

Deeply bound pionic atoms from the (γ, p) reaction in nuclei

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Abstract

We study the (γ, p) reaction on ^{208}Pb leading to ^{207}Pb with a bound pion attached to it in the lowest 1s or 2p pionic levels. The reaction can be made recoilless to optimize the production cross section but we must choose a bit higher photon energy to overcome the Coulomb barrier in the proton emission. The cross sections obtained are easily measurable and can be larger than 50 per cent of the background from inclusive (γ, p) . This makes it a clear case for the detection of the pionic atom signals, converting this reaction into a practical tool to produce deeply bound pionic atoms.

1 Introduction

In the past decade a search, both theoretical and experimental, for deeply bound states was conducted, which led to the successful detection of these states in Pb isotopes in [1, 2]. A review of the methods proposed and early attempts prior to the detection at GSI can be found in [3]. Out of many reactions proposed it was envisaged in [3] that two reactions stood better chances, the $(d, ^3\text{He})$ reaction [4] and the radiative capture in low energy pion scattering (π^-, γ) [5], both of them leaving a bound pion in the nucleus. The first reaction offers a special characteristic, very dear in production of bound particles in nuclei, which is its recoilless nature for some kinematics. The second reaction is also nearly recoilless and has the additional advantage of being a coherent reaction, hence benefiting from an extra A^2 factor in the cross section. This extra advantage is however counterbalanced by the fact that the pions are secondary beams and hence one has smaller fluxes than with primary beams like the d in the first reaction. The first reaction is the

one that led to the successful detection of the pionic states, while the second one, carried out at TRIUMF [6], offered a much less clear evidence because lack of enough resolution in the photon detector. Yet, it proved a worth method to be considered in the future when better resolution is achieved since it produces the pionic states in the ground state of stable nuclei, like ^{208}Pb . The $(d, {}^3\text{He})$ reaction leads instead both to ground and excited states of A-odd nuclei where the atomic and nuclear levels mix.

The experience on the history of these reactions also stresses the importance of having a recoilless reaction and using primary beams. Another reaction which fulfills these conditions is the (γ, p) reaction where a particular kinematics can be chosen to make the reaction recoilless in the production of the pionic atom. A suggestion to use this reaction for the production of omega bound states in nuclei has been done in [7], although the large width predicted for these states would most probably prevent the observation of clean peaks. In the present case we already know from experiment that the widths are smaller than the separation of the levels. The success of the reaction is then tied to the magnitude of the cross sections for the reaction and the ratio of signal to the background coming from other reactions where no pions are produced but a proton is detected. Indeed, consideration of the background is important since the signal for the bound pion production is the detection of a proton with an energy equal to the one of the photon minus the pion mass (and the binding energies). However, the same protons can be obtained from the inclusive (γ, p) process in which the proton has collisions and loses energy.

In the present work we perform calculations for the reaction

$$\gamma + {}^{208}\text{Pb} \rightarrow p + ({}^{207}\text{Pb} \cdot \pi_b^-)$$

which is depicted diagrammatically in fig. 1. The elementary reaction is $\gamma n \rightarrow \pi^- p$ and the final proton is emitted leaving a nuclear state of ${}^{207}\text{Pb}$ with a bound pion tied to it.

Since the reaction is made practically recoilless, the elementary amplitude for the process is extremely simple since only the Kroll Ruderman term contributes. Thus the nuclear amplitude for the process of fig. 1 is given by

$$-iT = \int d^3r \frac{f_{\pi NN}}{m_\pi} e\sqrt{2} \left(\frac{2M_N}{2M_N - m_\pi} \right) \vec{\sigma} \cdot \vec{\epsilon} \frac{1}{\sqrt{V}} e^{i\vec{k}\cdot\vec{r}} \frac{1}{\sqrt{V}} e^{-i\vec{p}\cdot\vec{r}} \Phi_{nlm}^*(\vec{r}) \phi_{JLM}(\vec{r}) \quad (1)$$

where Φ and ϕ are the pion and neutron wave function respectively, k, p the photon and proton momenta, and $\vec{\epsilon}$ the photon polarization.

In eq. (1) we have used a plane wave for the proton, but it is clear that a distorted wave should be used and we shall do that below. In addition we sum and average the cross section over final and initial polarizations. We

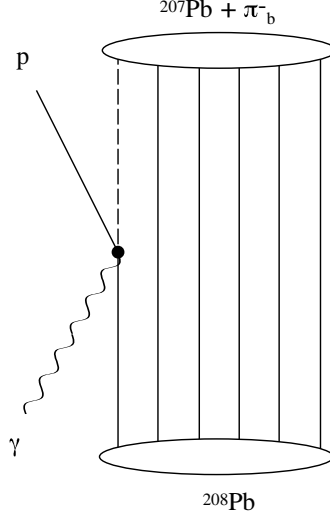


Figure 1: Diagram for the (γ, p) reactions to form pionic bound states on ^{207}Pb .

show explicitly below the results obtained with the photon polarization given by $\vec{\epsilon}_- = (\hat{i} - i\hat{j})/\sqrt{2}$.

We shall look at protons going in the forward direction. The matrix element of T , removing the volume V in the denominator, becomes T' given by

$$\begin{aligned}
T' &= 2\pi\delta_{M-1/2, m} \frac{f_{\pi NN}}{m_\pi} 2e \frac{2M_N}{2M_N - m_\pi} \\
&\times \sum_{l_p} \int_0^\infty b db \int_{-\infty}^\infty dz \tilde{R}_{nl}^*(r) R_{NL}(r) \tilde{Y}_{l, m}(\frac{z}{r}) \tilde{Y}_{L, M-1/2}(\frac{z}{r}) \\
&\times C(L, 1/2, J; M - 1/2, 1/2) e^{ikz} (2l_p + 1) (-i)^{l_p} \tilde{j}_{l_p}(pr) P_{l_p}(\frac{z}{r}) \quad (2)
\end{aligned}$$

where \tilde{R} and R are the radial wave functions of the pion and bound neutron states, and \tilde{Y} the spherical harmonics removing the $e^{im\varphi}$ factor. The proton distorted wave $\tilde{j}_{l_p}(pr)$ is obtained for each proton partial wave by solving the Schrödinger equation with the appropriate boundary condition shown in Eq. (12) in Ref. [8]. We take the proton-nucleus optical potential from [9] and it is given by

$$U(r) = \frac{V + iW}{1 + \exp[(r - R)/a]}, \quad (3)$$

where R and a are the radius and diffuseness parameters taken to be 7.35 fm and 0.65 fm for Pb, respectively. The energy dependent potential strength

V and W are shown in Fig. 2.10 (for the real part) and Fig. 4.6 (for the imaginary part) in Ref. [9]. We also add the Coulomb potential with finite size of the nucleus, which is the same one used for the π^- with opposite sign.

The cross section for the process is then given by

$$\begin{aligned} \frac{d^2\sigma}{d\Omega dE_p} &= \frac{pM_N}{2m_\pi} \frac{1}{(2\pi)^3} \frac{1}{2k} \\ &\times \sum_{(n^{-1}\otimes\pi)} \frac{\Gamma}{[k + M(^{208}\text{Pb}) - E_p - M(^{207}\text{Pb} \cdot \pi_b^-)]^2 + (\Gamma/2)^2} \\ &\times \sum \sum |T'|^2 \end{aligned} \quad (4)$$

where Γ is the width of the pionic atom state.

By numerical calculations, we find that the effect of the Coulomb barrier for the emitted proton is large for low energy protons, suppressing the signals significantly. On the other hand, if we increase the proton kinetic energy in the final states, which is equivalent to increasing the incident photon energy, this moves us away from the recoilless condition of the reaction. Thus, we evaluate the pionic atom formation spectra for several incident photon energies in order to find the optimal kinematical condition. We conclude that we have the largest signals at an incident photon energy $k = 170\text{MeV}$, while the recoilless condition appears at $k = 155\text{MeV}$. The results for the double differential cross section of the reaction are shown in fig. 2. As we expect for the nearly recoilless kinematics, the substitutional states make the largest peaks and the dominant contributions come from the 2p pionic state with neutron $p_{3/2}$ and $p_{1/2}$ hole states. We can also see the pionic 1s state formation at $T_p=29 \sim 30\text{ MeV}$. The formation cross section is reduced by around the 30 % from the plane wave approximation for the largest signal due to the distortion effects on the emitted proton and is estimated to be about $20\ \mu\text{b}/\text{sr}/\text{MeV}$ for the largest signal.

As for the background for the present reaction it can be easily estimated using experimental results already available from the study of the inclusive (γ, p) reaction in nuclei [10]. There we can see results in ^{208}Pb at $k = 227\text{MeV}$ and 390MeV . The cross sections go down to $E_p=40\text{MeV}$ and hence it is easy to extrapolate the results smoothly to $E_p=30\text{MeV}$ that we have in the present case. The differential cross sections for a proton angle of 52° are $50\ \mu\text{b}/\text{sr}/\text{MeV}$ and $100\ \mu\text{b}/\text{sr}/\text{MeV}$ for $k = 227\text{MeV}$ and $k = 390\text{MeV}$, respectively. Extrapolating from these two data to $k = 170\text{MeV}$ we obtain a cross section of $32\ \mu\text{b}/\text{sr}/\text{MeV}$ for the background of inclusive (γ, p) in our reaction at this angle. This result could be also obtained theoretically using the approach of [11] where a Monte Carlo simulation was performed with the probabilities for the primary nuclear steps evaluated with a microscopic many body calculation in [12]. This inclusive (γ, p) cross section is about

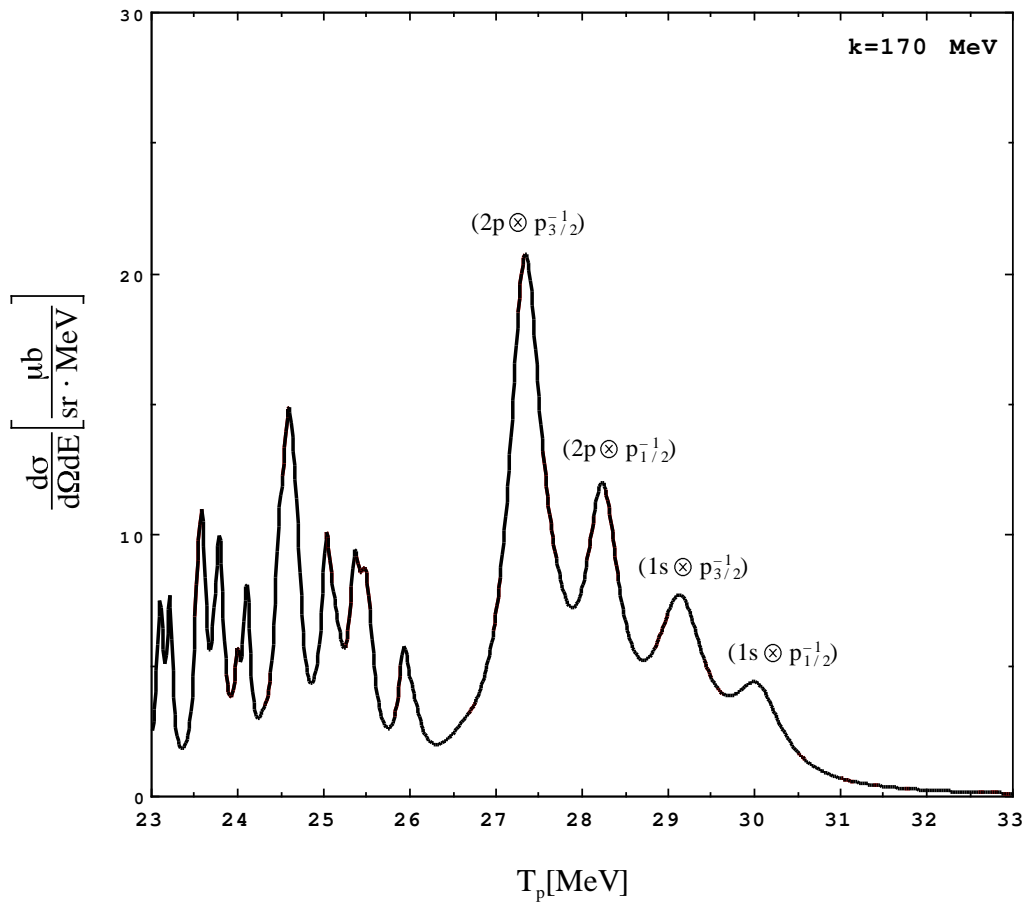


Figure 2: Expected spectra of the $^{208}\text{Pb}(\gamma,p)^{207}\text{Pb}\cdot\pi_b^-$ reaction at the photon energy $k=170$ MeV as a function of the emitted proton energy. A convolution with the experimental resolution of 50 keV FWHM is implemented in the results. For a resolution of 200 keV the figure is similar, but the strength at the peak of the p-wave states is reduced by about 20 %.

double the one obtained for the peaks of the signals of the pionic atoms in an average. However, at small angles, where we have evaluated the pionic atom formation cross sections, the background should be even smaller, and this is the case in the theoretical model of [11], because kinematically it is not possible to have contribution to the process with just one collision.

This situation is particularly rewarding in view to distinguish these states experimentally. On the other hand, although our calculations do not deem it necessary, it should be possible to further increase the ratio of signal to background using delayed fission of pion absorption fragments, a technique used with success in the production of Λ hypernuclei in [13] and tentatively suggested for the present reaction [14]. The set up for the experiment is suited to present experimental facilities, particularly those of low energies, and the cross sections predicted are of the order of those presently being measured with high precision in the (γ, p) reaction [10], which makes this reaction a very practical method to produce deeply bound pionic atoms.

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