pionic states, with differences of up to a factor 5 in the widths of the 1s states of heavy nuclei. In spite of these large differences, these two and other standard optical potentials appear to share the property that the widths of the states are narrower than the separation between the levels[3,4], which makes it a clear case for experimental observations.

The (n, p) reaction suggested in ref.[5] stimulated a new wave of experimental activity at several Laboratories, TRIUMF[6], Saturne[7], Julich[8], Indiana Cyclotron[9], GSI[10]. Some other recent theoretical studies have analyzed different reactions like the (π^-, π^+)[11], (e, e')[12,13], (γ, π^+)[14], (n, d)[15] all of them creating an extra π^- bound in the nucleus. The latter two provide better ratios of signal to background than the (n, p).

One of the reasons for the new wave of experiments was the prediction of very large ratios of signal to background in ref.[5]. However, these results were based on the plane wave approximation for the neutron and proton waves and the dominance of pion exchange in the $NN \rightarrow NN\pi$ transition, thus ignoring the effect of the Landau-Migdal force in this transition as well as the contribution from the transverse part. A reanalysis of the reaction incorporating all these ingredients[16] leads to ratios of signal to background much smaller than those early predictions, at the level or smaller than 1-4%, and smaller than one per thousand for the kinematical set up of the TRIUMF experiment, which is consistent with the non observation of any signal in this experiment[6].

One of the reasons for the small cross sections is the large

momentum transfer given to the pionic atom, of the order of 200 MeV/c at T_n = 400 MeV, which is difficult to accomodate in the atom. This large momentum transfer has also another unwanted side effect: the distortion of the n and p waves reduces the cross section appreciably with reduction factors of 30-100 as an average. It is easy to realize why the momentum transfer influences the distortion. The distortion eliminates much of the contribution from small impact parameters and concentrates on large values of b. Hence the transition matrix elements, involving the factor exp $(i \vec{q}\,\vec{r})$ with large $\vec{q}$ and $\vec{r}$, will have large cancellations.

This is why some of the new proposals go in the direction of making the reaction recoilless or near recoilless like those of refs.[8,15]. In ref.[15] the momentum transfer is tuned such that qR (R, nuclear radius) is equal to 1, the angular momentum of the pionic nuclear state formed. However, there is one price to pay for this gain: these reactions, ejecting one nucleon from the nucleus, involve directly only the valence nucleons, while in the (n, p) reaction all the nucleons contribute coherently to the amplitude and one benefits from the A^2 factor in the cross section.

It would be thus ideal to find a reaction combining these two features: recoilless and coherent. The reason why this is not possible with the (n, p) reaction is that the pion energy comes from the difference between the neutron and proton kinetic energies and as a consequence there must be a difference between the neutron and proton momenta. The transfer of energy and no momentum is possible if we have a reaction of the type (a, b) with two particles where $m_a - m_b \simeq m_\pi$. There is no such possibility using stable particles and a reaction which proceeds through strong or electromagnetic interaction to ensure reasonable cross sections. However there is a close case in the (Σ^-, Λ) reaction, where 82 MeV of the pion energy can come from the Σ^-, Λ mass difference, thus resulting in smaller momentum transfer to the pionic atom. This is indeed the case as one can see in fig. 1 where we plot the momentum transfer given to the pionic atom for the (n, p) and (Σ^-, Λ) reactions as a function of the n or Σ^- kinetic energies. As we can see, for kinetic energies around 400–800 MeV the momentum transfer in the (Σ^-, Λ) reaction is appreciably smaller than in the (n, p) reaction.

From the technical point of view the (Σ^-, Λ) reaction is very similar to the (n, p). Indeed the $\Sigma^- p \to \Lambda n$, in the meson exchange language, is mediated in both cases by π and ρ exchange. Hence only the coupling constants and isospin factors are different from one case to the other, although the peculiar hard core interaction of the Nijmegen model[17, 18], which we use, and the lack of form factor in the hyperon–meson vertices, produces slight differences. We use version D of the Nijmegen model[17]. We follow exactly the same steps as in ref.[16] and the same equations are valid with minor changes. The couplings of the mesons to the baryons are given in detail in ref.[19] and with the help of these two references we can immediately write

$$\frac{d^2\sigma}{d\Omega_\Lambda dE_\Lambda} = \frac{|\vec{p}_\Lambda|}{|\vec{p}_\Sigma|} M_\Sigma M_\Lambda \frac{1}{2\omega_\pi} \frac{1}{(2\pi)^3} \frac{\Gamma}{[E_\Sigma + M_\Lambda - E_\Lambda - E(A\pi^-)]^2 + (\Gamma/2)^2}$$

$$\times \bar{\Sigma}\Sigma |T|^2 \qquad (1)$$

where ω_π, Γ are the energy and width of the pionic state and T is the transition t matrix from the model depicted diagramatically in fig. 2, which gets contribution with π exchange followed by the $\pi N \to \pi N$ s-wave interactions, $\pi + \rho$ exchange with p-wave meson–N coupling exciting a Δ (including the indirect effect of correlations which generate the Landau Migdal force in the formalism of ref.[20]) and π exchange followed by the Coulomb interaction of the pion with the nucleus. Thus

$$T = T^{(s)} + T^{(p)} + T^{(c)} \qquad (2)$$

where

$$-iT^{(s)} = -\frac{f_{\Sigma\Lambda\pi}}{\mu} \vec{\sigma}\,\vec{q}\,\frac{i}{q^{o2} - \vec{q}^{\,2} - \mu^2} (-1)\,4\pi \left\{ \frac{2\lambda_1}{\mu} + \frac{2\lambda_2}{\mu} \left(\frac{N-Z}{A} \right) \right\}$$

(Continued in the next page)

$$\cdot \int \rho(\vec{r})\, e^{i\vec{q}\vec{r}}\, \Phi^*_{nlm}(\vec{r})\, d^3r$$

$$-iT^{(p)} = -\frac{f_{\Sigma\Lambda\pi}}{\mu} \left(\frac{f^*}{\mu}\right)^2 \frac{2}{3} \frac{1}{\sqrt{s} - M_\Delta} \left\{ \frac{1}{3} \frac{Z}{A} + \frac{N}{A} \right\}$$

$$\sigma_i p_j \left\{ V_l'\, \hat{q}_i \hat{q}_j + V_t'(\delta_{ij} - \hat{q}_i \hat{q}_j) \right\}$$

$$\cdot \int \rho(\vec{r})\, e^{i\vec{q}\vec{r}}\, \Phi^*_{nlm}(\vec{r})\, d^3r$$

$$V_l' = \vec{q}^{\,2} D_\pi(q) F_\pi(q) - \vec{q}^{\,2} \tilde{D}_\pi(q) \tilde{F}_\pi(q) \left[1 + \frac{4}{3} q_c^2 \tilde{D}_\pi(q) \right] -$$

$$- \frac{1}{3} q_c^2 \tilde{D}_\pi(q) \tilde{F}_\pi(q) - \frac{2}{3} q_c^2 \tilde{D}_\rho(q) \tilde{F}_\rho(q) C_\rho'$$

$$V_t' = \vec{q}^{\,2} D_\rho(q) F_\rho(q) C_\rho' - \vec{q}^{\,2} \tilde{D}_\rho(q) \tilde{F}_\rho(q) \left[1 + \frac{4}{3} q_c^2 \tilde{D}_\rho(q) \right] C_\rho'$$

$$- \frac{1}{3} q_c^2 \tilde{D}_\pi(q) \tilde{F}_\pi(q) - \frac{2}{3} q_c^2 \tilde{D}_\rho(q) \tilde{F}_\rho(q) C_\rho'$$

$$-iT^{(c)} = -\frac{f_{\Sigma\Lambda\pi}}{\mu} \vec{\sigma}\,\vec{q}\, \frac{i}{q^{o2} - \vec{q}^{\,2} - \mu^2} (-i)\, 2\omega_\pi \int d^3r\, e^{i\vec{q}\vec{r}}\, V_c(\vec{r})\, \Phi^*_{nlm}(\vec{r})$$

$$(3)$$

with F_π, F_ρ the pion and ρ meson form factors (we take monopole form factors of the type $F_i(q) = (\Lambda_i^2 - m_i^2)/(\Lambda_i - q^2)$), C_ρ' the ratio of $\Sigma\Lambda\rho$ to $\Sigma\Lambda\pi$ coupling constants squared. $\tilde{D}_{\pi,\rho}(q)$ is the meson propagator $D_{\pi,\rho}(q)$ substituting $\vec{q}^{\,2}$ by $\vec{q}^{\,2} + q_c^2$ (q_c = 475 MeV[19]), and the same prescription for the function $\tilde{F}(q)$. M_Δ, μ are the delta and pion masses, $\vec{p}$ is the momentum of the trapped pion ($\vec{p}\,\Phi^*_{nlm} = i\,\vec{\nabla}\,\Phi^*_{nlm}$), $s' = (q + p_N)^2 \simeq (q_0 + M_N)^2 - \vec{q}^{\,2}$ (with M_N the nucleon mass), $\rho(\vec{r})$ is the nuclear density and $\Phi_{nlm}(\vec{r})$ the wave function of the pion in the atomic orbit n, l, m.

The set of parameters taken are[16,19] $f^2_{\Sigma\Lambda\pi}/4\pi = 0.019$, $f^{*2}/4\pi = 0.36$, $C'_\rho = 3.95$, $\Lambda_\pi = 1300$ MeV, $\Lambda_\rho = 1400$ MeV, $\lambda_1 = 0.017$, $\lambda_2 = 0.0528$, where λ_1 is modified from the free value to account for higger order contribution in the real s-wave part of the pion nucleus optical potential. The matrix T is Lorentz invariant and this implies that vertices must be Lorentz invariant. This is accomplished, by replacing $\vec{q}^{\,2}$ in the expresions of V'_l and V'_t by $2(P_\Lambda . P_\Sigma - M_\Lambda M_\Sigma)$ and $\vec{q}$ in $\vec{\sigma}\,\vec{q}$ of $T^{(s)}$ and $T^{(c)}$ by $\vec{q}\,[2(P_\Lambda . P_\Sigma - M_\Lambda M_\Sigma)/|\vec{q}|^2]^{1/2}$. On the other hand, in the $\pi N\Delta$ vertex corresponding to the bound pion, the momentum should be the CM momentum. This is accomplished by multiplying $\vec{p}$ in $T^{(P)}$ by $M_N/\sqrt{s'}$.

The distortion of the Σ^- and Λ waves is done in the eikonal approximation as in ref.[16] with the replacement

$$e^{i\vec{q}\,\vec{r}} = e^{i\vec{p}_\Sigma\vec{r}}\, e^{-i\vec{p}_\Lambda\vec{r}} \longrightarrow$$

$$e^{i\vec{p}_\Sigma\vec{r}}\; e^{-1/2\int_{-\infty}^{z}\sigma_{\Sigma N}(p_\Sigma)\,\rho(\vec{b},z')\,dz'} \qquad (4)$$

$$.\; e^{-i\vec{p}_\Lambda\vec{r}}\; e^{-1/2\int_0^\infty \sigma_{\Lambda N}(p_\Lambda)\,\rho(\vec{r}\,')\,dl}$$

with $$\vec{r}\,' = \vec{r} + \frac{\vec{p}}{|\vec{p}_\Lambda|}\, l \qquad (5)$$

The values for the cross sections of ΣN and ΛN are taken from experiment[21,22] and from refs.[17,18] . For the ΣN total cross sections entering the distortion through eq. (4) we take $\sigma_{\Sigma N} = 30$ mb and $\sigma_{\Lambda N} = 20$ mb at the two energies $T_\Sigma = 600$ and 800 MeV which we have considered.

In figs. 3 and 4 we show the results for the excitation of the 1s and 2p pionic states of ^{208}Pb at the peak of the Lorentzian distribution with and

without distortion, as a function of the scattering angle for $T_\Sigma = 600$ MeV. As we can see the effect of distortion on the 1s state is more pronounced than in the 2p state, as we might expect since the s-state gets contribution from the inner part of the nucleus, which is eliminated by the distortion, while the p-state gets contribution more from the surface. The peak of the distributions corresponds to 0°.

It is interesting to compare the effect of the distortion with the case of the (n, p) reaction[16]. The effect of distortion depends very much on the momentum transfer. The momentum transfer at T_n or $T_\Sigma = 600$ MeV and zero degrees are of the order of 175 MeV and 107 MeV respectively. If we concentrate at zero degrees for the purpose of comparison, the reduction factor here is 45 for the 1s state while this factor is 650 in the (n, p) reaction at the same kinetic energy (600 MeV). For the 2p states the reduction factors are 2.65 and 60 respectively. In both cases there is a gain of a factor 15 to 20 in the (Σ^-, Λ) reaction with respect to the (n, p), because of the more moderate role played by the distortion in the (Σ^-, Λ) reaction. For the absolute values of the cross sections without distortion we obtain 0.4 mb/sr MeV here, versus 0.08 mb/sr MeV of the (n, p) reaction for the 1s state at zero degrees. In the case of the 2p state these numbers are 0.23 mb/sr MeV and 0.35 mb/sr MeV. This is in spite of a factor 8 smaller from the coupling constants in the (Σ^-, Λ) case versus the (n, p) reaction, which means that we have also gained in the undistorted transition amplitude because of the smaller momentum transfer.

The results at $T_\Sigma = 800$ MeV are very similar with slightly larger cross sections. We have also evaluated the results for the $\Sigma^- + {}^{40}Ca \longrightarrow \Lambda + ({}^{40}Ca\ \pi^-)$ reaction. In Table I we show the results for the two nuclei at zero degrees and $T_\Sigma = 800$ MeV. For the ^{40}Ca case we evaluate the cross section for the 1s state only since the 2p state is already observable with the X ray technique.

The background for the reaction comes from the inclusive (Σ^-, Λ) reaction while in the (n, p) reaction it comes from the inclusive (n, p).

Experimentally the cross section for $\Sigma^- p \to \Lambda n$ is known[23] up to $p_{\Sigma^-} \simeq 0.6$ GeV/c and we have $\sigma \simeq 20$ mb. A smooth extrapolation of the theoretical results of ref.[17] at the higher energies needed here gives $\sigma \simeq 5-10$ $\sigma \simeq 5-10$ mb. The $np \to np$ cross section is about 35 mb. The $\Sigma N \to \Sigma N$ and ΛN $\Lambda N \to \Lambda N$ are similar to the $NN \to NN$ cross sections. Hence we should expect a background for the inclusive (Σ^-, Λ) at least 5 times smaller than the one for the (n, p) reaction which is of the order of 0.8 mb/sr MeV for ^{208}Pb from the experiment of ref.[6]. Thus we will assume a background of the order of 0.16 mb/sr MeV for this nucleus and, assuming a simple A scaling, 0.03 mb/sr MeV for the ^{40}Ca case. With these results the ratio of signal to background with distorted waves is given in brackets in table 1. The ratios of signal to background are 10 % for the 1s state in ^{208}Pb, 20 % for the 1s state in ^{40}Ca and 56 % for the 2p state in ^{208}Pb.

For the pionic wave functions we have used the potential of ref.[2]. If we use the potential of ref.[24] the results change at the level of 25 % for the 2p state in Pb and 50 % in the 1s state in Pb. We have also investigated the sensitivity of the results to the distortion parameters. If instead of 30 mb, 20 mb for the ΣN and ΛN cross sections we use 35 mb, 25 mb (25 mb, 15 mb) we decrease (increase) the cross section by a factor two for the 1s states and reduce (increase) it by about 30% for the 2p states. Even with uncertainties in the estimation of the ratio of signal to background of the order of a factor 2, it is clear that the reaction offers much cleaner signals than the (n, p) even at the optimal energy of $T_n = 1000$ MeV investigated in ref.[16]. Indeed, with the results of Table 1, we gain a factor 50 increase in this ratio for the 1s state and about a factor 10 for the 2p state in ^{208}Pb.

Note that the 1s state is more easily populated here than in the (n, p) reaction. Apart from the more moderate role of the distortion already discussed, the excitation of the 1s state in the forward direction is only sensitive to the V'_l part of eq. (3) (apart from the s-wave and Coulomb pieces). This part is larger here than in the (n, p) reaction as a consequence

of the Σ, Λ mass difference $(2(P_\Sigma . P_\Lambda - M_\Lambda . M_\Sigma)$, the invariant $\vec{q}^2$ factor in eq. (3), is smaller than $2(P_p . P_n - M^2)$, the corresponding factor for the (n, p) reaction. Hence in the (Σ, Λ) case $V_l' \simeq V_t'$ in the forward direction, while in the (n, p) case $V_l' \ll V_t'$).

The ratios obtained here are sufficiently large to make the direct detection possible by simple investigation of $d^2\sigma/d\Omega\, dE$, without the need of an extra coincidence experiment to detect the decay products of the pion as suggested in ref.[16] in connection with the (n, p) reaction.

The reaction suggested here could be properly addressed in the planned KAON factory at Vancouver.

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Fig. 1.- Momentum transfer in the (n, p) and (Σ^-, Λ) reaction creating a π^- bound, as a function of the kinetic energy of the n or the Σ^- respectively.

Fig. 2.- Feynman diagrams considered in the $\Sigma^- N \longrightarrow \Lambda N \pi^-$ processes. ***a)*** pion exchange with $\pi N \longrightarrow \pi N$ s-wave scattering; ***b)*** $\pi + \rho$ exchange including the indirect effect of nuclear correlations with p-wave $\pi N \longrightarrow \pi N$ scattering mediated by Δ excitation; ***c)*** π exchange with π Coulomb interaction with the protons.

Fig. 3.- $d^2\sigma/d\Omega\, dE$ at the peak of the Lorentzian distribution for the $\Sigma^- + {}^{208}Pb \rightarrow \Lambda + ({}^{208}Pb\, \pi^-)$ at T_Σ = 600 MeV creating a pion in the 1s state as a function of the scattering angle. Dashed line: results without distortion. Continuous line: results with distortion.

Fig. 4.- Same as fig. 3 for the 2p state.

TABLE I

$d^2\sigma/d\Omega\, dE$ [mb/sr MeV] at the peak for T_Σ = 800 MeV and $\theta = 0°$.

	^{40}Ca	^{208}Pb
	without/with distortion $\left(\frac{\text{Signal}}{\text{Background}}\right)$	without/with distortion $\left(\frac{\text{Signal}}{\text{Background}}\right)$
1s	0.066/0.0060 (20 %)	0.49/0.015 (10 %)
2p	———	0.29/0.090 (56 %)

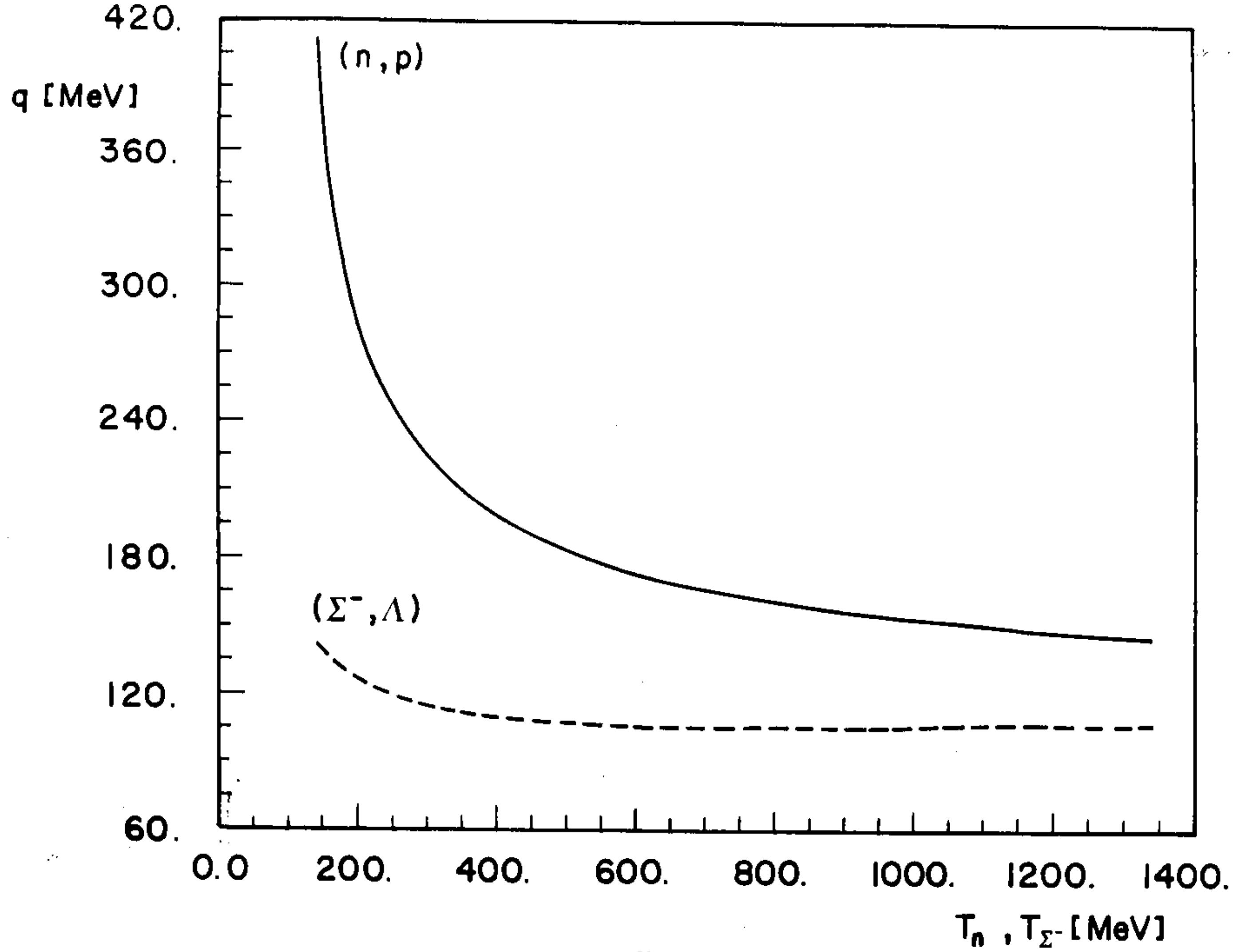

420.
q [MeV]
360.
300.
240.
180.
120.
60.
(n,p)
(Σ⁻,Λ)
0.0
200.
400.
600.
800.
1000.
1200.
1400.
Tn , TΣ- [MeV]

fig.1

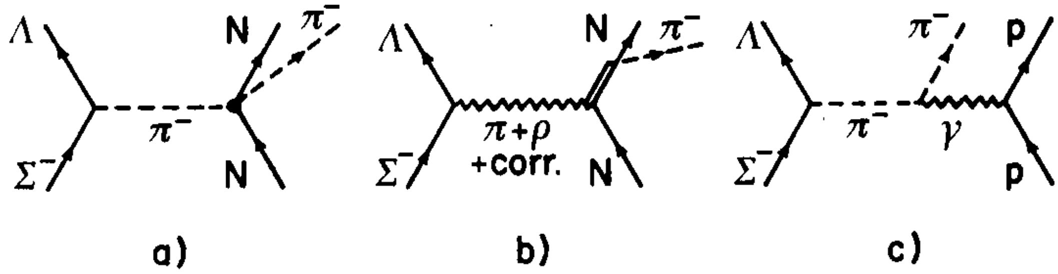
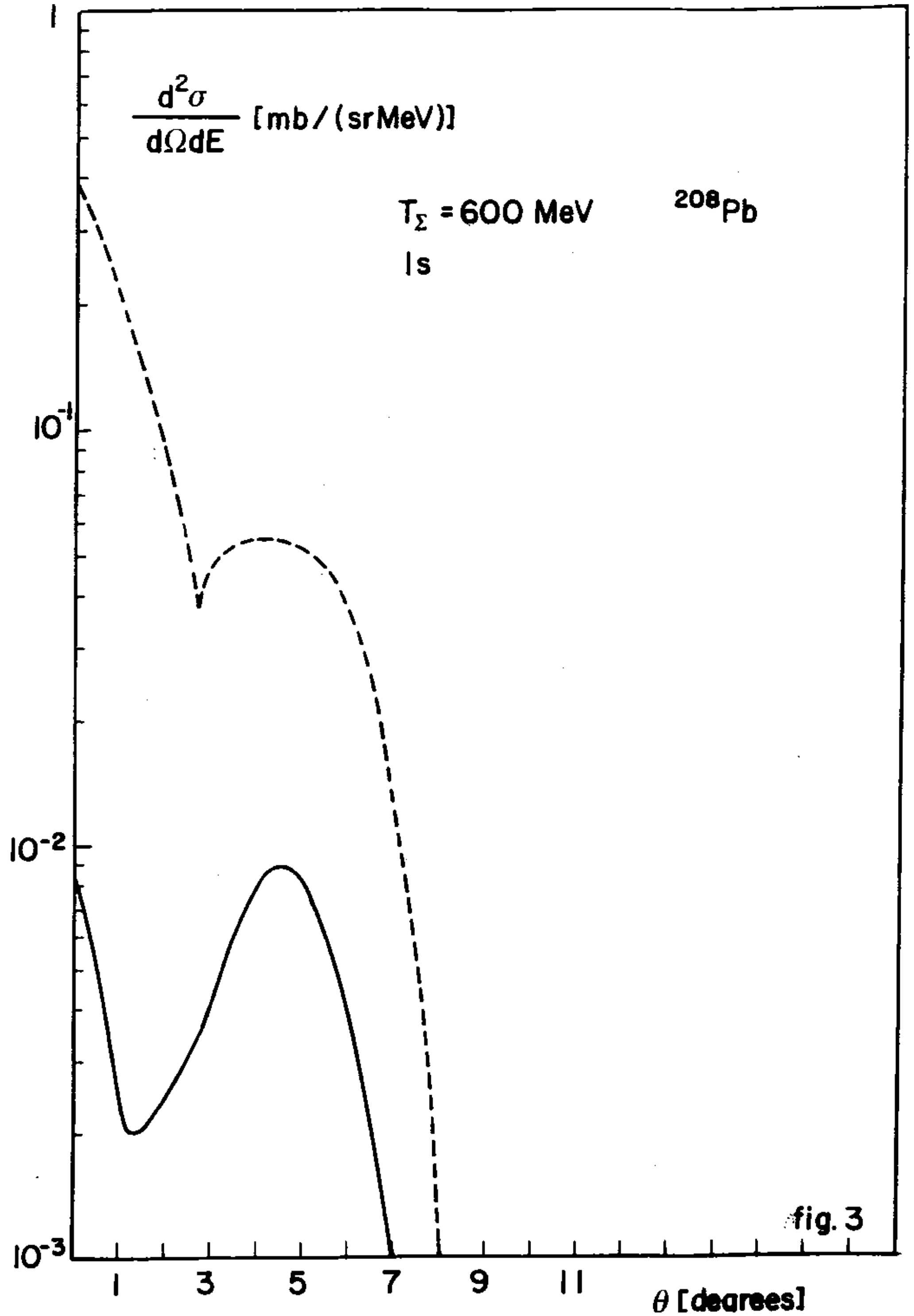
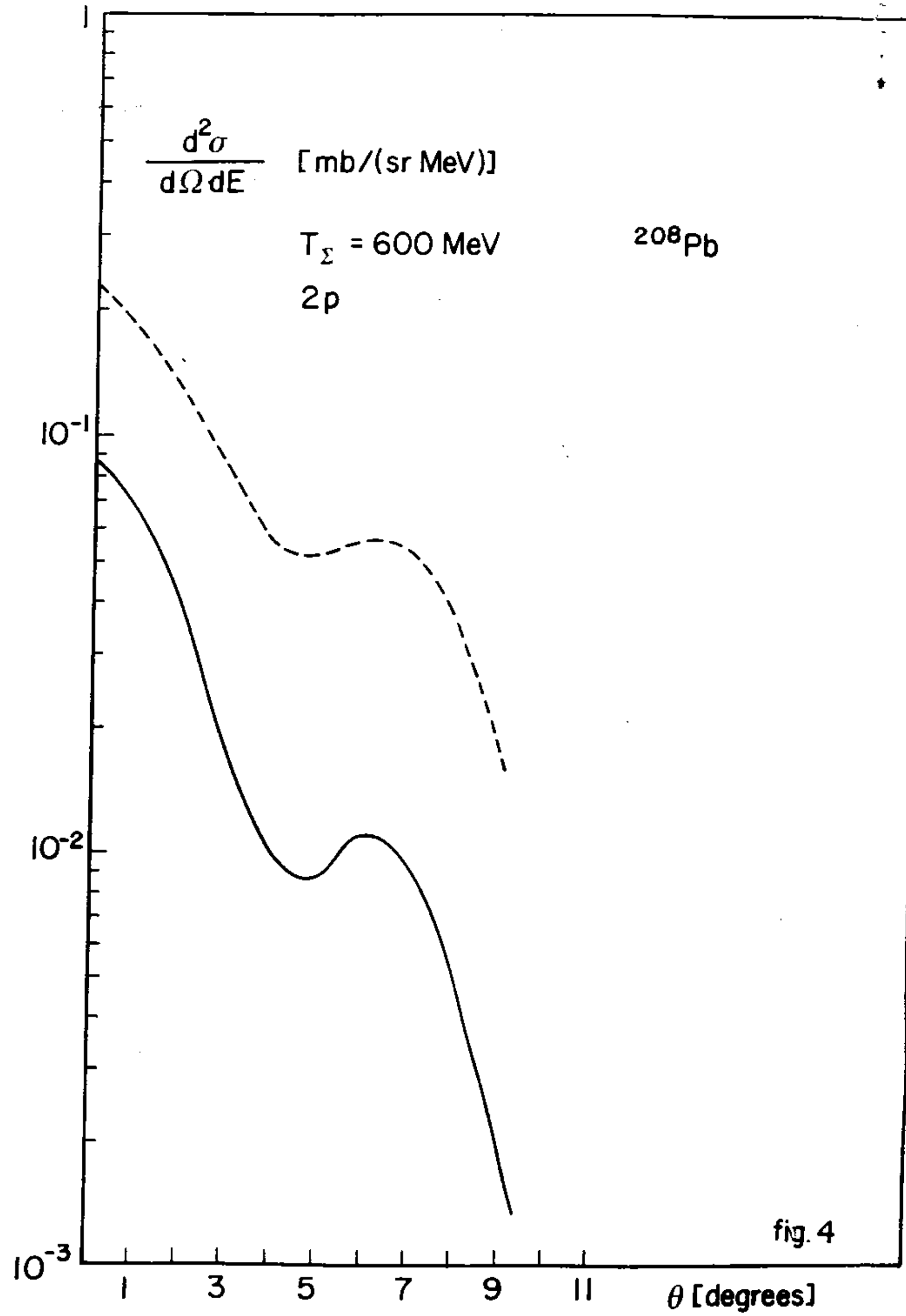

Λ
Σ⁻
π⁻
N
N
π⁻
a)
Λ
Σ⁻
π+ρ
+corr.
N
N
π⁻
b)
Λ
Σ⁻
π⁻
γ
π⁻
p
p
c)

fig.2



$\frac{d^2\sigma}{d\Omega dE}$ [mb/(srMeV)]
T_Σ = 600 MeV
1s
^{208}Pb
1
10^{-1}
10^{-2}
10^{-3}
1 3 5 7 9 11
θ [degrees]

fig. 3



$\frac{d^2\sigma}{d\Omega dE}$ [mb/(sr MeV)]
T_Σ = 600 MeV
2p
^{208}Pb
1
10^{-1}
10^{-2}
10^{-3}
1 3 5 7 9 11
θ [degrees]

fig. 4